CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Buildings End-Use
Energy Efficiency

RESIDENTIAL THERMAL DISTRIBUTION SYSTEMS: DISTRIBUTION EFFECTIVENESS AND IMPACTS ON EQUIPMENT SIZING

Gray Davis, *Governor*

OCTOBER 1999

CALIFORNIA
ENERGY
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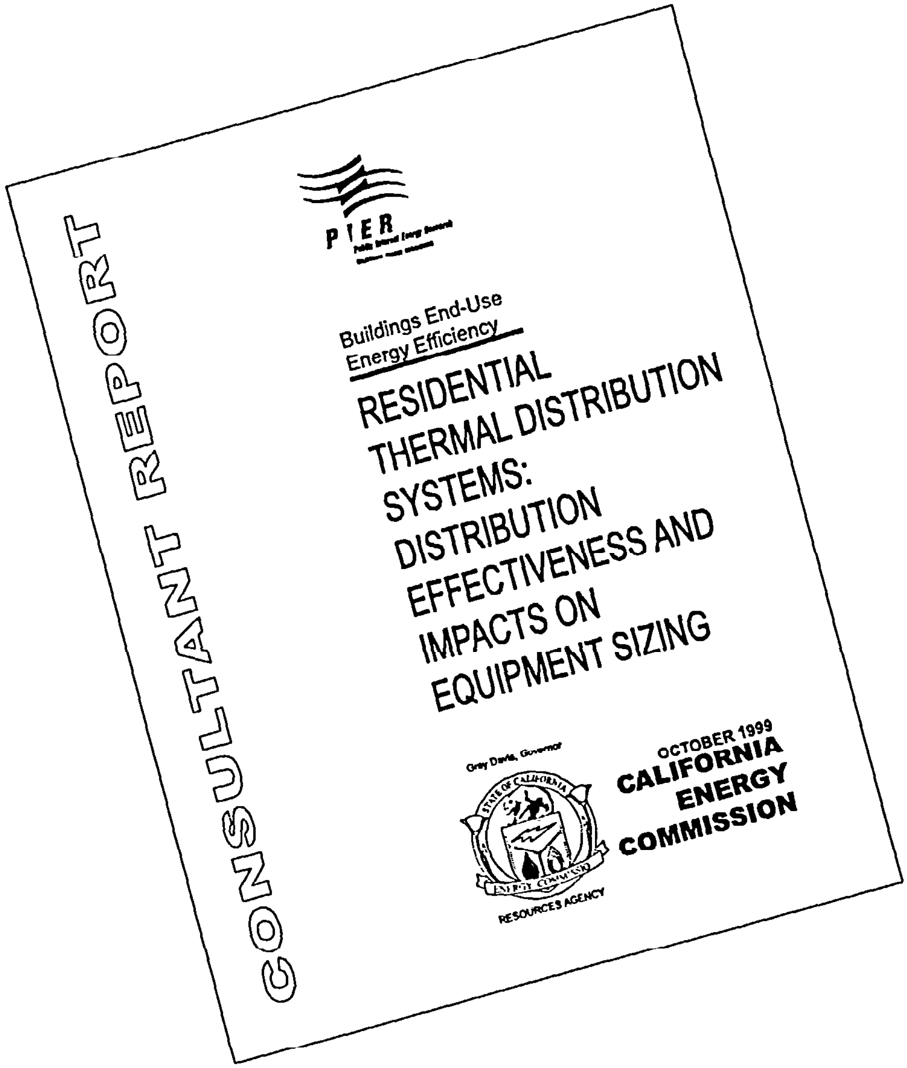
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Legal Notice

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Table of Contents

Section **Page**

Appendices

List of Figures

Figure **Page**

List of Tables

Table **Page**

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial / Agricultural / Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Residential Thermal Distribution Systems: Distribution Effectiveness and Impacts on Equipment Sizing, one of nine projects conducted by the California Institute for Energy Efficiency. This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

This report summarizes the work performed by Lawrence Berkeley National Laboratory (LBNL) between October 1998 and September 1999 on Thermal Energy Distribution Systems in Residential Buildings. The California Energy Commission through the Public Interest Energy Research (PIER) Transition Program agreement with the California Institute supported this research project for Energy Efficiency (CIEE). The U.S. Department of Energy also provided funding support for selected components of this research through a separate agreement with LBNL. The work builds on the Residential Thermal Distribution Systems multi-year research project supported by CIEE.

Introduction

This study examines, through field-testing and computer simulation, the potential for improving the effectiveness of residential Heating, Ventilation and Air Conditioning (HVAC) systems. Improving the effectiveness of HVAC systems can lead to use of downsized equipment to deliver the same cooling to conditioned space as a typical HVAC system. Downsizing, with a good distribution system, results in savings for the consumer, both in initial equipment expense and energy bills. The cooling of the conditioned space is evaluated by looking at the concept introduced in a previous phase of this study: “Tons At the Register" (TAR) together with comfort issues, such as how quickly a house is cooled (or “pulldown time”), and the distribution of cooling throughout the house. In addition, alternative methods for testing duct leakage were investigated. This report concludes with descriptions of efforts to bring this research to the marketplace.

This executive summary presents brief descriptions of each of the four major sections of this final report, including brief descriptions of objectives outcomes, conclusions and recommendations.

Duct Leakage Diagnostics

Objectives

- Improve duct leakage test methods.
- Update the American Society for Testing and Materials (ASTM) Standard E1554: “Determining External Air Leakage of Air Distribution Systems by Fan Pressurization”

Outcomes

Several diagnostic techniques for measuring duct leakage were evaluated in an earlier phase of the current work. These included the house pressure test, the nulling pressure test, tracer gas, duct and house pressurization and duct only pressurization. None of these methods was considered ideal, so further efforts were undertaken to develop a better duct leakage test. The result of an American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) workshop, committee meetings and discussions with other researchers yielded a new test method, termed the Delta Q.

Conclusions and Recommendations

The test is simple, quick and not as sensitive to wind conditions as some other tests.

Next steps: Further experience is needed in conducting the test in more homes and to include repeatability studies. Additional studies will also be required to perform analytical analyses for error propagation, uncertainty and sensitivity to input parameters.

Duct Sealants and Longevity Testing

Objective

- Develop and introduce a draft ASTM standard for longevity testing of duct sealants

Outcome

A draft standard for the longevity testing of duct sealants, based on research conducted in a previous phase of this project, was developed and submitted to the American Society of Testing Materials (ASTM). A technical issue raised during review of the method concerned the peak temperatures that should be used in the accelerated longevity test, with one ASTM committee member noting that attic temperatures could exceed the value used in the test. A literature search was undertaken in this study to address the issue.

Conclusions and Recommendations

Based on that search and temperature limits set by manufacturers for duct tape, a compromise temperature of 180 degrees Fahrenheit was reached, leading to revisions in the longevity test apparatus.

Next Steps:

The longevity test apparatus will be used to test different procedures for evaluating longevity. The procedures include:

- The existing procedure of alternating between hot (150°F) and cold (0°F) air flows with a pressure difference across the seal.
- Changing the temperatures in the alternating temperature test to be more extreme (180°F).
- Splitting the test into a hot test and a cold test. The hot test will vary the temperatures in the range of 70°F (close to room temperature) to 180°F. The cold test will have the range from 70°F down to 0°F. This narrower temperature range will allow for more rapid cycling and greater temperature extremes (e.g., we could possibly go lower than 0°F). For both the hot and cold test there will be a pressure difference maintained across the leakage sites.
- Having no cycling of temperature and maintaining a steady hot (180°F) or steady cold (0°F) temperature. Unlike the previous baking tests there will be airflow through these samples and pressure differences across the leaks.

Duct System Interactions with System Sizing

Objectives

- Measure the performance of residential cooling equipment and associated distribution systems.
- Compare the REGCAP simulation model to the measured field data.

In this study the duct system interactions with system sizing were examined using both computer simulations and measured data. The measured data were used to examine field performance of cooling systems and to evaluate and validate the computer simulations but were not used to tune any model coefficients so that the model retains its general applicability. The following subsections summarized the outcomes, and conclusions and recommendations for the (1) field measurements and (2) computer simulations components of this overall effort.

1. Field Measurements

Outcomes

Cooling system performance was measured in six new houses, five in California and one in Texas. Testing was performed on homes in their "as found" condition and then with the duct systems sealed. Supply and return duct leakage varied from one to six percent for five of the six homes. These results indicate that the duct systems were better than average installations, with the exception of one home. The results from this home were surprising in that the duct system was located in interior partitioned walls, a preferred design from an energy efficiency perspective, rather than the attic. However, most of the leakage was at the plenum to duct connections located in the garage. This result reinforces the value of field-testing duct systems.

Refrigerant charge was also checked at the sites. All but two sites had near the correct refrigerant charge. One of the two undercharged systems was so low that significant equipment damage could have occurred.

The possibility of resizing systems to reduce HVAC equipment cost and peak energy consumption was also explored. Nameplate capacities indicated significant oversizing compared to calculated loads. In addition, two sites with the same nameplate capacity exhibited a one ton (12,000 BTU / hr) difference in actual delivered cooling to the conditioned space. These and other results show that nameplate capacity is a poor indicator of the capacity of the system. The oversizing of nameplate capacity, however, was offset by lower actual equipment performance.

Six performance metrics were determined for each site, including the pulldown time, tons of cooling at the register, air conditioner capacity, the air conditioner Coefficient of Performance (COP), system COP and delivery efficiency. Although these metrics are useful in understanding cooling system performance, they are strongly influenced by many external factors such as duct leakage, refrigerant charge, evaporator airflow, indoor temperature and humidity, etc. These factors, and limited periods of measurement, make interpretation of the data difficult. Nevertheless, this report compares individual sites where test conditions were similar.

Conclusions and Recommendations

- Installed capacity is considerably less than nameplate and ARI ratings.
- Nameplate and ARI ratings exceed ACCA Manual J load estimates.
- Thermal distribution system losses and poor equipment installation combine to reduce nameplate and ARI capacities close to ACCA Manual J load estimates.
- Improving ducts by reducing leakage can lead to significant energy efficiency gains in addition to increasing the TAR, thereby increasing comfort by reducing pulldown time.
- Leakage specification must be checked by measurement.
- Systems can have good efficiency, but not give sufficient comfort to occupants due to poor distribution.
- Systems with poor distribution need to run much longer if all rooms are to be comfortable.
- Using higher SEER units indicated significant peak energy savings of about 25 percent with no apparent drawbacks.

Next steps:

For sizing issues, more field tests are required to include a wider range of homes, construction techniques and weather conditions in order to convince the building industry of the downsizing potential with good duct systems. For evaluating high SEER air conditioners more field studies are required. These studies need to include both dry and humid climates and long-term evaluations (at least a month) in order to capture the effect of different weather conditions.

Computer Simulations

Outcomes

Several improvements were made to the Register Capacity (REGCAP) model used in earlier phases of this work. The upgraded model was then used to reexamine the pulldown simulations performed in a previous part of this study. Eight different distribution systems were modeled in the same house under the same weather conditions. The better systems were able to pulldown the house in a reasonably short time, under three hours, but the poorer systems took over six hours. Simulation results show that resized systems with good ducts can be as good or better than an existing system.

Conclusions and Recommendations

- Improved ducts and system installation can allow the use of a smaller nameplate capacity air conditioner (almost one ton less in one case, and at least one ton in more demanding situations) without any comfort penalty in terms of pulldown, and with large energy savings (roughly halving energy consumption).
- If system nameplate capacity is unchanged, either improving duct systems and correctly installing the equipment, or moving the ducts inside, results in significant pulldown performance improvements.
- Systems do not provide their nominal capacity at design conditions, when system capacity is most critical.

The model accuracy was evaluated by comparing predicted temperatures for attic, house, return duct, and supply duct air to measured temperatures. Over 100 days of measured data at five sites were used. Detailed comparisons are charted for two sites in Sacramento. Overall there was very good agreement between predicted and measured values for house and attic temperatures and good agreement for duct air temperatures when the air handler fan was on, but not good agreement when the air handler was off. The predicted duct temperature with the air handler off was much hotter (about 5 degrees Celsius) than the measured temperature. However, this result is not significant for the objectives of this study, namely to predict the pulldown time and tons of cooling at the register, since only house air temperature and supply duct air temperature with the air handler on are necessary for the calculations.

Next Steps:

Further refinement of the equipment model is needed. LBNL is working together with Proctor Engineering Group on this issue. The capability of placing ducts in other locations outside conditioned space (e.g., garages and crawlspaces) needs to be added to the model. Developing a streamlined user interface will allow REGCAP to be used by a wider audience (possible as part of energy code style calculations).

Title 24 and HERS Support and Technology Transfer

Objectives

- Provide technical support to the California Energy Commission (CEC) for: (a) updating the "Low-Rise Residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings"; (b) Procedures for HVAC System Design and Installation (for HERS); and (c) CIEE, CBIA, CEC and NRDC Collaborative California procedures for improved design, fabrication, installation and testing of HVAC systems
- Support ASHRAE, ASTM and EPA duct leakage research and interface with related projects funded by other agencies.

Outcomes

- Duct efficiency calculations are included in the Low-Rise Residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings" (CEC (1999)).
- Procedures for HVAC System Design and Installation (for Home Energy Raters) have been updated.
- Field testing has shown that standard flowhoods can be poor for measuring residential register flows and the use of powered flowhoods can reduce measurement problems.
- Various contributions to ASHRAE and ASTM standards were made in the course of this work. A web-based tool was developed to perform ASHRAE standard 152P duct leakage calculations. A draft standard for testing the longevity of duct sealants was prepared and submitted to ASTM. A new draft of an ASTM standard for measuring leakage was also submitted and included the new Delta Q leakage test.

Abstract

This study examines, through field testing and computer simulation, the potential for improving the effectiveness of residential Heating, Ventilation and Air Conditioning (HVAC) systems. Improving the effectiveness of HVAC systems can lead to use of downsized equipment to deliver the same cooling to conditioned space as a typical HVAC system. Downsizing, with a good distribution system, results in savings for the consumer, both in initial equipment expense and energy bills. The cooling of the conditioned space is evaluated by looking at the concept introduced in a previous phase of this study: “Tons At the Register" (TAR) together with comfort issues, such as how quickly a house is cooled (or “pulldown time”), and the distribution of cooling throughout the house. In addition, alternative methods for testing duct leakage were investigated. This report concludes with descriptions of efforts to bring this research to the marketplace.

Some of the key results discussed in this report include:

- development of a new duct leakage test, termed Delta Q, as an alternative method for diagnostic duct testing
- introduction of a draft American Society of Testing Materials (ASTM) standard for longevity testing of duct sealants
- rewrite of the existing ASTM Standard (E1554) for measuring duct leakage
- simulations of summer temperature pulldown time show 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 Seasonal Energy Efficiency Ratio (SEER)
- variations in distribution of cooling that do not match room loads can cause large comfort problems and excess energy consumption if the whole house is cooled until all rooms are at an acceptable temperature
- thermal distribution system losses and poor equipment installations act to reduce the nameplate and American Refrigeration Institute (ARI) rating capacities close to those estimated using Air Conditioning Contractors of America (ACCA) Manual J
- the installation of high SEER units can reduce energy consumption with no apparent drawbacks

1.0 Introduction

Previous studies (including earlier phases of this research project) have shown that losses from residential thermal distribution systems have significant energy and comfort implications. This study looks at the potential for improvement of thermal distribution systems and the possibility of reducing equipment size as a result. These distribution system and equipment interactions were examined through field testing and computer simulation. 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 the Transitional Phase of this Residential Thermal Distribution Systems research. Results of earlier Phases were described in Walker et al. (1997 and 1998).

2.0 Duct Leakage Diagnostics

2.1 Objectives

The objectives of this task were:

- Improve duct leakage test methods.
- Update the American Society for Testing and Materials (ASTM) Standard E1554 – "Determining External Air Leakage of Air Distribution Systems by Fan Pressurization"

2.2 Summary of Duct Leakage Diagnostics in Previous Phases

In Phase V of this work we performed field evaluations of several diagnostic techniques for measuring duct leakage:

- House Pressure Test (HPT).
- Nulling Pressure Test (NPT).
- Duct and house pressurization with separate supply and return leakage.
- Duct only pressurization with combined return and supply leakage.
- Tracer gas.

These tests were evaluated in terms of ease of use, time requirements and the bias and precision errors associated with each test by using the tests in several houses. The results of the testing indicated that none of these methods was ideal (hence our continuing work on improving duct leakage diagnostics). However, for screening of low leakage levels for compliance testing the duct leakage diagnostic of choice is the fan pressurization test of total duct leakage (test 4). 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.
- Repeatability. Combining the results of both the phase V and VI reports together with the field experience of other users showed that the repeatability of the pressurization testing was found to be very good.
- Precision. The uncertainty in leakage flow will be small if the allowable leakage is set to a low number because the uncertainties for the pressurization test scale with the amount of leakage.
- Simplicity. It is 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.
- 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 biggest drawback with this test is the requirement of covering all the registers, which can be time consuming. In addition, this precision of this test is reduced at higher leakage levels that might be found by home energy raters in existing construction, rather than the low leakage levels required in compliance testing. Because this test measures the total leakage and not just the leakage to outside it will overestimate the leakage required for energy loss estimates, however, from a compliance testing point of view, this error is in the right direction because it means that the true losses will be less than those indicated by the test. In other words, a system whose total leakage passes a leakage specification is guaranteed to have the leakage to outside be less than the specification.

In Phase VI we extended the duct leakage measurements to include separate measurements of the boot and cabinet leakage because these were thought to be two main leakage sites. The measurement results confirmed this idea: combining these two leakage sites together accounted for about three quarters of all duct leakage. The average leakage to the outside was about 25 cfm for the boots and about 34 cfm for the cabinets.

2.3 A New Duct Leakage Test: DeltaQ

In order to find a duct leakage test that is better than those discussed above, a duct leakage measurement workshop was held as part of the ASHRAE Standard 152P (ASHRAE, 1999) committee meetings in January 1999. We have prepared a summary of this workshop, and it is included as Appendix I. In addition, we discussed potential innovative measurement techniques with other researchers throughout the US and Canada.

The result of these discussions is a new technique for measuring duct leakage that we have evaluated using a pilot study of local homes. This new technique is called the DeltaQ test because it measures changes in flow (Q) caused by distribution system operation. This new test method has several features that give it the potential for success:

- It has simple equipment requirements. Only a blower door and some pressure sensors are required to perform the test. The blower door is a common item that most building diagnosticians already have and are familiar with its operating principles. Some existing tests require less common equipment, for example specialized combined fan/flowmeters for pressurization tests, or tracer gas analysis equipment.
- It directly measures the value that we want from the test: the leakage to outside at operating conditions of the supply and return separately. Other existing tests require conversion from measured pressures to operating pressures, or they require complex balancing of house and duct pressures to obtain leakage to outside rather than total duct leakage.
- It is quick. There is no requirement for blocking off all the registers or blocking between the supply and return parts of the system.
- It is robust. Our field testing has shown that the DeltaQ test is not as sensitive to wind induced envelope pressure fluctuations as the House Pressure Test, or Nulling Pressure Test.
- It does not have the detailed assumptions (that lead to additional uncertainties) about the house envelope that the House Pressure Test requires.

The DeltaQ test works by using a blower door to maintain the same pressure across the building envelope with the duct system fan on and off. The flow with the system on and off is measured over a range of envelope pressures. This results in pairs of flow data (one with the system fan on and one with the system fan off) at several pressures. As the blower door pressurizes (or depressurizes) the house relative to outside, the pressures in the ducts will also change relative to outside by the same amount. Because the pressure across the leak changes, the flow through the leak changes and this change in leakage flow appears as a change in envelope flow through the blower door. In addition the operating pressures in the ducts when under normal operating conditions are also measured. These operating pressures are measured at the plenums because this gives the biggest and most repeatable pressure signal and avoids the uncertainties of register pressure measurements. Combining the measured system pressures and the pairs of blower door flow data together with the algebraic analysis of the changes in duct leakage flow allows the calculation of the supply and return leakage coefficients and pressure exponents. Appendix II gives more details of the derivation and application of the test method.

So far, only three houses have been DeltaQ tested and more houses will be tested in the near future. Of these three houses, one test was at low wind conditions and gave results that closely matched other measurement techniques. The second test was on a windy day, but still managed to give reasonable results based on visual observation of the duct system, i.e., it showed that the ducts were not very leaky. This is a significant result because other tests that use envelope pressures (HPT, NPT and duct and house pressurization) have not given reasonable results under windy conditions. The third house was tested on a very windy day (wind speeds > 20 m.p.h. and highly variable) and the DeltaQ test did not give satisfactory results under these extreme conditions. These three tests have shown that the DeltaQ test is more robust than most of the existing tests but still fails at the very high wind speeds. Under extremely windy conditions the only test that can be used on ducts is the duct pressurization test because it does not require envelop pressure measurement or measured flow through a fan flowmeter between the house and outside. Future work will apply the DeltaQ test to more houses and include repeatability studies.

2.4 ASTM Duct Leakage Standard (E1554)

The existing test procedure in E1554 is called the blower door subtraction method and is no longer used by many researchers due to the poor results obtained from the test. This standard is currently due to be revised by ASTM so we have prepared a revision of E1554 (ASTM (1999)) that incorporates the DeltaQ test together with the combined house and duct fan pressurization test from proposed ASHRAE 152P. In addition to revising the standard, we have also been performing administrative tasks such as attending ASTM meetings and collaborating with ASTM staff to produce this revised standard. This revision of E1554 will be evaluated by an ASTM Task Group in October 1999. After initial review by the Task Group, it will take a year or two for the revised draft to become a test method. This time allows us and other potential users to evaluate the revised procedures in more homes. At the ASHRAE 152P meetings in June 1999 the ASHRAE 152P committee members were given copies of the test procedure and asked to use it and report back to us in order that we can build up a consensus of experience with this test method in as broad a range of homes and test conditions as possible.

2.5 Outcomes

The duct leakage diagnostic outcomes were:

- This investigation yielded a new duct leakage test called DeltaQ.
- The existing ASTM Standard (E1554) for measuring duct leakage has been rewritten and submitted to the ASTM standards review process.

3.0 Duct Sealants and Longevity Testing

3.1 Objective

The objective of this task was to:

- Develop and introduce a draft ASTM standard for longevity testing of duct sealants

3.2 Sealants and Testing

The development of the longevity test method and preliminary results have been discussed in previous phases (Walker et al. 1997 and 1998). The final results and details of the experiment were 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 results of work in previous phases of this study have been included in California's Residential Energy Code (usually referred to as Title 24). In the Alternative Calculations Manual of Title 24 no cloth backed rubber adhesive duct tape is allowed as a duct sealant on systems obtaining credit for energy efficient duct systems. This has caused some consternation on the part of HVAC installers and duct tape distributors; however, we have been able to show these concerned parties that the test results are real and that there are viable alternatives. In addition, some of the duct systems that were tested for phase VI of this study, and other systems we have observed over the last six months have been sealed in accordance with Title 24 requirements and our leakage measurements have shown them to be well sealed systems.

The longevity test method (ASTM (1999b)) was prepared in ASTM standard format and submitted to ASTM Subcommittee E06.41 for consideration. The ballot results had only one significant technical comment that the high temperatures were too low because some attics can be at a higher temperature than those used in the test (150 °F surface temperatures). This comment says that in order for the longevity test to be "accelerated" the attic temperatures should be at least as high as measured peak temperatures and possibly higher. However, the evidence for extreme attic temperatures higher than 150°F is poor. A literature search of attic temperature studies was undertaken to find evidence of higher measured temperatures. Much of the existing literature does not address peak or extreme values because the studies were interested in estimating energy savings where longer time average values are needed. However, a few studies were found that gave explicit attic peak temperature information, and those with the highest reported peaks are discussed here. Some of the following studies tested several houses but we discuss the results from the hottest attic only. Carlson et al. (1992) measured peak attic air temperatures of 155°F. Parker et al. (1997) measured attic temperatures of 134°F in a house in Florida, however, this was an average of the hottest 2.5 percent of the summer hours, so peak temperatures would be expected to be higher. The tests discussed in Phase VI of the current study had a peak attic air temperature of 151°F for a house in Sacramento.

An additional parameter that changes duct temperatures is the radiant exchange between the ducts and the roof deck surfaces that are hotter than attic air under peak conditions. For example, Wu (1989) measured attic floor temperatures 7 °F hotter than the attic air. The upper exterior surfaces of ducts in attics are heated by a similar amount. It is important to consider this increase in surface temperature due to radiation because duct sealants are generally applied from the outside and will experience these elevated exterior surface temperatures. Combining the existing peak temperature field data with the radiation effect results in a temperature of about 160°F being a reasonable target temperature.

Another point of view is to look at the duct temperatures experienced by heating systems, which can be higher than those for cooling systems. Field studies have found that many furnaces are operating on their high-limit switches – usually set at about 200°F. The Uniform Mechanical Code (ICBO (1994)) has a limit of 250°F (121°C) for furnace and duct heater controls. The Canadian Natural Gas Installation Code (CGA (1995)) gives the same limit of 250°F (121°C) for forced air systems, but includes a higher limit of 350°F (175°C) for gravity furnaces.

This indicates that the 160°F high-temperature limit from the peak attic temperatures would be too conservative for heating systems. However, the furnace high-limit temperatures will not be used because there is an additional high temperature limit constraint imposed by duct tape manufacturers of 200°F for some of their products. A reasonable compromise is to be half way between the upper limit for cooling (160°F) and the limit set for tape (200°F) resulting in an upper temperature of 180°F. This compromise was chosen to be far enough away from the upper limit for tape that we can be reasonably sure that the tape does not exceed this limit during testing because the temperature control in the experimental apparatus has some uncertainty.

The major difference between the heating and cooling values is that the extreme temperatures for cooling ducts in hot attics occur with the system off and the heating ducts have their extreme with the system running, so the heating limit may be a more realistic scenario. In addition, the temperature gradient across the duct (hot inside air, cool surroundings) is the correct situation for the heating duct case. However, it is the explicit duct surface temperatures that are the temperatures experienced by the duct sealant and so not too much importance should be placed on whether or not the ducts are being heated “in the right direction”.

Based on the above temperature limit changes and other feedback from ASTM members and other interested parties, in addition to our own research, we have begun development work on a revised longevity test apparatus funded by the Department of Energy. This new apparatus will allow us to test different procedures for evaluating longevity. The procedures include:

- The existing procedure of alternating between hot (150°F) and cold (0°F) air flows with a pressure difference across the seal.
- Changing the temperatures in the alternating temperature test to be more extreme (180°F).
- Splitting the test into a hot test and a cold test. The hot test will vary the temperatures in the range of 70°F (close to room temperature) to 180°F. The cold test will have the range from 70°F down to 0°F. This narrower temperature range will allow for more rapid cycling and greater temperature extremes (e.g., we could possibly go lower than 0°F). For both the hot and cold test there will be a pressure difference maintained across the leakage sites.

- Having no cycling of temperature and maintaining a steady hot (180°F) or steady cold (0°F) temperature. Unlike the previous baking tests there will be airflow through these samples and pressure differences across the leaks.

The leakage testing will be the same as in the previous apparatus. Periodically the samples will be removed for individual leakage testing of leakage flows at 25 Pa. The leakage of the samples will be measured before any sealing and immediately after sealing before installation in the test apparatus. The "failure" of a sample will be determined the same as in the previous study, by evaluating the leakage flow as a fraction of the unsealed flow. The failure level is fixed at 10 percent of the unsealed leakage. The 10 percent level was chosen by examining test results to determine the point beyond which failure can be rapid and difficult to measure. This 10 percent leakage also corresponds to empirical estimates of "unacceptable" leakage for an individual connection.

3.3 Outcomes

The duct sealant longevity testing outcomes were:

- A draft ASTM standard for longevity testing of duct sealants was developed. A draft was submitted to ASTM subcommittee E06.41 for balloting and comment. The comments on the draft resulted in changes to the test method and apparatus.
- A new test apparatus was constructed with funding from the Department of Energy (DOE) and will be used to evaluate new sealants.

4.0 Duct System Interactions with System Sizing

4.1 Objectives

The objectives of this task were:

- Measure the performance of residential cooling equipment and associated distribution systems.
- Compare the REGCAP simulation model to the measured field data.

In this study the duct system interactions with system sizing were examined using both computer simulations and measured data. The measured data were used to examine field performance of cooling systems and to evaluate and validate the computer simulations but were not used to tune any model coefficients so that the model retains its general applicability. The following sections discuss the field measurements, computer simulations and comparisons between the two.

4.2 Field measurements

The cooling system performance was measured in six test houses. Each house was tested in several configurations in order to estimate the effect of duct systems on the capacity, energy performance and comfort. The previous Phase (Walker et al. (1999)) reported the preliminary results considering sensible Tons At the Register (TAR) ("delivered capacity") and capacities only. The current study looks in more detail at pulldown tests and equipment performance for both latent and sensible cases. The pulldown tests were evaluated by determining the pulldown time (the amount of time to cool down a house) for different parts of the house: at the thermostat, the master bedroom and the kitchen. In addition the temperature in each location at the end of pulldown as indicated by the thermostat was investigated. The differences between these locations indicate the relative comfort for the occupants. e.g., in the summer, a house where the temperature is much higher for the master bedroom when the system turns off (end of pulldown at the thermostat) will not be comfortable when the occupants go to bed. This is a common complaint about air conditioning systems and was specifically mentioned by the people who lived in the occupied house used for this study.

The field 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 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.

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. Details of the HVAC systems and house construction can be found in the report on the previous phase of this work in Walker et al. (1999).

Table 1 summarizes the most significant diagnostic test results for the thermal distribution system and equipment for the six test houses. The air handler flows for these systems were higher than has been found in previous studies (e.g., Blasnik at el. 1996) that suggested that most systems typically had about 15 percent less than the 400 cfm / ton recommended by manufacturers. In several cases the air handler flow was considerably higher than the 400cfm / ton benchmark, particularly at site 4 with almost 550 cfm / ton. This high flowrate will limit the ability of the system to handle latent loads. However, site 4 is located in Sacramento, CA and does not have a high latent load, so these high flows are probably acceptable. The leakage expressed as a fraction of fan flow is lower than has been found in previous studies, indicating that these duct systems were better than average installations, in fact they were some of the least leaky systems we have tested. The exception to this was surprisingly Site 3, where most of the duct system was in interior partition walls or dropped soffits between the first and second floor, with none of the duct system in the attic. A detailed examination of the ducts at Site 3 showed that much of the leakage was at the plenum to duct connections that were in the garage because the air handler, cooling coils, furnace and plenums were all in the garage. In addition, the soffits and partition walls were not air sealed with respect to the garage or the attic so that air leaking from the ducts did not leak into the conditioned space but was allowed to escape to outside. This result reinforces the requirement of field testing duct systems for leakage because this system that looks like it is inside conditioned space in engineering drawings and initial visual inspection leaks considerably to outside.

Table 1 also shows that these systems were close to having the correct system refrigerant charge, except for sites 2 and 4, where the systems showed the undercharging that was typical of that found in other studies. Site 2 was the only site where the system charge was an extreme concern because at only 70 percent of required charge, this system is undercharged to the point where significant equipment damage could occur.

Table 1. Diagnostic Test Results

Site	Nominal AC Capacity [Tons]	Air Handler Flow [CFM/Ton]	Supply Leakage Fraction [%]	Return Leakage Fraction [%]	% of Correct Refrigerant Charge [%]
1	5	375	4%	2%	98%
2	5	379	4%	1%	70%
3	3.5	491	8%	19%	101%
4	2	547	5%	3%	85%
5	2.5	467	6%	4%	95%
6	3	501	4%	5%	91%

Part of this study examines the possibility of resizing systems in order to reduce HVAC system first cost and peak energy consumption. To provide background information for answering this question, Table 2 contains a comparison of system capacities. For each site, the ACCA Manual J (1986) sensible load was calculated using the measured house dimensions and construction details. This was compared to data from the manufacturer (nameplate capacity), from the ARI (1999) ratings and the measured sensible TAR. The measured TAR were the quasi-steady-state values obtained after the equipment had been operating for some time so as not to include transient effects that are not part of the other ratings. Table 2 shows that the nameplate capacities far exceed the requirements of the Manual J calculations indicating significant oversizing. The ARI and maximum sensible ratings diminish the oversizing effect and reinforce the overrating in the nameplate capacities. For Site 6 the maximum sensible capacity is actually very close to the Manual J load estimate and this is probably the correct size air conditioner for this house. The measured TAR is even closer to the Manual J estimates and at Site 6 the TAR is less than the Manual J load estimate. The variation in TAR illustrates the impact of the system performance in converting from what is purchased by the homeowner or contractor (nameplate capacity) and is actually delivered to the conditioned space. At sites 1 and 2 the nameplate capacity is the same but the delivered TAR is a ton less for Site 2. Site 3, with a 1.5 ton less nameplate capacity system has almost the same TAR as Site 2. Sites 3 and 4 have TAR that are almost the same as the Maximum Sensible Capacity of the equipment, but the other sites have considerable lower TAR than this maximum. Site 1 is the only site with a significantly higher TAR than the Manual J estimate. Overall, the results shown in Table 2 illustrate that nameplate capacity is a poor way to evaluate the capacity of the equipment (compared to Maximum Sensible Capacity) and the system as a whole (TAR). In addition, the apparently gross oversizing of nameplate capacity compared to Manual J is offset by lower actual equipment performance and thermal distribution system losses.

Table 2. System Capacity Comparisons

Site	Manual J Sensible Load[1] [Tons]	Nameplate Capacity [Tons]	ARI Capacity [Tons]	Maximum Sensible Capacity [Tons]	Tons at the Register [Tons]
1	2.25	5	4.4	3.98	3.6
2	2.18	5	4.4	3.61	2.7
3	1.63	3.5	3.3	2.56	2.5
4	1.02	2	1.9	1.56	1.5
5	1.45	2.5	2.4	2.14	1.7
6	2.28	3	2.9	2.34	1.8

[1]What the capacity should be assuming no duct leakage, 400CFM / ton airflow, perfect refrigerant charge, no additional safety factor.

4.2.1 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 and relative humidities 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.

An overview of all the test data, averaged by a consistent set of test conditions (i.e. amount of duct leakage, refrigerant charge, type of air conditioning unit) appears in Appendix III. The performance metrics that were calculated are listed in Table 3. Each metric has a sensible and a latent component (reported as a sensible and total) and for all of the metrics except the pulldown time, the value is reported from an average of a minute of data at 5, 30, and 60 minutes from when the pulldown test began. This range of times for evaluation purposes was used due to the large transient changes in system performance between the beginning of a cycle and the quasi-steady-state operation reached later in the pulldown test.

Table 3. Performance Metrics

Pulldown Time	Time that it takes for a zone to reach 24°C. Three pulldown times are reported: for the thermostat (how the house would actually respond), kitchen, and master bedroom. A wide disparity between these times indicates an inadequate distribution system.
Tons at the register (TAR)	Amount of energy delivered to the space
Air Conditioner Capacity	Capacity of the air conditioner calculated from temperatures and relative humidities measured in the supply and return plenums
Air Conditioner Coefficient of Performance (COP)	Air condition capacity divided by power consumed by air conditioner, **including fan energy**
System COP	Tons at the register divided by power consumed by air conditioner, **including fan energy**
Delivery Efficiency	Tons at the register divided by air conditioner capacity

Pulldown time is often very different for each of the three reported locations: thermostat, kitchen, master bedroom. For example, Site 3 was a two-story house with very poor distribution, particularly upstairs to the master bedroom. The upper floor of this house had had a significantly increased load due to several skylights in the space as well as an inadequate return system (there was no return from upstairs). At Site 3 the pulldown time at the thermostat was less than half an hour, but the upstairs took another hour and a half to pulldown to the same temperature. When the thermostat had reached the pulldown temperature it was 3°C (6°F) hotter upstairs than downstairs.

TAR is often negative when the air conditioner first comes on because the hot air inside the duct system is blown into the house. This rapid initial change in temperature (a rapid initial increase followed by a gradual cooling further into the cycle) made analysis of the 5-minute data difficult because of the response time of the sensors. The response time of the temperature sensors is rapid enough that any time response errors are insignificant. However, the slower response of the relative humidity (RH) sensors increases the uncertainty in the transient latent (and therefore total) TAR estimates. The time lag of the RH sensor compared to the temperature sensor means that the measured RHs are higher than they should be (assuming a reduction in moisture content of the air due to condensation on the coil) which leads to an underprediction of the latent TAR. Alternatively, if there is no moisture removal by the air conditioner, the RH of the air at the register should rise as the temperature drops. The longer time response of the

RH sensors means that they read artificially low and this overpredicts the TAR, i.e., it gives the appearance of moisture removal without there being any. Because this time response issue can drive the results high or low depending on the particular operating conditions, it is not possible to estimate a generalized effect that would apply to all the measurements (i.e. a bias), instead it simply adds to the uncertainty of the latent TAR calculations during the start of each cycle. Because of these uncertainties, most of the comparisons made in later sections of this report are based on the 30 minute value when the air conditioner is operating much closer to steady state.

Air Conditioner Capacity is a useful way of examining the effect of low evaporator air flow or incorrect refrigerant charge without confounding the impacts of a leaky duct system. It suffers the same sensor response limitations during the initial transient at the start of a cycle as TAR.

Air conditioner COP is a measure of efficiency of an air conditioner, and it is typically around 2-3 for a residential unit. Unlike the COPs presented by the manufacturer, the COPs reported here include the energy (and heat generation) of the air handler fan.

System COP is the most inclusive performance measure, and it is a simple ratio of the cooling energy delivered to the conditioned space (TAR) divided by the power consumption of the air conditioner and fan. System COP is affected by changes in the air conditioner capacity as well as any losses / gains in the distribution system.

Delivery efficiency is a simple ratio of the energy of the air that comes out of the registers divided by the energy of the air in the supply plenum. It is a measure of losses that occur in the duct system. The five-minute delivery efficiency is almost always higher than the 30 and 60 minute delivery efficiency. This is because after five minutes, the air in the ducts has not cooled down very much and conduction losses (which are proportional to the temperature difference between the ducts and the air around the ducts) are low. By the time the system has reached steady state, the conduction losses have increased and the delivery efficiency drops slightly.

Although these metrics are all intuitive and useful ways to understand cooling system performance, they have limited utility for comparing houses or even for comparing different conditions (amounts of duct leakage, refrigerant charge, etc.) at the same house. All are very strongly influenced by a large number of external factors (in addition to those already discussed such as duct leakage, evaporator airflow, refrigerant charge level, etc.), most notably indoor temperature and humidity, outdoor temperature and conditions, attic conditions. The tables in Appendix III list the average of these parameters at each of the conditions. Because only a few days of measurements were performed at each site condition, there are often large variations associated with each of the mean values for the performance parameters. Also, in some cases only a single day of data was taken resulting in a single data point being used as the “average”. Because of these limitations, the measured results often do not reveal the expected results and makes the data difficult to interpret.

For these reasons, this report concentrates on comparing individual sites where conditions are similar. Because weather conditions varied widely during the test period, there were few days that were identical to each other. Limiting comparisons to similar weather conditions means that the comparisons discussed below are often based on a single pulldown test at each condition and should be interpreted with some caution.

Site 1: At this site, there were two similar days of weather that allow us to examine the impact of sealing the ducts. Both the sensible and the total delivery efficiency improved 8 percentage points from 81 percent to 89 percent, about a 10 percent increase. Similarly the system COP improved, but only by 8 percent (total) and 3 percent(sensible). The latent improvement may be an overstatement because of uncertainties in the RH measurements, even though the air conditioner had been running for 30 minutes in each case and thus the relative humidity should not have been changing very rapidly. The relatively small improvement in system performance is an indication that inefficiencies of this large (5 ton) air conditioner tended to dominate the system losses, rather than the distribution system losses.

Site 2: Although there were four conditions at this site (as found duct leakage and low refrigerant charge, leaks added and low charge, leaks added and correct charge, ducts sealed and correct charge), only two days had similar enough weather conditions to compare them. Unfortunately, two things changed between the days that had comparable weather conditions: a very low level of refrigerant charge was corrected, which would tend to improve system performance and 212 cfm (12 percent of fan flow) of leakage was added to the duct system, which would tend to diminish system performance. The added leakage was split almost evenly, with 97 cfm (5.5 percent of fan flow) added to supply side and 115 cfm (6.5 percent of fan flow) added to the return side. Paradoxically, correcting the very low refrigerant charge level appeared to very slightly diminish the system performance. However, a close examination of the weather data indicated that, although the outdoor temperatures were very similar, both the enthalpy of the outdoor air was significantly greater when the charge was lower which made the unit appear to perform better. Comparisons of delivery efficiency showed a reduction of about 10 percent due to the added leaks.

Site 3. Correcting a slightly low charge level resulted in an increase in air conditioner capacity of about six percent and an improvement in COP of about eight percent. Sealing 200 cfm (14 percent of fan flow) of duct leakage improved the delivery efficiency by 11 percent. At this site, the ducts leaked into the garage (mostly outside) and into an interstitial space between the first and second floor that was thermally inside, but outside of the pressure boundary. These effects overall combined to improve the system COP by 17 percent.

Site 4. Many of the performance metrics are harder to interpret at this site because the new Energy Star™ unit consumed different amounts of electricity (probably due to a variable speed compressor). The air handler capacity of the Energy Star™ unit improved by five percent and the sensible COP improved by 25 percent. This result suggests that higher efficiency units may improve sensible cooling at the expense of latent cooling; however the uncertainty of RH measurements means that this result requires additional verification. The delivery efficiency dropped by about four percent after changing the equipment. This drop might have been due to small variations in outdoor and attic temperatures, however, it may have also been caused by the lower supply plenum temperatures (and hence higher temperature differences for conduction losses) of the new unit. Adding 107 cfm (nine percent of fan flow) of leakage at Site 4 reduced the delivery efficiency by six percent. The extra leakage was greater on the supply side 75 cfm (six percent of fan flow) vs. 32 cfm (three percent of fan flow) for the return side.

Site 5. Sealing 92 cfm of leakage (seven percent of fan flow) caused insignificant improvements of the delivery efficiency (between 1 and 2 percent). The overall COP was improved by three percent, however (as with other sites) the uncertainty in the RH and plenum temperature measurements means that this change is about the same as the uncertainty in the measurements and cannot be interpreted as a significant change.

Site 6. The combination of highly variable weather and some data collection problems at site six means that there were no results suitable for comparison. A more detailed analysis of the measured data will be required if any conclusions are to be drawn from the Site 6 measurements.

4.3 Computer Simulations

The details of an earlier version of the simulation model (called REGCAP – short for REGister CAPacity) have been given previously by Walker et al. (1998 and 1998b). A flowchart for the simulation program is shown in Appendix IV. The changes made to improve the simulation model for this study are discussed below. This improved model was compared to measured results for validation purposes. In the previous work, the simulations were used to show how pulldown time changed with duct system performance, different weather conditions (a typical design day and a peak day) and with system capacity. The simulations were able to show several key results:

- A good duct system allowed the capacity of the equipment to be reduced by about one third: from four tons to three tons nameplate capacity.
- 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 model results also showed the wide range of pulldown times for different duct systems.

4.3.1 Simulation Model Improvements

In our continuing efforts to develop models of HVAC system performance, the model used in the last Phase has been upgraded:

- It includes additional air flow paths through duct leaks when the system is not operating.
- It has a simple moisture balance for use in latent load and equipment capacity calculations.
- Solar load and thermal mass calculations for building load have been improved.
- A simple thermostat model and the ability to make calculations at small timesteps allowed the model to be used for examining cyclic effects.
- Improved equipment modeling accounts for changes in capacity and energy consumption with outdoor weather conditions, fan flow, system charge and indoor air conditions.

The equipment model used to predict the capacity of the air conditioners for the REGCAP simulation is an empirical model developed by John Proctor (Proctor (1999)). This model is the only available model that accounts for refrigerant charge level and is sufficiently general for use in this project. Proctor has used this model in much of his research (see Proctor (1997), (1998) and (1998b)) and continues to update as he collects new data. Currently, the portion of the model that accounts for deviation from recommended refrigerant charge is taken directly from Rodriguez et al. (1995) and the rest of the model is based on Proctor Engineering Group fieldwork in about one hundred houses.

The model requires the following inputs: nominal (nameplate), capacity, ARI capacity, air flow, outside temperature, indoor (return plenum) enthalpy, refrigerant charge level, and expansion valve type (capillary tube / orifice or TXV (thermostatic expansion valve)). The model predicts sensible capacity and, with the assumption of a sensible heat ratio for the unit, latent and / or total capacity can also be predicted. The comparison of the measured capacities at the six houses (8 air conditioners) in this study indicate that the model overpredicts capacity by about 10 percent. There is no obvious reason for this consistent deviation from Proctor's data, but a possible reason is that most of the Proctor's verification of the model occurred in very dry climates, rather than the more humid weather that we encountered during the field testing.

4.3.2 Extension of Previous Simulations

The improved model was used to reexamine the pulldown simulations performed in the previous part of this study. In these simulations, eight different thermal distribution systems are used in the same house for the same weather conditions. Table 4 lists the simulation cases that were examined here. 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. The INTERIOR system examines the gains to be had if duct systems are moved out of the attic and into conditioned space. The INTERIOR RESIZED system examines the system performance if reduced capacity equipment is used together with interior ducts. 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).

The difference between the simulation cases listed in Table 4 and those done previously is that the flow used for the “correct flow” cases is 400 cfm instead of 425 cfm. This minor change was done because the equipment used in the equipment model was rated at this flowrate. The large range for pulldown results are illustrated in Figure 1, with each simulation starting at the same time. The better systems were able to pulldown the house in a reasonably short time (under three hours) but the poor systems took over six hours. The longer pulldown times mean that the house would not be comfortable for occupants returning in the afternoon. For example, the house with the POOR system is still not pulled down at 8:00 p.m. For the occupants this would be unacceptable and a better question to ask is: At what time would an occupant have to turn on the air conditioning in order to have the house comfortable upon returning home in the afternoon at 5:00 p.m?

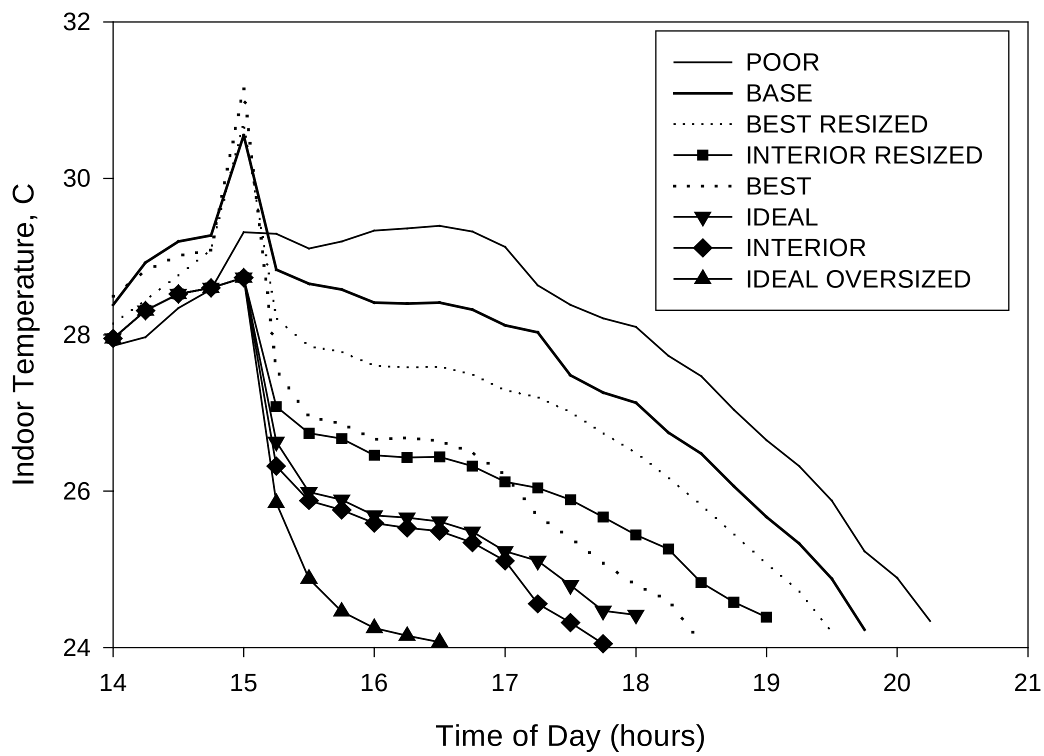

Figure 1. Simulations of Pulldowns from 3:00 p.m. on a Sacramento Design Day

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	400	3	Attic	4
BEST RESIZED	100	400	3	Attic	3
INTERIOR	85	345	0	House	4
INTERIOR RESIZED	85	345	0	House	3
IDEAL	100	400	0	House	3
IDEAL OVERSIZED	100	400	0	House	4

Table 5. Start Time to Pulldown by 5:00 p.m.

	Rated Capacity [Tons]	Start Time
BASE	4	10:30 a.m.
POOR	4	Not possible[1]
BEST	4	2:30 p.m.
BEST RESIZED	3	11:45 a.m.
INTERIOR	4	1:45 p.m.
INTERIOR RESIZED	3	9:45 a.m.[2]
IDEAL	3	12:30 p.m.
IDEAL OVERSIZED	4	2:30 p.m.

1- 37°C at 5:00 p.m., pulldown to 24°C at 9:00 p.m. (drawing in cool outdoor air through return leaks)

2- Although this system is basically on all day, this result is misleading because the indoor temperature never gets above 25°C and a more lenient pulldown criteria drastically changes this result. For example, increasing the setpoint temperature by 1°C (to 25°C) changes the system ontime to 11:00 a.m. and makes it better, not worse, than the base case.

The results in Table 5 show that the time that the systems have to run covers a very wide range from two and a half hours for the BEST and IDEAL OVERSIZED systems to all day for the POOR system. In effect, looking at pulldown this way has further exaggerated the differences between the systems. This is mostly because the systems are now operating more during the heat of day rather than the cooler evening and night time. As with the results reported previously, this table shows that resized systems with good ducts can be as good or better than an existing BASE system and that there are large gains to be had by improving the duct systems. Assuming that the energy consumption scales with system capacity and ontime, and normalizing by the BASE case energy consumption it is possible to calculate the relative energy consumption for each simulation, as shown in Table 6.

Table 6. Relative Energy Consumed in Order to Pulldown by 5:00 p.m.

	Percent of BASE case
BASE	100
POOR	260
BEST	40
BEST RESIZED	60
INTERIOR	50
INTERIOR RESIZED	85
IDEAL	50
IDEAL OVERSIZED	40

Because the poor system is on all day, the energy consumption is far greater than for the other systems. All the other systems consume less energy than the base case while providing equal or superior comfort in terms of pulldown time. In particular, the resized systems all consumed less energy than the BASE case for these simulations.

Table 7. Model Delivered Capacity (TAR) Comparison (system on for 1.75 hours)

	Nameplate Capacity [Tons]	Tons at the Register [Tons]	Tons at the Register / Nameplate Capacity [%]	Ratio to Base Case [%]
BASE	4	1.66	42%	100%
POOR	4	1.51	38%	91%
BEST	4	2.21	55%	133%
BEST RESIZED	3	1.66	55%	133%
INTERIOR	4	1.84	46%	110%
INTERIOR RESIZED	3	1.36	45%	109%
IDEAL	3	1.68	56%	135%
IDEAL OVERSIZED	4	2.28	57%	137%

Table 7 compares the results of the calculated TAR between the simulations. Note that for these calculations the systems have been running for almost two hours and are at quasi-steady-state and do not show the transient capacity reductions at the start of the pulldown. This was done so that the results are as close as possible to the manufacturers rating conditions, and we are not unfairly comparing the nameplate capacity to the transient system performance. In other words, we are being as generous as possible in our comparisons by reporting close to the highest system capacities. All but the POOR ducts are better than the BASE case in terms of delivered TAR and also TAR as a fraction of the nominal (nameplate) capacity of the equipment. All of the resized systems deliver higher TAR, and their TAR values are all closer to the nominal capacity. However in all cases (even the ideal situation with correct system charge and airflow and minimal duct losses) the equipment capacities are much less than the nominal nameplate rating that a homeowner has paid for.

4.3.3 Comparison of Field Measurements and Computer Simulations

The model was evaluated by comparing predicted temperatures to measured temperatures. Given the same temperatures, other variables used to determine energy flows (e.g., register flowrates) and comfort parameters (e.g., pulldown times) are the same for both modeled and measured data. An essential part of simulation design and use was verifying that the simulation makes accurate predictions. In this case, we were interested in predicting two parameters: tons at the register (delivered capacity) and pulldown time (time to cool down the house). For this purpose, we examined the temperatures of the four air nodes described above (attic, house, supply duct, return duct).

Over 100 days of measured data at 5 sites were used to evaluate the simulation model (4 in California and 1 in Texas). Overall there was very good agreement between the modeled and measured house and attic temperatures and good agreement between the duct air temperatures when the air handler fan was on, but not very good agreement when the air handler was off. In order to illustrate these and other strengths and weaknesses of REGCAP, the modeled / measured comparison is shown for two sites and each of the four-modeled temperatures will be discussed individually. There was no attempt to show data that was either particularly favoring or condemning of REGCAP: the following illustrations are included to demonstrate both the strengths and the weaknesses of the model. Appendix V contains a preliminary analysis of some of the problems encountered when comparing modeled and measured results due to the sensitivity of the model to measured weather data.

The results for two homes are described in this section (sites 4 and 5). Both homes have floor areas of approximately 140m^2 (1500 ft^2) and are located in a subdivision in Sacramento, CA. The ducts, air handler, furnace and indoor cooling coil were located in the attic in both homes. Site 4 had supply duct leakage fraction that is five percent of air handler flow, return leakage is three percent. Site 5 had a very tight duct system (both leakage fractions are less then three percent). Site 4 had a 2-ton system with a fixed orifice expansion valve and was found at 85 percent of manufacturers refrigerant charge. Site 5 had a nominally 2.5 ton system with a thermal expansion valve (TXV) and was fully charged. For brevity, graphs comparing modeled and measured data are shown for sites 4 and 5 only, and the generalized discussion applies to all the comparisons between measured and modeled data.

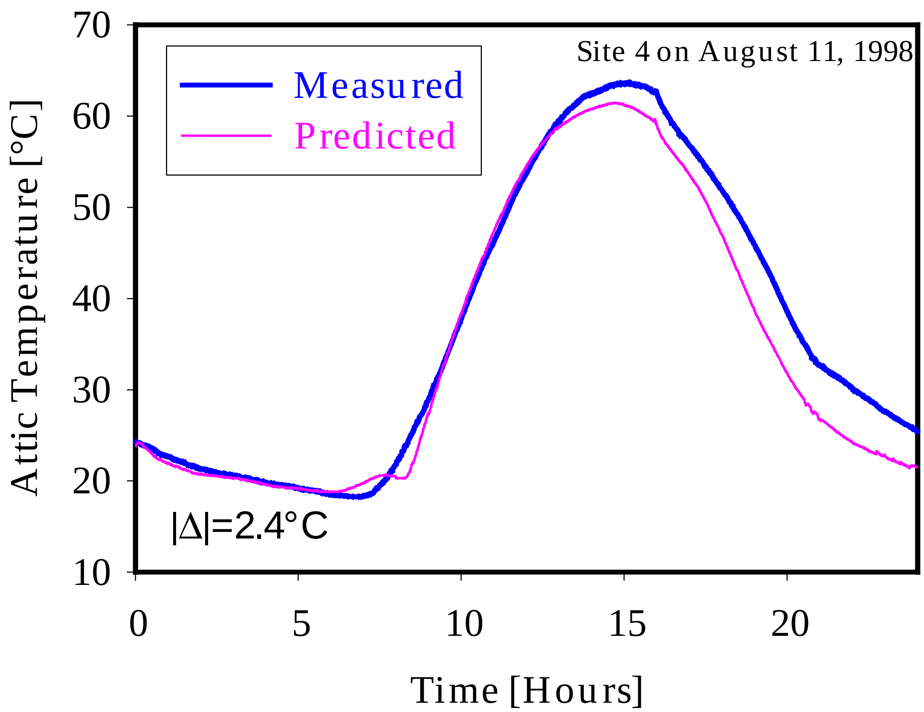

Figure 2. Modeled and Measured Attic Temperatures at Site 4 on August 11, 1998

4.3.4 Attic Temperature

These two houses show excellent agreement between the modeled and the measured attic temperature over the whole day. The agreement at site 4 is near perfect for the first half of the day and then the predicted temperature drops slightly below the measured temperature (Figure 3).

The average absolute difference in temperatures is 2.4°C (4.3°F). There are several hypotheses that explain this small discrepancy: the most plausible is a problem with the measured solar radiation input data (the dip in the data when the sun comes up is an indication of this) or, perhaps, the ducts are too strongly coupled with the house so that when the air conditioner comes on the duct leakage cools the attic more in the modeled case than in the measured case. Another possible problem is the fact that the radiative transfer involving the attic endwalls and the combined mass of wood in the attic was neglected. The modeled data at site 5 overpredicts the temperature for the first half of the day and then underpredicts it for the last half, but the overall average absolute temperature difference is 1.9°C (3.4°F), smaller than the difference at site

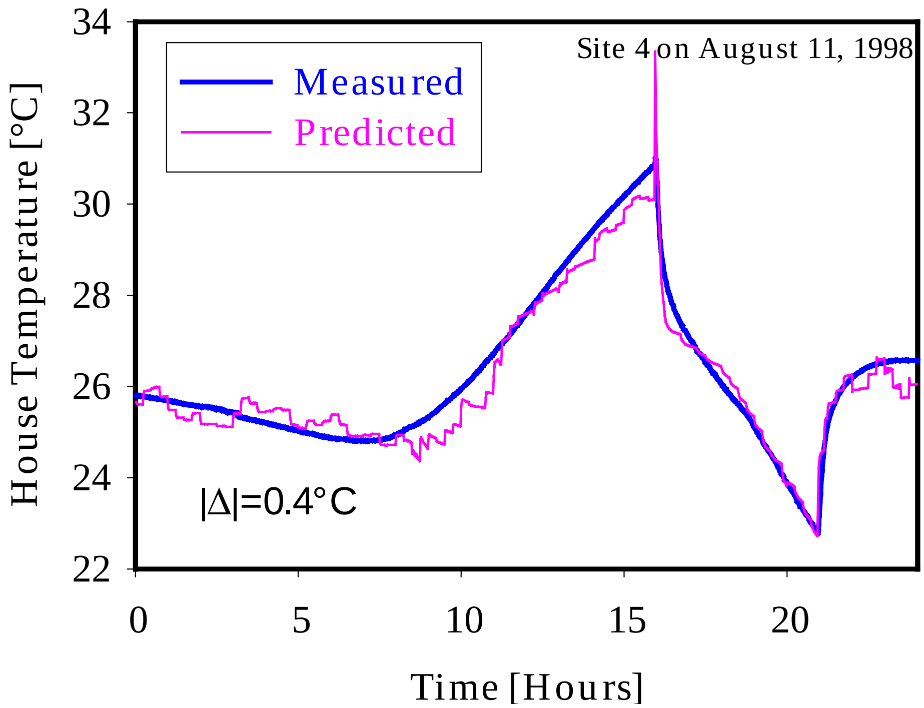

Figure 3. Modeled and Measured House Air Temperatures at Site 4 on August 11, 1998

4.3.5 House Temperature

The comparison of house temperatures at site 4 is shown in Figure 3. The average absolute difference between the modeled and the measured values is 0.4°C (0.7°F). The modeled house air responds very quickly to changes in climatic conditions. This may be due to insufficient coupling between the house air and the house mass. The agreement at site 5 is not as good, with an average absolute temperature difference of 0.6°C (1°F): examination of the weather data collected on the day of test indicates very strong winds from about 11am until 6pm. This is a failure of the model to deal with extreme conditions and is probably the cause of the wide temperature swings evident in the measured data. Both modeled houses have a single spike in the temperature when the air conditioner come on. This is an artifact of the ducts pushing hot air into the house that doesn't seem to be evident in the measured data (which was collected every 10 seconds, a finer resolution than the minute long timestep of the simulation). Despite these discrepancies, both sets of simulated data seem to reflect the overall shape of the temperature curve in each house. An improved house load model, such as Suncode,™ will probably increase the accuracy.

One problem with the house model is that the thermal mass of the house seems to be very weakly coupled to the house air. There are two most likely causes of this problem: the first is that the convection heat transfer coefficient for the house mass is biased towards natural, rather than forced, convection. This is an issue when there are strong winds (which lead to larger pressure differences and air velocities in the house), and when the air handler is on. This is a good example of where reducing the input value (i.e., no average air velocity in the house) leads to a less accurate predicted result. The second is that the surface area active in heat exchange between the thermal mass of the house and house air is too small in the model. Future work will further investigate this thermal mass issue.

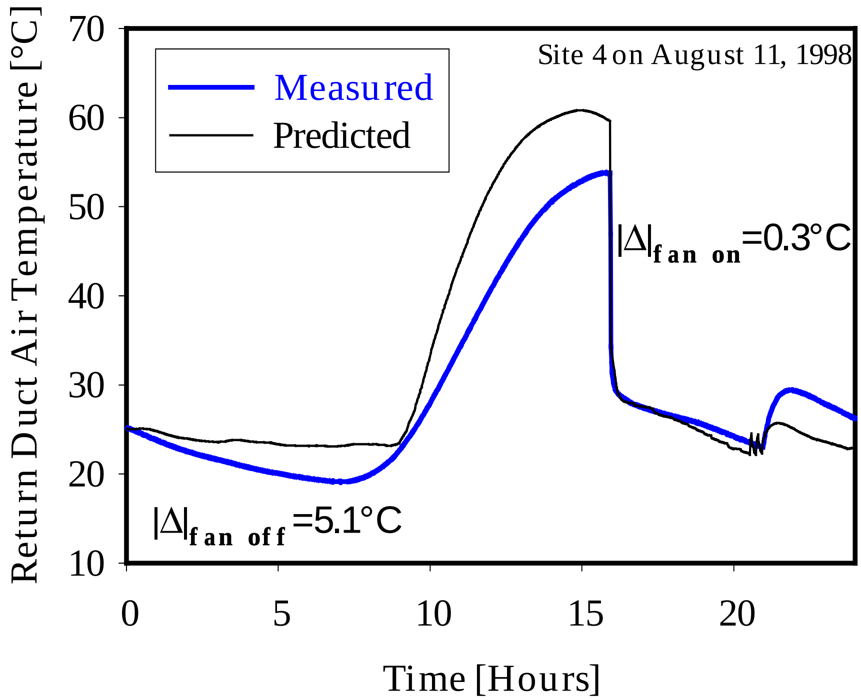

Figure 4. Modeled and Measured Return Duct Air Temperatures at Site 4 on August 11, 1998

4.3.6 Return Duct Air Temperature

The return duct agreement is quite good at site 4 (Figure 4) when the air conditioner is on (absolute difference of only 0.3°C). When it is off, the predicted duct temperature is much hotter than the measured temperature (absolute difference of 5.1°C). A very similar pattern occurs at site 5, with the same average absolute difference between the modeled and measured. The strong winds in the middle of day again affect the simulation quite strongly. Overall, REGCAP does an adequate job of prediction the temperature plots at both sites when the air handler fan is on.

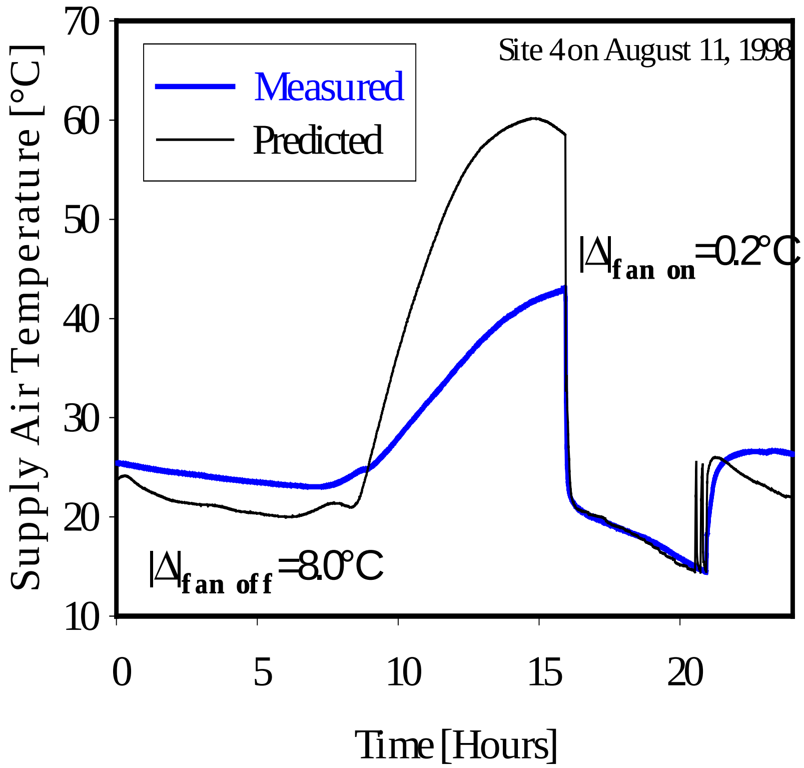

Figure 5. Modeled and Measured Supply Duct Air Temperatures at Site 4 on August 11, 1998

4.3.7 Supply Duct Air Temperature

The supply duct air temperature has a very similar pattern at both sites (Site 4 is shown in Figure 5). Like the return duct, the temperature shows good agreement when the air handler fan is on, but poor agreement when the air handler fan is off. When the air handler is off, the modeled supply duct temperature is very strongly influenced by the attic temperature and radiation exchange with the interior attic surfaces. The fact that the agreement is not very good for the duct air temperatures when the air handler is off may seem surprising because the model explicitly calculates the mass flow through these ducts when the air handler is off. However, there is a subtle distinction: REGCAP calculates the mass flow of air passing from the attic to the house (or the house to the attic) through the ducts, but does not calculate thermosiphon flows. Thermosiphon flows occur as air moves in one register and out another when the air handler is off. These flows are very difficult to calculate because to do so requires extensive information about the geometry of the duct system as well as being able to model flows between and within different rooms in the house.

The lack of air-handler off agreement for the duct temperatures is not particularly significant for the objectives of this study: predicting the pulldown time and the tons of cooling at the register. The only temperatures that are directly needed for these calculations are the house air temperature and the supply duct air temperature when the air conditioning fan is on. For this reason, REGCAP is well suited to calculating the performance parameters that are the focus of this project.

4.4 Outcomes

The field measurement and computer simulation outcomes were:

- Improved ducts and system installation can allow the use of a smaller nameplate capacity air conditioner (almost one ton less in the simulations presented here, and at least one ton in more demanding situations) without any comfort penalty in terms of pulldown, and with large energy savings (roughly halving energy consumption).
- If system nameplate capacity is unchanged, either improving duct systems and correctly installing the equipment, or moving the ducts inside results in significant pulldown performance improvements.
- Simulations confirm field test results regarding delivered capacity and equipment and distribution system performance.
- Comparisons of computer simulation results to measured field data show that the simulations predict the equipment attic and house performance with sufficient accuracy to be a useful prediction tool.
- Field measurements of delivered cooling capacity are considerably less (20 percent to 50 percent) than nameplate & ARI ratings.
- Nameplate and ARI capacity ratings of equipment installed in houses exceed those indicated by ACCA Manual J load calculations.
- Thermal distribution system losses and poor equipment installation combine to reduce delivered capacity. Measured delivered capacities are close to those indicated as necessary by ACCA Manual J load calculations.
- Improving ducts by reducing leakage can lead to significant energy efficiency gains in addition to cooling the house faster.
- Efficient systems can still have problems satisfying occupant comfort even though the total delivered capacity for the system is correct due to room-to-room variations in delivered capacity for each room. These room-to-room variations result in large temperature variations throughout the house.
- Using higher SEER units indicated significant peak energy savings of about 25 percent with no apparent drawbacks in the houses measured.

5.0 Support for Title 24 and HERS

5.1 Objective

The objective of this task was to:

- Provide technical support to the California Energy Commission (CEC) for updating the "Low-Rise Residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings" (CEC (1999)) and Procedures for HVAC System Design and Installation (for HERS).

5.2 Technical Support

One of the most significant technology transfer activities in this project has been the inclusion of credits for energy efficient ducts in the Low-Rise Residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings (ACM). The changes and additions were made to the Alternative Calculations Manual based on our technical and editorial input. They allow an energy credit to be claimed by having improved ducts that are field tested for leakage and cannot use rubber adhesive cloth tape for duct seals.

We have also provided technical support for research sponsored by the California Energy Commission (CEC) on home diagnostics (for HERS). We have worked with Davis Energy Group (DEG) on the development of residential commissioning test protocols for these home diagnostics. This has included measurement of register flows, fan flows and duct leakage. For the register flow measurements, a combined study with DEG, LBNL, CEC and The Energy Conservatory that used flowhoods to measure register flows was undertaken. Eight different flowhoods were evaluated in a new house in Sacramento. The results of this testing (given in detail in Appendix VI) showed that standard flowhoods can be poor at measuring the register flows. This is due to a combination of:

- Low flows, so the pressure signal from the flowhoods is small, leading to low precision.
- Poor calibration. Some of the flowhoods had large bias errors for all measurements, indicating a calibration problem.
- Sensitivity to flow asymmetry. The flowhoods are calibrated and designed to be used on registers with a uniform face velocities, but the registers in residential buildings are rarely operated in this manner and have strong flow variations across the face of the register.
- Flow restriction lowering the flow during the measurement. The restriction of flow due to inserting the flowmeters can be significant.

All of these problems were reduced by using fan assisted flowhoods. The fan assist is used to balance the pressure in the hood with the static pressure in the room. This was originally done to remove the effect of restricting the flow, but the side benefits are of equal, or greater, importance because the fan assist tends to remove the flow asymmetries and give better results with any remaining asymmetry. The calibrations for the flowmeters are well known and easily checked, and the flowmeter can be adjusted to be sensitive to low flow rates, thus improving the precision of the measurements. Unfortunately, the fan assisted flowhood is extra equipment to carry around a house and is equipment that home testers would have to become familiar with, plus there is the added expense of additional equipment purchase.

In addition to individual register flows, the CEC is also interested in requiring fan flow to be measured. The proposed method in ASHRAE 152P (and as used in our field testing) that requires blocking of the return and matching operating pressures is considered too time consuming and difficult. Some alternatives – such as measuring return grille flows with a flowhood and adding an estimate of the return leakage – are insufficiently accurate for use in a rating tool. Future possibilities for measuring fan flow may include the use of device under development at ECOTOPE that attaches in place of the filters in the system and requires less time and effort. We hope to evaluate the ECOTOPE system in the near future.

We are working on improving the ASHRAE 152P method by developing a new fan flow measurement device that utilizes a large powerful (but still portable) fan with a built in flowmeter. This device replaces the small fan flowmeters used in previous studies and should allow us to replicate the fan flow in most residential systems without having to extrapolate from the measurement point to the system operating point as required with the small fan flowmeters.

We worked with the staff of the CEC to evaluate an HVAC system performance tool developed by Federal Air Conditioning Technologies (FACT). This tool evaluates both the duct air flow and thermal performance and the refrigerant systems. We did comparison tests on a house in Sacramento and in LBNL's Building 51 laboratory with LBNL measurement equipment and the FACT equipment. We found some important measurement differences between the two types of equipment. However, without additional testing, it was not possible to pinpoint the exact reason for the discrepancies.

A collaborative of CIEE, CEC, the California Building Industry Association (CBIA) and the Natural Resources Defense Council (NRDC) developed procedures for improved design, fabrication, installation and testing of HVAC systems. We supported the updating of these procedures to ensure compatibility with the changes incorporated into the ACM for duct energy efficiency credits by reviewing a draft of "Procedures for HVAC System Design and Installation" (Hammon 1999). The draft procedures are in Appendix VII. We are collaborating with CONSOL (the contractor who is upgrading this document) through this review process.

5.3 Outcomes

The key outcomes of this task were:

- Duct efficiency calculations are included in the Low-Rise Residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings" (CEC (1999)).
- Procedures for HVAC System Design and Installation (for Home Energy Raters) have been updated.
- Field testing has shown that standard flowhoods can be poor for measuring residential register flows.

6.0 Technology Transfer

6.1 Objective

The objective of this task was to:

- Support ASHRAE, ASTM and EPA duct leakage research and interface with related projects funded by other agencies.

6.2 ASHRAE: Rating of Distribution Systems - ASHRAE 152P

ASHRAE published and distributed a draft version of ASHRAE 152P for public review during May and June 1999. It is expected that the final draft of this standard will be ready by January 2000. We have also developed a web-based tool for performing 152P calculations. This tool can be accessed at http://ducts.lbl.gov. This web tool includes many defaults as guides for the uninitiated user that are taken from the appendices of 152P. These defaults are intended to make this web-tool easier to use.

6.3 ASTM: Rating of duct sealants and revising duct leakage measurement methods

6.4 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:

6.4.1 Health and Safety Assessment of Aerosol Sealant (EPA)

As with any new industrial material, concern exists over the potential health hazards related to human exposure. Potential health and safety issues regarding the duct seal material were evaluated and discussed in Buchanan and Sherman (1999). This report examines the characteristics of the sealants' individual components as determined from current literature. There are three primary means by which exposure could occur: ingestion, eye/dermal contact, and inhalation. Each of these possibilities is examined. Exposure and safety risks were assessed with regard to the currently known constituents that are believed to pose potential hazards; VAP, VAM, 2EH, and acetaldehyde.

6.4.2 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, but there was no resizing of the 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.

6.4.3 Developing Energy Star Ratings for Duct Systems (EPA)

In addition to previous work on incorporating duct system efficiency in Energy Star Ratings for houses, we have also worked with EPA on developing rating methods, baseline studies and possible duct efficiency improvements for an Energy Star rating system. A preliminary report by Walker (1999) summarizes a sensitivity study performed for EPA that examines variability of distribution system efficiency with geographic location (climate) and duct system parameters (e.g., leakage). Additional ongoing work will determine baseline duct efficiencies throughout the country and estimate how much of the energy losses could be saved. This program is currently aimed at existing houses, but we plan to adapt it in the future for application to new construction.

6.4.4 Public Dissemination of Research Results

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 disseminating information about thermal distribution systems in buildings, and the papers resulting from the work done for the current project will be "published" on this web site. We have also assisted CEC by preparing information for their thermal distribution system web page. We have further assisted CEC by participating in their triennial review process.

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 7 lists recent publications associated with this research program.

Walker, I.S., (1999), "Distribution System Leakage Impacts on Apartment Building Ventilation Rates", ASHRAE Trans. Vol. No. (presented at ASHRAE TC 4.10 Symposium, January 1999), LBNL 42127.

Walker, I.S. and Sherman, M.H, (1999), "Assessing the Longevity of Residential Duct Sealants", RILEM 3rd International Symposium: Durability of Building and Construction Sealants, February 2000. LBNL 43381.

Walker, I., Sherman, M., Siegel, J., and Modera, M., (1999), "Comfort Impacts of Duct Improvement and Energy-Star Equipment", EPA Contract Report, LBNL 43723.

Walker, I, (1999), CIEE report on Benefits Estimates for CIEE Residential Thermal Distribution projects

Walker, I.S., (1999), "Sensitivity of Forced Air Distribution System Efficiency to Climate, Duct Location and Duct Leakage", EPA Report, LBNL 43371.

Walker, I.S., and Sherman, M.H., (1999), "Can Duct Tape Take the Heat", LBNL 41434.

6.5 Outcomes

The key outcomes of this task were:

- ASHRAE standard 152P for rating distribution systems has been prepared for and submitted to the ASHRAE public review process.
- The ASTM standard for duct leakage testing has begun the review process and a new standard for longevity of duct sealants has been proposed to ASTM.
- Support was provided for several thermal distribution system efficiency tasks sponsored by EPA.
- Several reports and papers have been published to allow public dissemination of research results.

7.0 Conclusions and Recommendations

7.1 Duct Leakage Diagnostics

Several diagnostic techniques for measuring duct leakage were evaluated in an earlier phase of the current work. These included the house pressure test, the nulling pressure test, tracer gas, duct and house pressurization and duct only pressurization. None of these methods was considered ideal, so further efforts were undertaken to develop a better duct leakage test. The result of an American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) workshop, committee meetings and discussions with other researchers yielded a new test method, termed the Delta Q. This test method was used on a pilot scale of local homes in this study with encouraging results. The test is simple, quick and not as sensitive to wind conditions as some other tests.

Next steps: Further experience is needed in conducting the test in more homes and to include repeatability studies. Additional studies will also be required to perform analytical analyses for error propagation, uncertainty and sensitivity to input parameters.

7.2 Duct Sealants and Longevity Testing

A duct sealant longevity test method, developed under a previous phase of this project, was submitted to the ASTM. A technical issue raised during review of the method concerned the peak temperatures that should be used in the accelerated longevity test, with one ASTM committee member noting that attic temperatures could exceed the value used in the test. A literature search was undertaken in this study to address the issue. Based on that search and temperature limits set by manufacturers for duct tape, a compromise temperature of 180 degrees Fahrenheit was reached, leading to revisions in the longevity test apparatus.

Next steps:

The longevity test apparatus will be used to test different procedures for evaluating longevity. The procedures include:

- The existing procedure of alternating between hot (150°F) and cold (0°F) air flows with a pressure difference across the seal.
- Changing the temperatures in the alternating temperature test to be more extreme (180°F).
- Splitting the test into a hot test and a cold test. The hot test will vary the temperatures in the range of 70°F (close to room temperature) to 180°F. The cold test will have the range from 70°F down to 0°F. This narrower temperature range will allow for more rapid cycling and greater temperature extremes (e.g., we could possibly go lower than 0°F). For both the hot and cold test there will be a pressure difference maintained across the leakage sites.
- Having no cycling of temperature and maintaining a steady hot (180°F) or steady cold (0°F) temperature. Unlike the previous baking tests there will be airflow through these samples and pressure differences across the leaks.

7.3 Duct System Interactions with System Sizing

7.3.1.1 Field Measurements

Cooling system performance was measured in six new houses, five in California and one in Texas. Testing was performed on homes in their "as found" condition and then with the duct systems sealed. Supply and return duct leakage varied from one to six percent for five of the six homes. These results indicate that the duct systems were better than average installations, with the exception of one home. The results from this home were surprising in that the duct system was located in interior partitioned walls, a preferred design from an energy efficiency perspective, rather than the attic. However, most of the leakage was at the plenum to duct connections located in the garage. This result reinforces the value of field testing duct systems.

Refrigerant charge was also checked at the sites. All but two sites had near the correct refrigerant charge. One of the two undercharged systems was so low that significant equipment damage could have occurred.

The possibility of resizing systems to reduce HVAC equipment cost and peak energy consumption was also explored. Nameplate capacities indicated significant oversizing compared to calculated loads. In addition, two sites with the same nameplate capacity exhibited a one ton (12,000 BTU / hr) difference in actual delivered cooling to the conditioned space. These and other results show that nameplate capacity is a poor indicator of the capacity of the system. The oversizing of nameplate capacity, however, was offset by lower actual equipment performance.

Six performance metrics were determined for each site, including the pulldown time, tons of cooling at the register, air conditioner capacity, the air conditioner Coefficient of Performance (COP), system COP and delivery efficiency. Although these metrics are useful in understanding cooling system performance, they are strongly influenced by many external factors such as duct leakage, refrigerant charge, evaporator airflow, indoor temperature and humidity, etc. These factors, and limited periods of measurement, make interpretation of the data difficult. Nevertheless, this report compares individual sites where test conditions were similar.

Conclusions from the field measurement portion of the work include:

- Installed capacity is considerably less than nameplate and ARI ratings.
- Nameplate and ARI ratings exceed ACCA Manual J load estimates.
- Thermal distribution system losses and poor equipment installation combine to reduce nameplate and ARI capacities close to ACCA Manual J load estimates.
- Improving ducts by reducing leakage can lead to significant energy efficiency gains in addition to increasing the TAR, thereby increasing comfort by reducing pulldown time.
- Leakage specification must be checked by measurement.
- Systems can have good efficiency, but not give sufficient comfort to occupants due to poor distribution.

- Systems with poor distribution need to run much longer if all rooms are to be comfortable.
- Using higher SEER units indicated significant peak energy savings of about 25 percent with no apparent drawbacks.

Next steps:

For sizing issues, more field tests are required to include a wider range of homes, construction techniques and weather conditions in order to convince the building industry of the downsizing potential with good duct systems. For evaluating high SEER air conditioners more field studies are required. These studies need to include both dry and humid climates and long term evaluations (at least a month) in order to capture the effect of different weather conditions.

7.4 Computer Simulations

Several improvements were made to the Register Capacity (REGCAP) model used in earlier phases of this work. The upgraded model was then used to reexamine the pulldown simulations performed in a previous part of this study. Eight different distribution systems were modeled in the same house under the same weather conditions. The better systems were able to pulldown the house in a reasonably short time, under three hours, but the poorer systems took over six hours. Simulation results show that resized systems with good ducts can be as good or better than an existing system. The conclusions reinforced by the simulation results are:

- Improved ducts and system installation can allow the use of a smaller nameplate capacity air conditioner (almost one ton less in one case, and at least one ton in more demanding situations) without any comfort penalty in terms of pulldown, and with large energy savings (roughly halving energy consumption).
- If system nameplate capacity is unchanged, either improving duct systems and correctly installing the equipment, or moving the ducts inside, results in significant pulldown performance improvements.
- Systems do not provide their nominal capacity at design conditions, when system capacity is most critical.

The model accuracy was evaluated by comparing predicted temperatures for attic, house, return duct and supply duct air to measured temperatures. Over 100 days of measured data at five sites were used. Detailed comparisons are charted for two sites in Sacramento. Overall there was very good agreement between predicted and measured values for house and attic temperatures and good agreement for duct air temperatures when the air handler fan was on, but not good agreement when the air handler was off. The predicted duct temperature with the air handler off was much hotter (about 5 degrees Celsius) than the measured temperature. However, this result is not significant for the objectives of this study, namely to predict the pulldown time and tons of cooling at the register, since only house air temperature and supply duct air temperature with the air handler on are necessary for the calculations.

Next steps:

Further refinement of the equipment model is needed. LBNL is working together with Proctor Engineering Group on this issue. The capability of placing ducts in other locations outside conditioned space (e.g., garages and crawlspaces) needs to be added to the model. Developing a streamlined user interface will allow REGCAP to be used by a wider audience (possible as part of energy code style calculations).

7.5 Title 24 Support and Technology Transfer

Various Title 24 support activities were undertaken in this study. Technical support was provided on developing residential commissioning test protocols. This included the use of flowhoods to measure air flow at registers. Register flows were measured using eight different flowhoods. The results showed that standard flowhoods can be poor at measuring these flows. Using powered flowhoods reduced measurement problems.

Next steps:

Laboratory tests will be performed to evaluate different register flow measurement methods under controlled conditions.

Other activities involved technical contributions to a collaborative effort to develop procedures to improve the design, fabrication, installation and testing of HVAC systems. Various contributions to ASHRAE and ASTM standards also were made in the course of this work. A web-based tool was developed to perform ASHRAE standard 152P duct leakage calculations. A draft standard for testing the longevity of duct sealants was prepared and submitted to ASTM. A new draft of an ASTM standard for measuring leakage was also submitted and included the new Delta Q leakage test.

Next steps:

ASHRAE 152P will be edited in response to the public review comments and a new draft will be submitted for a second public review. The ASTM longevity standard will be edited based on the next round of sealant testing on the new longevity test apparatus that is almost completed. The ASTM duct leakage measurement standard will be edited based on the field results we obtain over the next few months using the DeltaQ test.

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

Next steps:

With respect to improved HVAC systems, the new Title 24 standards need to be evaluated as to their effectiveness. In such an evaluation, there are several issues that need to be addressed. The major issues and the corresponding variables to be measured are:

Issue	Variable
Has duct leakage decreased?	Duct leakage
Are systems sized correctly?	System size
Are ducts sized correctly?	Duct size, air flow
What energy savings have been achieved?	Energy use
What has been the cost to the builder; to the homeowner?	Costs
What is the market penetration of improved HVAC systems?	Market penetration
Has comfort improved?	Consumer surveys

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9.0 Recent Publications

Walker, I.S. 1999. Distribution System Leakage Impacts on Apartment Building Infiltration Rates. *ASHRAE Trans. Vol. 105 Part 1*. (presented at ASHRAE TC 4.10 Symposium, January 1999), LBNL 42127.

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APPENDIX I

ASHRAE SP152P Duct Leakage Workshop Subcommittee Meeting

APPENDIX II

Delta Q Duct Leakage Test

APPENDIX III

SUMMARY OF FIELD MEASUREMENT PERFORMANCE METRICS

APPENDIX IV

FLOWCHART FOR REGCAP MODEL

APPENDIX V

REGCAP SIMULATION SENSITIVITY TO INPUT DATA UNCERTAINTY

APPENDIX VI

Evaluation of Flow Hood Measurements of Residential Register Flows

APPENDIX VII

IMPROVING THE ENERGY EFFICIENCY OF AIR DISTRIBUTION SYSTEMS IN NEW CALIFORNIA HOMES

APPENDIX II

DELTA Q DUCT LEAKAGE TEST

Procedure:

1. Install blower door and envelop pressure difference tubing/sensor.
2. With blower door fan opening blocked, blower door off and system off measure pressure difference across envelope with blower door off ΔP_{zero}. ΔP_{zero} is subtracted off all the envelope pressure measurements (or remeasured at the end of the test and some average used).
3. Turn on the system and measure the pressure across the envelope, ΔP_{env} (at Q=0, where Q is the flow through the blower door).
4. Measure the plenum operating pressures - ΔP_s for supply and ΔP_r for return – relative to the conditioned space. Note that both pressures are recorded as positive numbers for use in the analysis, i.e., the return pressure is NOT negative.
5. Turn on the blower door until there is 5 Pa across the envelope. Record ΔP_{env}, and Q_{on}.
6. Turn off the system fan and adjust the blower door fan to obtain the same pressure ΔP_{env} across the envelope. When the pressures are matched, record Q_{off}.
7. Repeat steps 5 and 6, but with the envelope pressure, ΔP_{env}, incremented by about 5 Pa each time. At each ΔP_{env} there will be a pair of flows Q_{on} and Q_{off}.
8. Subtract ΔP_{zero} from each ΔP_{env} to obtain ΔP.
9. Calculate ΔQ_i at each P_i by subtracting $Q_{off,i}$ from $Q_{on,i}$.
10. Do a non-linear fit of the P and ΔQ pairs to:

$$\Delta Q(P) = Q_s\left[\left(1+\frac{P}{\Delta P_s}\right)^n - \left(\frac{P}{\Delta P_s}\right)^n\right] - Q_r\left[\left(1-\frac{P}{\Delta P_r}\right)^n + \left(\frac{P}{\Delta P_r}\right)^n\right]$$

to find supply leakage: Q_s, return leakage: Q_r, and the pressure exponent for duct leaks: n. Note that all envelope pressures are measured relative to outside – i.e. $P_{in} - P_{out}$, so that pressurization of the house is a positive pressure. Similarly, flows into the house through the blower door are also positive.

Derivation of DeltaQ test

Nomenclature:

C_{env} = flow coefficient for building envelope
C_r = flow coefficient for return duct leaks
C_s = flow coefficient for supply duct leaks
n_{env} = envelope pressure coefficient
n_r = return leak pressure coefficient
n_s= supply pressure coefficient
Q_{on} = measured flow through blower door with A/H fan on
Q_{off}= measured flow through blower door with A/H fan off
Q_s = supply leak flow at operating conditions to outside
Q_r = return leak flow at operating conditions to outside
ΔP = pressure difference across envelope (in-out)
ΔP_s = pressure difference across supply leaks at operating conditions.
ΔP_r = pressure difference across return leaks at operating conditions (note that this is a positive number for flow into ducts, so Q_r is positive)

With the A/H fan off we have:

$$Q_{off}(\Delta P) = C_{env}(\Delta P)^{n_{env}} + C_r(\Delta P)^{n_r} + C_s(\Delta P)^{n_s}$$

With the A / H fan on we have:

$$Q_{on}(\Delta P) = C_{env}(\Delta P)^{n_{env}} + C_r(\Delta P - \Delta P_r)^{n_r} + C_s(\Delta P + \Delta P_s)^{n_s}$$

"DeltaQ" is the difference between these two:

$$\Delta Q(\Delta P) = Q_{on}(\Delta P) - Q_{off}(\Delta P) = C_s\left[(\Delta P + \Delta P_s)^{n_s} - (\Delta P)^{n_s}\right] + C_r\left[(\Delta P - \Delta P_r)^{n_r} - (\Delta P)^{n_r}\right]$$

Defining the supply and return leakage flows:

$$Q_s = C_s(\Delta P_s)^{n_s} \qquad Q_r = C_r(\Delta P_r)^{n_r}$$

and $C_s = \dfrac{Q_s}{(\Delta P_s)^{n_s}} \qquad C_r = \dfrac{Q_r}{(\Delta P_r)^{n_r}}$

Substituting C_s and C_r into the deltaQ equation, we get:

$$\Delta Q(\Delta P) = Q_s\left[\left(\frac{\Delta P + \Delta P_s}{\Delta P_s}\right)^{n_s} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n_s}\right] + Q_r\left[\left(\frac{\Delta P - \Delta P_r}{\Delta P_r}\right)^{n_r} - \left(\frac{\Delta P}{\Delta P_r}\right)^{n_r}\right]$$

This equation can be solved for Q_s, Q_r, n_s and n_r given the measured plenum pressures, ΔQ's and ΔP's. However, it is easier (and more robust) if we fix the duct leakage pressure exponents. Experiments to characterize the pressure exponent have shown that a value of 0.6 is suitable for most duct systems. The variability in this exponent is between 0.5 and 0.7. If we fix the value of n, and do a little algebraic manipulation we get a form that gives DeltaQ in terms of a difference between the supply and return leaks and is a little clearer to interpret (e.g., it is easier to see that when ΔP=0, then ΔQ is the difference between supply and return leaks).

$$\Delta Q(\Delta P) = Q_s\left[\left(1 + \frac{\Delta P}{\Delta P_s}\right)^{n} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n}\right] - Q_r\left[\left(1 - \frac{\Delta P}{\Delta P_r}\right)^{n} + \left(\frac{\Delta P}{\Delta P_r}\right)^{n}\right]$$

Uncertainty Estimate for exponent and duct pressure assumptions

Using plenum pressures assumes that these pressures characterize the pressure across the leaks. The uncertainty associated with fixing the value of n and using plenum pressures has been investigated parametrically by using an actual DeltaQ test and varying n and the supply and pressures. The following table contains the results of this parametric study. In Table B1, the pressures were varied over a range that captures the variation we expect to find in a duct system. If the leaks were all at the registers, then we need to use a low pressure: 5 Pa in this case, and if we change the pressure measurement location (and orientation of the pressure probe) in a plenum we find that pressures can change by a factor of two: as shown by the increased pressures in the table. Note that in this table we have used the worst case values in order to bound the problem. An estimate of typical uncertainty would be less than the variation shown here.

Table B1 DeltaQ Sensitivity Test

ΔP_s, Pa	ΔP_r, Pa	n	Q_s, cfm	Q_r, cfm	
9.8	22.4	0.6	14	167	plenum pressures: actual measurements, fixed n
9.8	22.4	0.7	44	187	High value of n
9.8	22.4	0.5	-7	155	Low value of n
20	22.4	0.6	31	194	doubled supply pressure
5	22.4	0.6	-2	151	halved supply pressure
40	22.4	0.6	33	199	quadrupled supply pressure
9.8	10	0.6	1	177	halved return pressure
9.8	40	0.6	21	163	doubled return pressure
9.8	5	0.6	-18	178	quartered return pressure

These results show that this test method is not very sensitive to the assumed pressure exponent or the leak pressures. Note that this result only applies to this particular test, so we will have to do similar sensitivity studies on some more house results before we can say that the test method is insensitive for all situations.

Flow Adjustments for Exact Pressure Matching

The trickiest part of the test procedure is the matching of pressures with the distribution fan on and off. With an automated system that monitors the envelope pressure and can adjust the fan this would be made much easier (particularly if the envelope pressures have the typical fluctuations seen in field tests). Because the pressure and flow pairs will not be exactly matched, we need to have a procedure for determining what the flow difference should be with the pressures matched exactly. This procedure can also be automated as follows. If we take the system fan off as the reference pressure and flow condition we need to match the fan on conditions. By doing a power law fit to all the fan on data we can obtain the pressure exponent for the fan on data. Using this exponent and the ratio of the reference pressure to the actual fan on pressure we can find the fan on flow at the reference pressure:

Let the reference pressure for a given data point be ΔP_{off} and the corresponding flow is Q_{off}. We now take some distribution system fan on data at ΔP_{on} with a corresponding Q_{on}. Although ΔP_{on} and ΔP_{off} are close they are not exactly the same. If we fit to all of the fan on data we can obtain the pressure exponent n_{on}. The on flow can now be corrected to be at the same pressure as the off data:

$$Q_{on,corrected} = Q_{on}\left(\frac{P_{off}}{P_{on}}\right)^{n_{on}}$$

This correction can be applied to all the fan on data so that we have flows at exactly matched pressures. Because we aim to have the measured P_{off} and P_{on} close to begin with, any uncertainties in assuming that the pressure flow relationship is a power law and in evaluating the pressure exponent are small. In other words, because the flow corrections will be small anyway (probably less than five percent), the errors in this interpolation procedure will not be significant.

Comparison to Other Measurements

The pilot test of the DeltaQ procedure was performed in a house that we have already made many duct leakage measurements in. The following summarizes the test results for comparison purposes.

Table B2 Comparison of duct leakage measurement procedures

	DeltaQ	Duct Pressurization[1]	Duct Pressurization[2]	NPT[3]	Tracer gas
Q_s, cfm	14	51	30	17	n/a
Q_r, cfm	167	116	95	151	160

1- Converted to operating pressures using pressure pans
2- Converted to operating pressures using plenum pressures
3- NPT = Nulling Pressure Test.

APPENDIX III

SUMMARY OF FIELD MEASUREMENT PERFORMANCE METRICS

In the following tables, there are some results that are counter intuitive. The main culprit in these cases is the uncertainty in the relative humidity measurements. For example, in Table C1 there are some cases where the “total” TAR is less than the “sensible” TAR. This is particularly evident in the 5-minute results for Site 2, where the leaks sealed case gives the lowest TAR. Detailed examination of the measured data has shown that these anomalies are due to poor RH measurements. Improved RH measurements (and plenum temperatures) are needed to reduce the incidence of these results. For this reason, we are now performing improved RH calibrations on the RH sensors and also performing period field recalibrations.

Table C1 Tons At the Register						
	5minutes		30 Minutes		60 minutes	
	Total	Sensible	Total	Sensible	Total	Sensible
condition	Mean	Mean	Mean	Mean	Mean	Mean
Site 1 as found	1.8	1.6	3.0	3.0	2.8	2.9
Site 1 sealed	3.5	3.0	3.0	2.9	2.7	2.6
Site 2 as found	3.9	2.6	2.6	2.7	2.6	2.8
Site 2 leaks added	4.1	2.6	2.3	2.5	N/a	N/a
Site 2 leaks added, correct charge	4.8	2.6	3.1	2.4	2.2	2.4
Site 2 sealed, correct charge	2.6	2.8	2.2	2.6	2.2	2.6
Site 3 as found	3.3	2.1	2.9	2.1	2.8	2.1
Site 3 as found correct charge	3.4	2.2	3.1	2.3	3.1	2.3
Site 3 sealed, correct charge	4.1	2.4	3.7	2.6	3.6	2.7
Site 4 as found	3.1	1.1	3.0	1.2	2.9	1.3
Site 4 as found, new compressor	1.9	1.3	1.7	1.3	1.6	1.3
Site 4 Leaks added	1.4	1.0	1.3	1.0	1.4	1.2
Site 5 as found	1.8	1.3	1.6	1.2	1.6	1.4
Site 5 sealed	1.8	1.3	1.6	1.4	1.6	1.4
Site 6 as found	2.8	1.2	2.0	1.3	1.9	1.4
Site 6 as found, new compressor	n/a	n/a	2.2	1.4	2.0	1.4
Site 6 leaks added	2.8	1.4	2.1	1.4	2.0	1.4

Table C2 Capacity at the indoor coil						
	5 minutes		30 minutes		60 minutes	
	Total	Sensible	Total	Sensible	Total	Sensible
Condition	KW	kW	kW	kW	kW	kW
Site 1 as found	7.4	6.7	6.2	5.8	12.5	12.7
Site 1 sealed	13.6	12.2	12.45	11.7	11.6	11.2
Site 2 as found	18.2	12.3	11.9	12.3	11.9	12.7
Site 2 leaks added	18.4	12.4	11	12		
Site 2 leaks added, correct charge	20.9	12.3	14.4	11.8	10.9	12
Site 2 sealed, correct charge	10.9	11.6	10.1	11.6	9.8	11.2
Site 3 as found	13.7	8.6	12.1	8.8	11.386	8.4
Site 3 as found correct charge	13.2	8.2	12.2	8.56	12	8.7
Site 3 sealed, correct charge	14.5	8.2	13.6	9.5	13.2	9.7
Site 4 as found	12.3	4.8	11.7	5	11.5	5.2
Site 4 as found, new compressor	7.6	5.17	6.9	5.4	6.73	5.5
Site 4 Leaks added	6.1	4.53	5.6	4.7	5.49	4.67
Site 5 as found	9.9	6.9	8	7.1	7.8	7.1
Site 5 sealed	7.96	6.1	7.1	6.3	5.6	5
Site 6 as found	12.1	6	9.5	6.9	9.2	7.1
Site 6 as found, new compressor			9.94	7.17	9.7	7.4
Site 6 leaks added	11.8	6.6	9.3	6.7	8.97	6.8

Table C3 System Power consumption				
	5 minutes	30 minutes	60 minutes	fan as fraction of compressor
Condition	kW	kW	kW	
Site 1 as found	5.6	5.1	5.1	0.1
Site 1 sealed	5.4	5.3	6.1	0.1
Site 2 as found	5.6	5.7	5.4	0.1
Site 2 leaks added	5.3	5.2		0.1
Site 2 leaks added, correct charge	5.7	5.7	5.6	0.1
Site 2 sealed, correct charge	6.1	6.6	6.5	
Site 3 as found	4.6	4.5	4.7	0.2
Site 3 as found correct charge	4.4	4.2	4.2	0.2
Site 3 sealed, correct charge	4.2	4.2	4.2	0.2
Site 4 as found	2.9	2.9	2.8	0.2
Site 4 as found, new compressor	2.4	2.4	2.3	0.3[1]
Site 4 Leaks added	2.1	2.1	2.1	0.3
Site 5 as found	3.1	3.1	3.1	0.2
Site 5 sealed	3.2	3.2	3.1	0.2
Site 6 as found	3.7	3.7	33.7	0.2
Site 6 as found, new compressor		3.7	3.7	0.2
Site 6 leaks added	3.8	3.9	3.9	0.15

1 – Large variation indicating a variable speed compressor see above

Table C4 Key Temperatures and Enthalpies for calculating system performance									
	5 minutes			30 minutes			60 minutes		
condition	Tout[1] (°C)	hreturn[2] (kJ/kg)	Tattic[3] (°C)	Tout (°C)	hreturn (kJ/kg)	Tattic (°C)	Tout (°C)	hreturn (kJ/kg)	Tattic (°C)
Site 1 as found	29.3	44.4	35.4	26.9	36.4	30.3	26.7	35	37.3
Site 1 sealed	30.7	44.5	37.7	31.6	41.3	37.3	36.7	43.1	40.5
Site 2 as found	28.8	41.4	33.6	30.7	40.3	36.7	27.5	36.3	29.9
Site 2 leaks added	26	40.3	28.4	25.5	37.6	27.2			
Site 2 leaks added, correct charge	30.3	41.9	32.6	29.8	38.7	31.5	29.3	37	30.3
Site 2 sealed, correct charge	33.2	43.4	40.1	36.9	43.7	41.1	36.2	41.6	39.9
Site 3 as found	28.9	56.2		29.5	52.6		32.9	54.9	
Site 3 as found correct charge	26.3	55		25.6	50.7		24.4	48.5	
Site 3 sealed, correct charge	24.7	50.7		24.5	45.6		24.1	43.1	
Site 4 as found	36.9	61.4	60.2	36.5	56.1	57.5	35.8	53.6	55
Site 4 as found, new compressor	32.2	57.4	56	32.02	52.2	53.4	31.9	49.6	50.6
Site 4 Leaks added	32.82	55.7	53.6	32.6	51.8	50.9	31.9	49.6	48.1
Site 5 as found	31.6	52.4	44.5	31.7	47.1	40.3	31.3	44.8	38.6
Site 5 sealed	34.7	52.6	47.3	33.4	46.9	42.4	33.1	44.8	40.6
Site 6 as found	33.7	54.5	53.8	33.96	48.9	54.4	34.3	46.7	53.1
Site 6 as found, new compressor			38.8	33.4	48.8	48.9	33.8	46.3	50.6
Site 6 leaks added	27.4	41.8	37.1	27.1	46.4	37	27.2	43.6	35.8

1- outside air dry bulb temperature
2- enthalpy of air in return
3- attic air dry bulb temperature

Table C5 Temperature at different locations in the house during pulldown tests									
	5 minutes			30 minutes			60 minutes		
condition	Thermostat [°C]	Master BR [°C]	Kitchen [°C]	Thermostat [°C]	Master BR [°C]	Kitchen [°C]	Thermostat [°C]	Master BR [°C]	Kitchen [°C]
Site 1 as found	26.1	27.7	27.2	23.2	24.1	21.9	22.1	23.2	20.7
Site 1 sealed	25.8	27.1	25.1	24	25.3	23	23.1	25.2	22.7
Site 2 as found	25.8	25.7	23.8	23	24.7	22.3	22.5	22.9	19.9
Site 2 leaks added	24.5	24.3	22.6	22.5	22.6	20.4			
Site 2 leaks added, correct charge	24.7	25	23	22.9	23.3	20.9	22.1	22.8	20.3
Site 2 sealed, correct charge	25.2	26.3	23.9	24.8	26	23.3	23.8	25.2	22.3
Site 3 as found	25.3	27.7	25.1	23.6	26.6	23.64	23.9	27.4	24.2
Site 3 as found correct charge	25.7	28.2	25.2	23.8	26.7	23.2	23	26	22.6
Site 3 sealed, correct charge	25	27.7	24.6	23.2	25.5	22.7	22.2	24.7	21.9
Site 4 as found	30	26.9	28.1	28.5	26.7	25.9	27.6	26.1	25
Site 4 as found, new compressor	28.6	27.5	26.8	27	25.5	24.7	26.1	24.8	23.8
Site 4 Leaks added	28.1	27	26.9	26.7	25.1	24.9	26	24.4	24.1
Site 5 as found	28.4	31.1	27.6	25.4	29	24.8	24.6	28.6	23.9
Site 5 sealed	29.2	30.8	27	25.9	28.5	23.8	24.9	28	22.96
Site 6 as found	26.6	30.1	28	27.8	28.6	25.5	27.3	28.2	24.7
Site 6 as found, new compressor				27.6	28.4	25.2	27	27.7	24.4

Table C5 Temperature at different locations in the house during pulldown tests									
	5 minutes			30 minutes			60 minutes		
condition	Thermostat [°C]	Master BR [°C]	Kitchen [°C]	Thermostat [°C]	Master BR [°C]	Kitchen [°C]	Thermostat [°C]	Master BR [°C]	Kitchen [°C]
Site 6 leaks added	24.4	26	23.6	23.6	24.5	21.4	22.9	23.7	20.7

Table C6 Delivery Effectiveness						
	Sensible			Total		
	5 minutes	30 minutes	60 minutes	5 minutes	30 minutes	60 minutes
Site 1 as found	0.95	0.81	0.80	0.95	0.81	0.80
Site 1 sealed	0.88	0.85	0.82	0.88	0.85	0.83
Site 2 as found	0.76	0.76	0.77	0.83	0.78	0.76
Site 2 leaks added	0.73	0.74		0.79	0.73	
Site 2 leaks added, correct charge	0.74	0.72	0.72	0.81	0.75	0.70
Site 2 sealed, correct charge	0.85	0.79	0.80	0.85	0.78	0.78
Site 3 as found	0.87	0.86	0.89	0.85	0.85	0.87
Site 3 as found correct charge	0.95	0.94	0.94	0.90	0.90	0.91
Site 3 sealed, correct charge	1.05[1]	0.98	0.98	0.99	0.96	0.97
Site 4 as found	0.85	0.85	0.84	0.88	0.89	0.88
Site 4 as found, new compressor	0.86	0.83	0.85	0.88	0.85	0.87
Site 4 Leaks added	0.78	0.77	0.90	0.80	0.79	0.90
Site 5 as found	0.64	0.68	0.70	0.70	0.71	0.72
Site 5 sealed	0.72	0.77	0.79	0.77	0.80	0.80
Site 6 as found	0.69	0.67	0.67	0.82	0.75	0.74
Site 6 as found, new compressor		0.78	0.74			
Site 6 leaks	0.77	0.75	0.75	0.85	0.80	0.80

Table C6 Delivery Effectiveness						
	Sensible			Total		
	5 minutes	30 minutes	60 minutes	5 minutes	30 minutes	60 minutes
added						

1- Error in supply plenum temperature from spatial variation and response time

The Delivery Effectiveness is often higher at the start (5 minute values) due to lower conduction losses. A t the beginning of the cycle the air in the ducts is not as cool as later in the cycle.
The sensible DE is a function of both conduction and leakage. The total DE contains the moisture losses that are from leakage only.

Table C7 Equipment Coefficient of Performance (COP)						
	Sensible			Total		
	5 minutes	30 minutes	60 minutes	5 minutes	30 minutes	60 minutes
Site 1 as found	0.7	2.6	2.5	0.7	2.6	2.5
Site 1 sealed	2.3	2.1	2.0	2.5	2.1	2.1
Site 2 as found	2.3	2.1	2.4	3.5	2.1	2.2
Site 2 leaks added	2.4	2.3		3.5	2.1	
Site 2 leaks added, correct charge	2.2	2.1	2.0	3.7	2.5	1.9
Site 2 sealed, correct charge	1.9	1.7	1.7	1.8	1.5	1.5
Site 3 as found	1.9	2.0	1.8	3.0	2.7	2.4
Site 3 as found correct charge	1.9	2.0	2.1	3.0	2.9	2.9
Site 3 sealed, correct charge	1.9	2.3	2.3	3.4	3.2	0.3
Site 4 as found	1.7	1.8	1.9	4.4	4.3	4.3
Site 4 as found, new compressor	2.2	2.4	2.4	3.3	3.0	2.9
Site 4 Leaks added	2.2	2.2	2.2	2.9	2.7	2.6
Site 5 as found	2.2	2.3	2.3	2.9	2.6	2.5
Site 5 sealed	1.9	2.0	2.0	2.5	2.3	2.2
Site 6 as found	1.6	1.9	1.9	3.2	2.6	2.5
Site 6 as found, new compressor		1.9	2.0		2.7	2.6
Site 6 leaks added	1.8	1.7	1.8	3.1	2.4	2.3

Table C8 Total System Coefficient of Performance (COP)						
	Sensible			Total		
	5 minutes	30 minutes	60 minutes	5 minutes	30 minutes	60 minutes
Site 1 as found	0.7	2.1	2.0	0.7	2.1	2.0
Site 1 sealed	2.0	1.8	1.6	2.2	1.7	1.7
Site 2 as found	1.6	1.6	1.8	2.5	1.6	1.7
Site 2 leaks added	1.7	1.7		2.8	*1.5*	
Site 2 leaks added, correct charge	1.6	1.5	1.5	3.0	1.9	1.4
Site 2 sealed, correct charge	1.6	1.4	1.4	1.5	1.2	1.2
Site 3 as found	1.6	1.7	1.6	2.6	2.3	2.1
Site 3 as found correct charge	1.8	1.9	2.0	2.7	2.6	2.6
Site 3 sealed, correct charge	2.0	2.2	2.3	3.4	3.1	3.1
Site 4 as found	1.4	1.5	1.6	3.9	3.8	3.8
Site 4 as found, new compressor	1.9	2.0	2.1	2.8	2.5	2.6
Site 4 Leaks added	1.7	1.7	2.0	2.4	2.1	2.4
Site 5 as found	1.4	1.5	1.6	2.0	1.8	1.8
Site 5 sealed	1.4	1.5	1.6	1.9	1.8	1.8
Site 6 as found	1.1	1.2	1.3	2.7	1.9	1.8
Site 6 as found, new compressor		1.4	1.4		2.1	2.0
Site 6 leaks	1.4	1.3	1.3	2.6	1.9	1.9

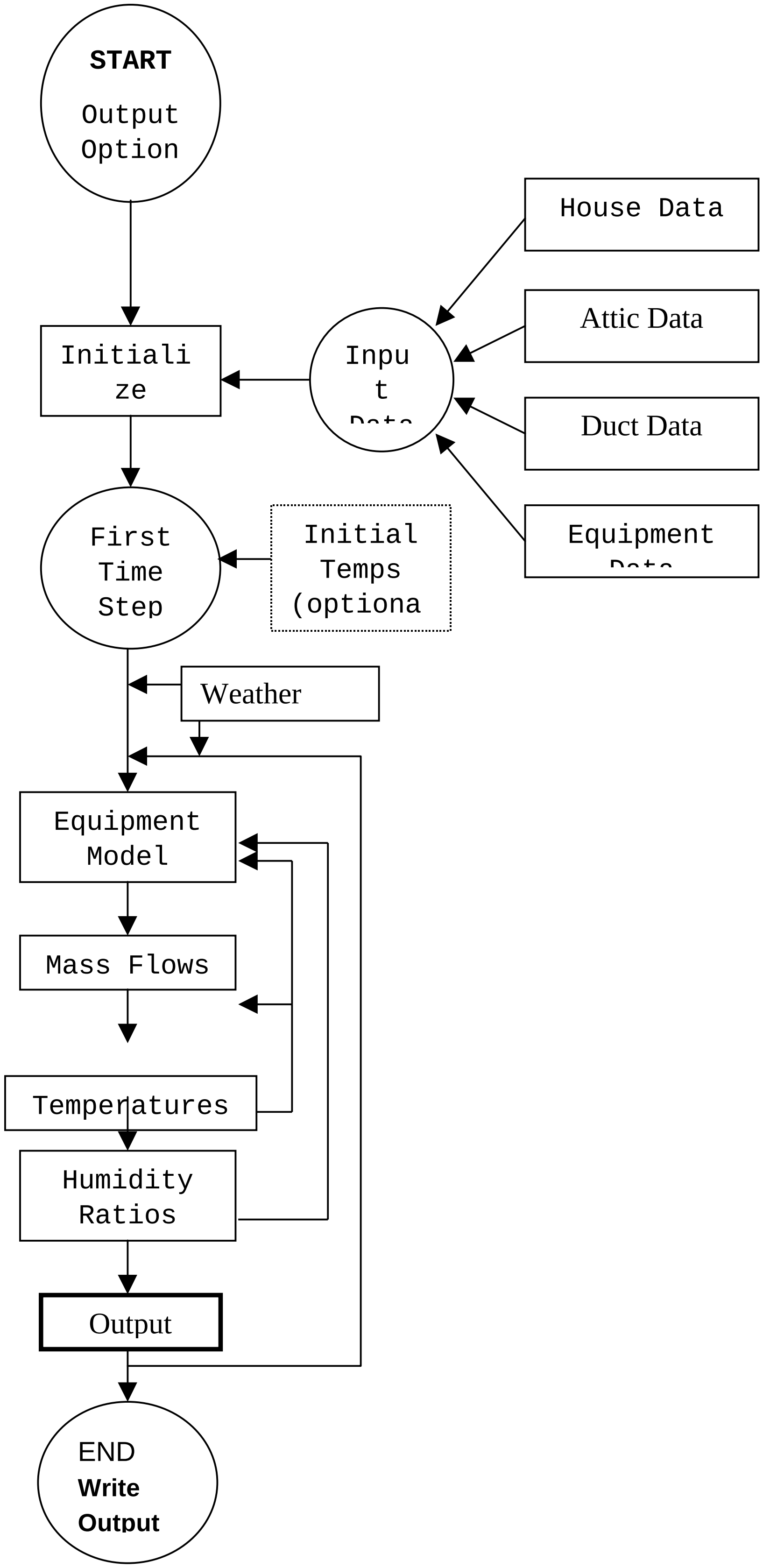
Table C8 Total System Coefficient of Performance (COP)						
	Sensible			Total		
	5 minutes	30 minutes	60 minutes	5 minutes	30 minutes	60 minutes
added						

Table C9 Pulldown time and temperature variation in different locations in the house						
	Pulldown Time (minutes)			Temperatures (°C)		
	Thermostat	Master BR	Kitchen	Thermostat	Master BR	Kitchen
Site 1 as found	11	14	22	24.3	25.2	26.8
Site 1 sealed	32	19	50	24.1	23.1	25.4
Site 2 as found	26	10	27	24.5	22.3	24.4
Site 2 leaks added	8	2	7	24.0	21.9	23.8
Site 2 leaks added, correct charge	10	3	13	24.0	22.2	24.2
Site 2 sealed, correct charge	30	10	55	23.9	22.8	25.3
Site 3 as found	29	45	120	24.0	24.1	27.0
Site 3 as found correct charge	28	14	180	24.0	23.4	26.8
Site 3 sealed, correct charge	15	10	95	24.0	23.6	26.6
Site 4 as found	239	122	198	24.1	21.9	23.2
Site 4 as found, new compressor	159	64	107	24.0	21.9	23.1
Site 4 Leaks added	170	75	92	24.0	22.1	22.7
Site 5 as found	87	63	204	23.9	23.5	27.7
Site 5 sealed	107	34	180	24.0	22.2	26.7
Site 6 as found	257	93	266	24.0	21.0	24.2
Site 6 as found, new compressor	118	20	123	23.2	20.3	23.1
Site 6 leaks	94	8	75	23.6	22.8	25.2

Table C9 Pulldown time and temperature variation in different locations in the house						
	Pulldown Time (minutes)			Temperatures (°C)		
	Thermostat	Master BR	Kitchen	Thermostat	Master BR	Kitchen
added						

APPENDIX IV

FLOWCHART FOR REGCAP MODEL


START
Output
Option
House Data
Attic Data
Initiali
ze
Inpu
t
Duct Data
First
Time
Step
Initial
Temps
(optiona
Equipment
Weather
Equipment
Model
Mass Flows
Temperatures
Humidity
Ratios
Output
END
Write
Output

APPENDIX V

REGCAP SIMULATION SENSITIVITY TO INPUT DATA UNCERTAINTY

Additional model verification tests have been completed at sites 1 and 2. The results of these comparisons are less encouraging, but are based on problems with the input (measured) data rather than problems with the model. The average absolute temperature differences for each air node at each site are shown below in Table E1. It is clear that the model to measured comparison is not very good at these sites, although it is acceptable in the house and ducts when the air handler is on during the pulldown tests. The model overpredicts the attic temperature difference by a very large margin both when the air handler is on and when the air handler is off. This discrepancy is caused by errors in the solar input data. The solar sensors were poorly calibrated at these two sites and the shading device was very rudimentary and didn't always work. This caused us to overestimate total horizontal radiation and to underestimate direct normal radiation. This in turn causes the model to incorrectly overpredict the solar gain on both the house and the attic (although more significantly on the attic). Other problems with the model that these two sites revealed include the lack of coupling between the solar gain and the house mass and the inadequate heat transfer coefficient between the house mass and the house air. These problems will be corrected when an improved load calculation routine is implemented.

Table E1. Comparison of measured and modeled temperatures illustrating problems with measured input data

Site	Date	$\lvert T_{hse} \rvert$		$\lvert T_{attic} \rvert$		$\lvert T_{supply} \rvert$		$\lvert T_{return} \rvert$	
		Whole day	Pulldown only	Whole day	Pulldown only	Whole day	Pulldown only	Whole day	Pulldown only
1	June 6, 1998	4.1	0.4	21.4	14.7	8.7	1.1	9.4	1.7
2	June 10, 1998	5.0	0.4	16.7	12.8	6.2	0.7	5.4	1.2

APPENDIX VI

EVALUATION OF FLOW HOOD MEASUREMENTS OF RESIDENTIAL REGISTER FLOWS

Table F1 Flowhood characteristics	
Code for flowhood	**Description/characteristics**
Hood1	Hard glass fiber capture hood with propeller flow measurement (manufacturer A)
Hood2	Standard flow hood with ΔP flow measurement (manufacturer B)
Hood3	Small flow hood with ΔP flow measurement – specifically for low residential flows (manufacturer B)
Hood4	Standard flow hood with ΔP flow measurement (manufacturer C)
Hood5	Standard flow hood with ΔP flow measurement (manufacturer D)
Hood6	Standard flow hood with ΔP flow measurement (manufacturer D – same model as Hood5, but different serial number)
Hood7	LBNL fan assisted flow hood – total hood pressure balance
Hood8	LBNL fan assisted flow hood – static hood pressure balance
Hood9	Energy Conservatory fan assisted flowhood – corner hood pressure balance
Hood10	Energy Conservatory fan assisted flowhood – near fan entry hood pressure balance

The following table summarizes the individual register measurements for each of these flowhoods:

Table F2 Comparison of flowhood measurements of supply registers (cfm)										
Register	Hood 1	Hood 2	Hood 3	Hood 4	Hood 5	Hood 6	Hood 7	Hood 8	Hood 9	Hood 10
1	184	194	182	205	240	226	197	194	197	203
2	167	181	163	173	232	238	169	186	173	175
3	234	243	275	265	370	341	239	246	244	250
4	156	162	158	164	233	248	151	154	149	164
5	68	69	80	86	110	122	75	75	72	72
6	56	52	55	60	91	66	58	65	53	53
7	103	84	93	102	153	157	98	96	90	95
8	54	43	53	43	83	4	49	53	45	46
9	51	43	52	60	87	82	44	52	47	46
sum	**1073**	**1071**	**1111**	**1158**	**1599**	**1484**	**1080**	**1121**	**1070**	**1104**

These results show that some flowhoods (4, 5 and 6) can give substantially different results from the others. In particular, Hoods 5 and 6 that are from the same manufacturer give flows that are much too high. There are also some significant differences on a register by register basis. If we take Hood 7 to be our measurement standard for comparison purposes, all the flowhoods except Hood 9 have differences for an individual register of 13 cfm or greater. This magnitude of difference may be a concern if the flowhood measurements are used to verify ACCA designs, for example. Another key result is that register 9 was in an interior bathroom and the duct design called for only 5 cfm at this register. Measuring flows this small is very difficult with existing portable flow measurement equipment and would be very difficult to verify. However, in a real duct system it is almost impossible to install it to get this low a flow and, as our results show, the actual flow out of the register is substantially higher than its design flow. This case shows that some interpretation of required design flows is required (for field test verification and compliance testing) because it is probably better to allow the higher than design flow in this case, rather than attempt to restrict the flow to the design value.

Static vs. total pressure balancing.

Comparing the two LNBL tests (Hood 7 – total and Hood 8 -static) shows that the static pressure balancing results in consistently (7 out of 9 registers) lower flow measurements. However, the differences are quite small – less than the specified flow measurement uncertainty (±3% of flow) for five of the nine registers and so this difference is not very significant.

Changing balancing pressure measurement location

Comparing the Hood 9 and Hood 10 results shows that measurement location is not critical. The differences between the two tests are less than the flow meter measurement uncertainty (±3% of flow) for all but two of the registers.

Comparing return measurements

Due to limited capacity not all of the flowhoods had the capability to measure the return flows. Table F3 compares the results for the six flow hoods that were used to measure the return flow. These results show good agreement between hoods 4 through 8, but hood 3 gave results that were too low. For hood 3, the return flow measurement was at the upper limit of its measurement range. This flowhood added significant flow restriction to the return, resulting in a lower flow through the register and flowhood.

Table F3 Comparison of flowhood measurements of return register flow (cfm)

Hood 3	Hood 4	Hood 5	Hood 6	Hood 7	Hood 8
860	995	1028	1055	1037	1057

APPENDIX VII

Updated Report

Improving the Energy Efficiency of Air Distribution Systems in New California Homes

Report for
California Institute for Energy Efficiency (CIEE)

July 5, 1996
Updated September 1999

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Update of original report

The original report for this project was released in 1996. Since then, the two most critical recommendations from the project have been adopted by the building industry and their regulators. The prevalent home energy rating system (HERS), CHEERS (California Home Energy Efficiency Rating System), now includes duct leakage as part of their rating, and the California Energy Commission (CEC) has included a credit in the California Residential Energy Efficiency Standards ("Title 24") for builders who choose to install tight ducts and test their HVAC systems to verify that they pass (the HVAC system leakage at 25 Pascals must be less than six percent of the system fan flow). The original CIEE project was instrumental in initiating these changes.

There was a need to update the original procedures to reflect the changes in the industry and to be consistent with the HERS and Title 24 requirements. Hence, the original report has been revised to meet this need.

Updated Procedures for HVAC System Design and Installation

The CIEE HVAC procedures were developed to provide information on design, materials, fabrication, installation, and testing that builders and subcontractors could use to produce improved installations. Since their development in 1995, there have been several changes in the industry that necessitated updating these procedures. The most important of these changes were results of the Lawrence Berkeley National Laboratory (LBNL) study on the longevity of different closure systems[1], and the adoption of credit in the California Residential Energy Efficiency Standards (Title 24) for installation of tight ducts (ducts that leak less than six percent of fan flow). The procedures in Appendix A have been updated to reflect these changes.

LBNL's study of closure materials demonstrated that normal duct tape (i.e., cloth-backed rubber-adhesive tape), failed rapidly under rapid-cycled heating and cooling conditions. For this reason, these tapes are not permitted in the revised procedures nor for duct systems installed to meet the Title 24 tight duct standard.

The other significant change in the procedures was changing the criterion for tight ducts from a ratio of leakage to floor area to a ratio of leakage to fan flow. Leakage is determined by pressurizing the system to 25 Pascals (Pa) and measuring the CFM flow to maintain this pressure. The resulting CFM_{25} is then divided by the system fan flow to determine total leakage. The leakage in a finished home must be less than six percent of fan flow to be considered tight. Fan flow can either be determined by direct measurement or by substituting measured return air flow.

There have been no new analyses of costs, cost-effectiveness, or benefits of tight duct systems. The authors believe that the original results still stand. However, it is likely that the implementation of tight ducts in the marketplace due to the changes in Title 24 regulations and other efficiency programs will reduce the costs of installing improved systems.

Implementation of the Recommendations from the Original Report

There were three main recommendations in the original report to get builders to improve the efficiencies of their duct systems:

- Change HERS to include energy savings from reduced duct leakage

[1] Home Energy Magazine: 15 #4, July / August, 1998

- Provide a credit in Title 24 for reduced duct leakage
- Provide motivation to builders through energy efficiency mortgages (EEMs)

For the longer term, there were additional issues to address:

- Provide for increased efficiency from: increased duct insulation, decreased duct surface area, placing ducts in conditioned space, and decreased attic temperature due to an attic radiant barrier.

The home energy rating system with the widest market distribution in California is CHEERS. They have changed their rating system in a manner consistent with the recommendations of the original CIEE report. They have reduced the efficiency of the HVAC system in the reference house to reflect that of the current market, and they provide for credit in the as-built house reflecting the efficiency improvement specified in the original CIEE report. Ratings are being done in California for homes with tight ducts using the new CHEERS system.

The California Energy Commission has adopted Title 24 Standards that will go into effect in July 1999 ("'98 Standards") that provide credit for tight ducts. The CEC approach was more sophisticated than the approach recommended in the CIEE report and includes all of the issues that the CIEE report listed as longer-term issues. The '98 Standards use a modified version of the ASHRAE 92P model to predict duct efficiency. For the standard-case code-house, the '98 Standards assume duct leakage of 22 percent from R-4.2 ducts located in the attic. These standards provide efficiency improvements for tight ducts (criterion leakage is less than six percent of fan flow), increased duct insulation, ducts in conditioned space, and attic radiant barrier. Thus, the CEC not only followed the recommendation that credit be provided for tight ducts, but also included credits for other HVAC system improvements, which were anticipated to take much longer.

The California Energy Commission is likely to initiate a rulemaking process for the technical requirements for HERS that would be approved for use in California. It is likely that the HERS technical requirements regarding HVAC systems will follow the changes employed in the '98 Standards. This would implement all of the recommendations of the initial CIEE report and standardize HERS credits for improved HVAC systems in California.

Builders were anticipated to use HERS to help sell improved homes financed by EEMs. Less progress has occurred in the EEM market. Freddie Mac has published rules that will allow builders to use HERS to document improved efficiency of their homes and use the energy savings in the rating to offset an equal amount of consumer debt. While this is exactly what the builders need to use the EEMs to finance improvements, most lenders and their underwriters are unaware of these rules.

Another goal that was not specified in the original report was a wide distribution and application of the installation procedures. This has also occurred. The three main distribution sources have been:

- Building Industry Institute (BII) Builder Energy Codes Training Program
- BII web page
- ConSol's ComfortWise[SM] program (see future directions).

[SM] ConSol, Inc., 1997, 1998, 1999

BII provides an energy codes / quality construction training program to production home builders. The training covers the requirements for Title 24 as well as additional construction issues that will help improve the energy-related quality and comfort of the home. The HVAC installation procedures have been incorporated into the training since 1996. The builders are instructed to follow the procedures and to incorporate them directly into the HVAC contract scope-of-work.

The procedures are also available on the World Wide Web via the BII web site.

Future Directions

There is an energy efficiency program that is designed to encourage new home builders to improve the efficiency of their duct systems, to document the improvement using a home energy rating (specifically a CHEERS rating), and to use EEMs to encourage builders to use the program. This program, ComfortWise, encourages builders to build ENERGY STAR® homes, and tight ducts is a mandatory requirement. The HVAC installation procedures are provided to participating builders for installing tight ducts.

ComfortWise is sponsored by two California utilities, Southern California Edison and San Diego Gas and Electric, as their new construction energy efficiency programs. The total market penetration goal of these two programs is 5,500 homes committed to ComfortWise in 1999. This program, if successful, should demonstrate the value of HERS and tight ducts to the building industry, at least in southern California. Presumably, as ComfortWise develops market share, other competing programs will arise. They should also require home energy ratings, and will hopefully require tight ducts and use the CIEE HVAC installation procedures.

® U.S. EPA

Original Report

EXECUTIVE SUMMARY

Procedures for improved design, fabrication, installation, and testing of HVAC systems for new homes were developed under this project. Draft procedures were developed based upon the findings of a review of existing programs that are provided by utilities and others for improved residential duct systems, in addition to discussions with other individuals active in this field. The draft procedures were distributed to production builders in California and their HVAC subcontractors for their review, comments, and estimates of differential costs to implement these procedures. A goal was to develop procedures that would be cost-effective, acceptable to California production builders and their subcontractors, and that would produce significant energy savings. The final version of the procedures, provided in Attachment A, are the result of this process.

This report discusses the potential costs, energy savings, and other benefits of improved residential HVAC systems. The costs were determined through the discussions with builders and HVAC subcontractors. The benefits were estimated through a review of other field studies, discussions with other individuals doing relevant research, and computer simulations of different field situations. A matrix summarizing the potential costs and benefits, separated into different improvement actions (duct sealing, system design, and duct layout), is provided in Section 1. An important finding is that there are immediate heating and cooling energy savings of 12 percent or more obtainable from duct sealing at an incremental cost of approximately $250 per home (assuming 100 percent testing). Over the longer term, this incremental cost can decrease to zero due to improved techniques and competition. With the addition of improved system design (such as those including ACCA Manual J and D calculations) and airflow verification, overall savings can be increased by an additional eight percent for cooling with little additional cost to production builders (i.e., builders whose costs are spread over multiple houses) in the short term, and potential cost savings in the longer term.

In developing these procedures, it became evident that current practice for sizing ducts and HVAC systems does not properly account for duct leakage and some other duct losses, making it difficult to properly size systems that have minimal leakage. Therefore, this project included a review of the Air Conditioning Contractors of America (ACCA) methods and procedures for design and sizing ducts and systems. Suggested modifications to these methods and procedures are provided in Section 2 of this report and are being actively pursued with ACCA.

Following development of these procedures, an implementation strategy was devised. The goals for this strategy are to provide practical, self-supporting means for the residential new construction industry to adopt and utilize these procedures to produce improved HVAC systems, without any third-party financial incentives. The proposed strategy involves first creating market value for builders using energy efficient mortgages and home energy ratings, which will result in market differentiation between homes with improved HVAC installations, and those with current-style HVAC installations. Second, the strategy proposes to provide credit in Title 24 for improved HVAC systems, and lastly, once there is significant market penetration of improved HVAC systems, require them as part of the energy codes. That strategy is detailed in Section 5 of this report.

Section 1: Improved design, specification and installation procedures

This project began with a survey of on-going residential duct programs to determine the state-of-the-art. From this information, a draft set of procedures was synthesized for California new construction. The original work statement for this project identified thirteen sources for information regarding improved design, specification and installation procedures. Of these, nine provided valuable information that was used in the development of the final draft procedures. Additional sources were identified during the survey process, and a total of fifteen contacts were made that provided valuable information that influenced development of the draft procedures (please see acknowledgments).

A factor that limited use of program information from other states was that most of the information uncovered from on-going residential programs was based on retrofit improvements to duct systems. This study was performed exclusively for new construction and focused on California construction techniques, which are primarily flexduct systems installed in the attic.

An important consideration to the installation procedures was whether they should be prescriptive or performance-based. Purely prescriptive programs, such as in Florida (State of Florida, 1993), have been developed that prescribe every detail of material and construction of the duct system. In addition, purely performance programs, such as in the Pacific Northwest (BPA, 1995), have been developed in which ducts may be installed however desired by the contractor, but they must be pressure-tested and proved not to leak more than a criterion amount of air.

The choice was made to make California procedures both prescriptive and performance based. The reasoning was that, while performance testing is thought to be required to ensure proper function, some materials need to be prescribed to ensure longevity of the tested performance. For instance, it is quite possible to install a duct system using low-quality duct tape that will perform very well initially, passing reasonable performance requirements, but that will degrade within a few years, resulting in considerable leakage. It is also very possible to use all of the best-prescribed materials, but install the system so that it is not easy to detect that there are leaks. Therefore, prescriptive requirements for materials and performance criteria were both determined to be necessary for a long-lasting, quality duct system.

Two California public utilities had DSM programs for tight ducts – Pacific Gas & Electric and Southern California Gas; both were quite popular with builders, both had both prescriptive and performance elements, and both resulted in improved duct systems. These were used as the core of the proposed procedures, enhanced by elements obtained through the nationwide telephone survey (including reports gained through the survey). The enhancements include requirements for load calculations, duct layout, duct sizing, equipment sizing, and increased testing requirements (i.e., system leakage, pressure, and airflow).

The procedures are written with a one-page summary of all requirements. That is followed by six pages of detailed information on materials requirements, suggested design, fabrication and installation procedures, and required tests and performance criteria, as well as reference sources for additional information. The procedures suggest room-by-room load calculations using Air Conditioning Contractors of America (ACCA) Manual J, a determination of detailed duct layout and sizing using ACCA Manual D, system sizing using ACCA Manual S calculations, installation using UL 181 approved materials and specified connection techniques, and tests for proper air conditioner size and charge, maximum duct leakage, proper plenum static pressures, and proper air flows. The one-page summary and detailed procedures are provided in Attachment A.

When the procedures are followed, there are two principal, separable actions that result in energy savings, and that have identifiable costs. These actions are 1) Duct sealing, and 2) System design and layout. Industry experience has clearly shown that prescriptive installation procedures alone will not consistently produce HVAC systems that are properly sealed, and that produce proper air flows and distribution. Some testing is required to ensure that the HVAC system is properly designed and installed. The energy savings estimated for each action assumes that sufficient testing is performed to ensure that the HVAC system is performing according to the recommended criteria.

The following matrix has been developed to summarize the potential energy savings and estimated costs and/or savings for each element from the three different issues addressed by the suggested procedures. The cost is per home for a production builder, and assumes volume purchasing discounts as well as amortization of design costs across 25 homes. Negative costs are cost savings.

Actions, Energy Savings, and Costs of Improvements to Residential New Construction Duct Systems

DUCT SEALING

Impact	Energy Savings	Cost (production builder $)
Decreased leakage	Approximately 12% heating and cooling energy savings	$214 materials and labor plus $131 to $163 testing; Estimate $100 to $150 for both with LBNL-aerosol sealing
Increase equipment efficiency by downsizing to keep equipment capacity constant	Approximately 3%	Possible small savings from small downsize of system
Improved system capacity from decreased leakage; same amount as total increase in energy efficiency, approximately 15%	None	-$100 (savings); Potential 1/2 ton downsize
Reduced duct diameter due to equipment downsize; Probably one size decrease; Maybe none if ducts are currently too small	Insufficient data to estimate savings	-$50 (Possible savings if ducts can be substantially downsized)
Two-speed equipment improvements (especially heat pumps)	Estimate 1.7 times single speed savings (20% savings rather than 12%)	None -- do not downsize equip, allow to run more at low speed
Uniform heating and cooling may provide savings through improved thermostat behavior	Insufficient data to estimate; probably less than 10%	None
Range of impacts[a]	12% to 30%	$377 to -$50 (savings)
Best estimate (short term)[b]	12%	$250
Best estimate (long term)[c]	20% to 25%	$0

System Design (Manual J and Manual D calculations)

Impact	Energy Savings	Cost (production builder $)
Increase system efficiency due to proper air flow	6% - 10% cooling savings on orifice systems for 10% to 20% increase in coil air flow; No substantial savings for TXV systems	$10 ($87 average cost of Manual J and Manual D calculations spread over 25 homes, plus intermittent field tests of flows ($50 every 8 homes or $25 every 4 homes))
Potential 10% capacity increase	None	-$60 (savings); average 0.3 ton decrease
Reduced duct diameter due to equipment downsizing -- produces improved system capacity (note: ducts may be too small now and there may be a resultant *increase* in size)	Insufficient data to estimate	±$; Unknown whether ducts and systems are currently too large or too small
Uniform heating and cooling; May provide savings through improved thermostat behavior; Unknown	Insufficient data to estimate; probably less than 10%	None
Range of impacts[a]	0% to 10% of cooling	$10 to -$50 (savings)
Best estimate (short term)[b]	4% of cooling	$10
Best estimate (long term)[c]	8% of cooling	-$30 (savings)

[a] Survey and estimate results
[b] Authors' best near-term estimate (some competition)
[c] Procedures part of common practice

Section 2:Summary of problems with accepted-practice design methods

The most comprehensive industry-standard practices for load calculation, duct and system sizing, and system selection are available from the Air Conditioning Contractors of America (ACCA) in their Manual J (loads calculation), Manual D (duct sizing), and Manual S (system selection) publications. The use of these manuals was therefore included in the quality installation protocols developed by this project. Unfortunately, there are simplifying assumptions in these ACCA manuals that can result in incorrect loads, and non-optimal duct and system sizing. The major concerns regarding Manual J are its assumptions that:

1. there is no duct leakage, and
2. the load due to duct conduction is independent of the length and design of the ducts.

The implication of the first assumption is that the actual load associated with duct losses is, in general, significantly higher than that assumed by Manual J. The second assumption implies that even if the average conduction losses in the duct-loss multipliers in Manual J are correct, the calculated room-by-room loads are incorrect due to non-uniform conduction losses. These two incorrect assumptions can lead to incorrect calculation of loads, and non-uniform heating and cooling. There are other assumptions within the Manual J method that are under control of the user which can be used to bring the calculated loads back into the correct range. These assumptions and some of the implications of their use are discussed in detail in Attachment B. Attachment B also includes a two-stage strategy for improving the quality of HVAC design in California. The two steps are:

1. modify ACCA Manual-J duct loss/gain multipliers to account for the non-uniformity of duct losses and instruct users in its correct use, and
2. incorporate an overall duct loss calculation procedure that determines duct losses based on actual duct lengths and velocities; this requires coordination of Manual J, duct layout, and Manual D calculations.

Attachment B also suggests how these strategies might be implemented through existing ASHRAE committees and standards.

Section 3:Potential impacts on the building industry and on their construction costs

Industry Survey using Proposed Procedures

Draft procedures were sent to 20 production builders and 25 HVAC subcontractors for review and comment. The reviewers were asked to comment on the practicality of the proposed procedures, to indicate what procedures they already followed, what problems they might encounter with the proposed procedures, and any additional costs or cost-savings that might be incurred due to the procedures.

Responses were obtained from 12 builders and 19 HVAC subcontractors. Their responses were used to make minor changes to the suggested procedures, to analyze costs of the procedures, and to aid in development of the implementation strategy.

Summary of Important Comments

This subsection is a summary of comments made by respondents to indicate their current view of residential HVAC practices in California, and some of the difficulties that the builders and HVAC contractors foresee in improving the HVAC systems.

It was generally held by the survey respondents that the procedures were a good idea, but that their implementation would produce additional costs and that the market would not, by itself, support these additional costs. There was also general consensus that the industry could benefit from improved regulation, but concern was expressed about any new regulations, how they might be structured, and most importantly, how they would be enforced. Many indicated that if current Uniform Mechanical Code (UMC) regulations were enforced that most duct leakage problems would be solved.

Those that had experience with high-performance (i.e., sealed) duct programs supported by utility incentives liked them. Through those programs, HVAC subs were provided with sufficient funds to install a better system and still make money. The builders also felt that they were receiving better ducts. One Southern California HVAC manufacturer said that only ¼ of the HVAC subs were able to work with the utility program requirements because of their limited experience and training. Most cost data for installing sealed ducts that was provided by builders and subcontractors came from experience in the utility programs. This cost data is therefore quite accurate in that it is based on actual experience in the installation of tight duct systems that were tested and passed program criteria.

There was general consensus that the California building industry typically does not employ ACCA or ASHRAE sizing calculations for the duct system. Rather, they are based on experience and "rules of thumb." This leaves an unquantified potential for implementation problems associated with requirements for detailed load calculations, duct layouts, and duct and equipment sizing and selection. A few individuals raised the issue as to whether such a requirement would increase their paperwork, which will add costs.

The potential impacts of testing were difficult to quantify from this survey. Because testing is currently not done on a regular basis, neither builders nor HVAC subcontractors (with a few exceptions) know what tolerances are reasonable, and what the cost would be to perform the testing. In addition, there were significant concerns voiced regarding the logistics of performing testing, mostly from the builders, and what they should be expected to do if the system fails testing, especially regarding air flow requirements. This concern came from both builders and subcontractors. In general, although most understood and appreciated the necessity of some testing, and of establishing tolerances for passing, they warned against too strenuous requirements that would not be cost effective.

Reviewers of the procedures were divided on what values should be used for supply and return air flow tolerances, most contending that as proposed they are not practical. For this reason, the tolerances for supply and return air flows, in section 3b of the testing requirements should be treated as place-holders until there are more test data that can be used to determine reasonable values. This could be done in a pilot program.

Increases in Construction Costs

The California residential building industry has limited experience with large portions of the suggested procedures; therefore, only a limited number of respondents were willing to estimate the incremental costs that would result from implementation of the suggested procedures. When costs were estimated, respondents were questioned to differentiate costs due to requirements for design, materials and labor for fabrication and installation, and testing of the systems. All those responding with cost information had participated in a utility tight-duct program and had direct experience with the costs for those programs. The utility programs also provided most of the respondents with some experience in the costs of testing, although it was more limited. When costs were estimated from utility incentive program experience, the respondents provided their best estimates of actual cost, not incentive values; both builders and HVAC subcontractors who provided this information were very open in their discussion of costs versus incentives. A summary of cost estimates from the survey is provided in Table 1.

Some respondents were only able to provide some of the desired cost information. For instance, some respondents (both builders and HVAC subcontractors) had no experience with ACCA procedures and therefore could not estimate the time and cost required to perform them. In such cases, a high estimate (for a production builder) of the cost -- deemed a placeholder value -- is included in Table 1. These placeholder values were based on this researcher's recent experience outside of this survey of higher costs that are paid by builders for these calculations. High-cost placeholder values were used to minimize the likelihood that the resultant average might underestimate the cost impact to the industry, which could otherwise lead to later invalidation of the findings and resultant recommendations. Table 1 provides average costs determined both with and without the placeholder values.

Cost estimates were also obtained through a direct bid process. Several builders were asked to submit plans to their HVAC subcontractor(s) to get a bid for a typical installation and a second bid on the same home using the suggested improved procedures. One HVAC subcontractor (H6) returned information for two builders. His bids that employed the recommended installation procedures were $167 more than without; this corresponds well to the survey estimate of $150 incremental cost for this HVAC subcontractor. This subcontractor currently includes some of the recommended procedures in his normal work and therefore did not add any incremental cost for these actions. For instance, he performs ACCA Manual J and D calculations on all homes for load calculations and duct sizing, and develops a duct layout on the plans so that he can prefabricate the duct system in his factory before shipment to the job site. Therefore, there was no additional cost for this HVAC subcontractor due to the requirement for these calculations under the proposed procedures.

TABLE 1
COSTS OF SYSTEMS IMPROVED

Participant	Design	Fab/Installation materials	labor	Leakage Testing	Total 25/design, test all	1/design, test all
H1	250	250	incl	125	385	625
H2	100	50	325	250	629	725
H3	250	100	220	incl	330	570
H4	150	150	75	150	381	525
H5	82.5	50	incl	60	113	193
H6	incl	150	incl	200	350	350
H7	250	45	150	100	305	545
H8	150	30	60	160	256	400
B1	250	300	incl	250	560	800
B2	250	100	incl	250	360	600
B3	40	300	incl	250	552	590
Average with placeholders	161	139	75	163	384	538
Average without placeholders	87	139	75	131	348	432

notes: [hatched cell] means high placeholder because no value was provided
participant prefix H denotes HVAC subs and B denotes builders

He also rejected certain recommendations and therefore omitted them from his bid. For instance, he oversizes the total system capacity by 20 percent (10 percent if it is a multi-zoned system) over the total load as a safety margin. He uses manufacturer and UL approved factory connections employing a clear duct tape that he argues seals well and has good longevity. He argues that there is no immediate method to obtain any cost savings due to downsizing that could result from sealed duct systems. He also has his own, manufacturer approved, method for sizing returns that he believes is adequate and provides the design static pressure. No data from systematic tests were provided or requested to substantiate these claims.

It is likely that with experience, builders and their HVAC subcontractors will find methods to design, fabricate, install, and test their duct systems that are more cost-effective than the experience upon which they base their current predictions. It is anticipated that once there is recognized market value for improved HVAC systems, that due to experience and competition, the combined cost for the fabrication, installation, and testing will be closer to $250 for the recommended procedures than the average $346 - $383 estimated from the survey results. In addition, as new techniques become available, these costs will be even lower. For instance, the authors estimate that the LBNL aerosol sealing technique, which combines sealing and pressure testing in a single effort, will cost $100 to $150 for production homes (Modera et al. 1996).

Decreases in Construction Costs

During the survey and bidding processes, respondents, especially HVAC subcontractors, were asked to consider and estimate potential cost savings that could result from downsizing equipment and ducts. None saw any immediate potential for such savings. This is because they either do not currently use sizing procedures such as the ACCA Manual J, D, and S procedures and have no experience or basis to estimate a savings, or because they do use these methods and assume (correctly, if all other assumptions are held constant -- see Section 2 and Attachment B) that they will get the same sizing results from their calculations after adoption of the proposed fabrication and installation procedures as they do now with their current fabrication and installation procedures.

Nevertheless, it should be possible for HVAC systems to be downsized from their current values due to duct sealing. Field studies have demonstrated increases in system capacity associated with duct-system retrofits (Modera and Jump, 1995). Downsizing could be realized in practice through improved ACCA calculation methods, which would require the more widespread use of these standard calculation methods and procedures for loads and sizing, and standardization of the calculation variables, as discussed in Section 2 and Attachment B. Downsizing could also result from industry experience with sealed ducts. Builders and HVAC subcontractors should come to understand that if additional cooling and heating capacity is provided because the ducts are sealed, then a similar amount of capacity can be removed from the system requirements. This will require industry education and experience with sealed HVAC systems, but may be the quickest route to system downsizing.

If downsizing due to tight duct systems occurs, for a 3 to 3½ ton air conditioning system, which is typical in California new construction, a 15 percent or approximately ½ ton decrease in capacity should be possible, resulting in a cost savings of approximately $100 for a minimum efficiency, 10 SEER air conditioner (this is the approximate savings to a production builder – savings to custom builders would be greater). Savings for high-efficiency systems will be greater. Savings may also be available for downsizing the ducts; however, it is not currently known whether California duct systems are typically over, under, or correctly sized, so no savings can immediately be predicted.

Section 4:Value of improved air distribution systems to the building industry

Value Perceived by the Industry

There was general agreement among survey participants that the building industry needs to improve the duct systems. The main value was perceived as improved quality of the homes. There was no consensus that these improved ducts would save builder costs by decreasing consumer call-backs, allowing for down-sizing, or decreasing liability exposure. However, it was the consensus of an industry working group, including the Technical Director of CBIA and the Chairman of the CBIA Energy Committee, that there will be real but currently not quantifiable (due to lack of data) savings to builders due to decreased call-backs, equipment downsizing, and decreased litigation costs resulting from improper heating and cooling. The savings from decreased call-backs will occur immediately, but are not currently quantifiable because there are no comprehensive data currently available regarding the frequency of HVAC call-backs -- for either the HVAC subcontractor or the builder. The potential savings from equipment downsizing will occur over a longer term as the industry improves its sizing procedures and becomes convinced that with tight ducts equipment can be downsized.

There was general agreement that improved ducts could cost-effectively decrease homeowner energy use, which was good, and which could be used to help market comfortable, energy efficient homes, but that it would not *a priori* help them sell homes.

Energy Savings Potential

To estimate the potential energy savings from tight ducts, building simulations were performed. The losses in a duct system derive from a combination of conduction through the duct walls and leaks at the connections in the air distribution system. Through improvements in connections to decrease leakage, duct efficiency can be improved 12 percent to 15 percent if sealing procedures such as those proposed were implemented (Jump et al., 1996; Modera, 1993; Modera and Jump, 1995; CEC, 1995; Proctor and Pernick, 1994).

These energy savings percentages can be understood based on the following. The leakage specification of the leakage flow in cubic feet per minute (cfm) at 50 Pa pressure differential being less than or equal to 0.07 times the house floor area (ft^2) translates to the elimination of approximately 70 percent of the duct leakage in a typical installation. For example, a 1761 ft^2 house would be allowed to have 123 cfm of leakage at 50 Pa, as compared to an average leakage of 406 cfm at 50 Pa for a typical California house of this size (Modera, 1993). The typical leakage areas correspond to leakage flows on the order of 15 percent of the fan flow on both the supply and return sides (Jump et al. 1996, Jump and Modera 1994), where the results from Jump were reduced to account for their somewhat larger than average leakage rates. Given these results, the reduction in supply leakage results in a 10.5 percent increase in energy delivery, and reducing the return leakage results in a 5.25 percent decrease in energy load (assuming that the energy flux across return leaks is approximately half that across supply leaks, $\Delta T_{return,winter}$ = 20-30^oF versus $\Delta T_{supply,winter}$ = 40-70^oF, and $\Delta T_{return,summer}$ = 10-40^oF versus $\Delta T_{supply,summer}$ = 20^oF). Adding in the impact of reduced air infiltration while the unit is off (0.7(fraction sealed – from procedures, also CEC, 1995; Modera, 1993)*0.2(fraction of envelope leakage in ducts – CEC, 1995; Modera, 1993)*0.33(fraction of load due to infiltration)*0.85 (fraction of time that equipment is not running)=>4%) yields a total savings of approximately 20 percent. Some of this savings is not expected to be realized because: 1) some of the leakage is to/from inside the house and new duct installations may be tighter than typical installations, at least in the short term (see

CEC 1995), 2) there is some small recovery of losses to buffer zone (attic or crawl space), 3) there will be increased conduction losses if the ducts are sealed without any changes in design or insulation due to reduced flow rate through the HVAC system (see Jump et al. 1996), and 4) some of the savings will be lost due to degradation of equipment efficiency (due to relative oversizing resulting from sealing).

The energy savings from this improvement in distribution system efficiency were estimated using California Residential Energy Efficiency Standards (Title 24) energy use analyses under the typical and improved conditions. A house typical of current new construction practices was modeled using standard Title 24 procedures.

Typical builders in California use the performance approach to Title 24 compliance because it provides them with flexibility to design and build their homes to their own distinctive styles. Title 24 prescriptive packages have glazing limitations and thermal mass requirements that make them impractical for the production builder. Using the performance approach, the builder can "trade" other features for more glass and less thermal mass, for instance. To do so, the builders proposed design is determined, using the Title 24 modeling assumptions, to utilize no more energy for space conditioning and water heating than would have been used had the home been designed using the prescriptive packages. The performance approach was used to determine potential energy savings and to compare these savings to those available from other potential energy conservation features with different costs and benefits.

This energy analysis used a typical two-story house with 1761 square feet of conditioned floor area. For each climate zone, the glazing percentage was set to be the Title 24 package limitation for that climate zone: 16 percent or 20 percent glazing (depending upon climate zone), which was equally distributed on each side. The heating, cooling and water heating systems had minimum efficiencies. For each climate zone analyses were performed to investigate the impact of a 12 percent improvement in duct efficiency due to tighter ducts (using 75 percent and 84 percent distribution system efficiencies).

The home was modeled using MICROPAS4 in all sixteen climate zones. The estimated energy savings was calculated from the differences between the typical and improved-case Title 24 heating and cooling budgets for each climate zone. State-wide savings were determined by averaging the savings across climate zones, weighting each climate zone by the new home construction in that climate zone. Each climate zone weighting factor was the percent of the total statewide single-family building from each climate zone in 1993, as published by the Construction Industry Research Board, 1994.

The result was a state-wide average annual savings from duct sealing of 38 Therms and 239 kWh for this typical home. Using current-construction (i.e., not baseline) residential energy costs from PG&E, SCE, SCG, and SDG&E, averaged using the 1990 CEC estimate of utility market shares, these energy savings equate to an annual cost savings of $63 from duct sealing alone.

Energy lost due to ducts leaking is the most easily recaptured. Nonetheless, there are additional, quantifiable savings available through downsizing that can result from the duct sealing, as well as from improved air flow across the air conditioning coil. These savings are estimated to be three percent from equipment downsizing to maintain equipment efficiency (Treidler and Modera 1996, Treidler et. al. 1996), and eight percent of the cooling energy for increased air flow across the coil for non-TXV air-conditioners (Rodriguez et al. 1995). This is an additional 10 Therms and 220 kWh or $38 annual savings. There are additional heating-energy savings (particularly for heat pumps) associated with increased air flows, however these are not quantified or included in this report. These savings come at the additional cost of $87 for the duct layout, ACCA Manual J and Manual D calculations plus the cost of flow testing in 12-25 percent of the homes, which, when amortized over 25 homes, comes to $10 per home.

These savings estimates are all based on Title 24 calculated, climate-zone weighted, average annual budgets of 319 Therms for heating and 1995 kWh for cooling. These values could be optimistic for statewide energy-savings estimates due to the Title 24 use of occupancy schedules that assume that someone is home during the day, its choice of thermostat settings, and fact that it allows cross-over use of heating and cooling in the same day. To determine whether this Title-24-based analysis seriously over or under estimates heating or cooling energy use in this study, a comparison was made to the CEC published typical heating and cooling energy use in their 1990 report on Occupancy Patterns and Energy Consumption in New California Houses. That report provides statewide average energy use (UECs) for California Homes built between 1984 and 1987 of 320 Therms for heating and 1370 kWh for cooling (based upon conditional demand analysis, and which includes a lower air conditioner saturation rate than is found in production housing, therefore underestimating cooling energy use compared to this study). These data are similar to those used as the base for this study, and suggest that the savings estimates from this study are reasonable.

Cost/Benefit Comparisons of Duct Sealing to Other Features

To determine the relative cost-effectiveness of tight ducts to other features, a parametric analysis of 38 other features was performed and a cost-benefit ratio was used to compare tight ducts to the other conservation features. These other features included increased insulation levels, improved windows (both U-values and shading coefficients), shading devices, increased HVAC efficiencies, and water heating equipment efficiencies and features. Each feature was analyzed separately, to determine the energy savings that it would produce independent of other design changes. In addition, incremental costs for each feature were determined from a cost database that ConSol maintains based on on-going discussions with builders, subcontractors, and vendors. To determine energy savings, the home was modeled with none of the improved features (the base-case) for each of three representative climate zones (CZ03 Bay Area, CZ10 Los Angeles, CZ12 Central Valley), and these results were compared to the energy use when the improved feature was included. The resulting energy savings for each feature, as a function of the incremental cost, were compared using the cost-benefit ratio (incremental cost divided by the kBtu/ft^{2}yr savings). For illustration, the feature from each improvement category that had the lowest ratio (low cost, high benefit) from each category of feature is provided in Table 2 for each climate zone. As can be seen in this illustration, duct sealing is two to four times as cost effective as all other permanent features (i.e., not including roller shades), depending upon the severity of the climate zone.

Table 2: Comparative Cost Effectiveness
($ incremental cost / kBtu/ft^{2}yr energy savings)

	Climate Zone		
Improvement	**3**	**10**	**12**
Duct sealing	*83*	*41*	*34*
Insulation	435	280	521
Window U-values	223	151	162
Window SC	n/a	169	266
Roller Shades	n/a	48	42

A/C SEER	816	263	130
Furnace AFUE	208	101	132
Duct insulation	436	202	177
Water heater EF	185	185	185

Details of this analysis are provided in Attachment C. Detailed information includes the energy savings, incremental cost, and cost/benefit for each of the forty-one features analyzed in all three climate zones.

Duct Sealing Cost-Effectiveness

The portion of the suggested procedures that are the best understood and easiest to implement, and that have the greatest effect on energy use are those that affect duct air leakage. A reasonable method to demonstrate their cost effectiveness is a calculation of simple pay back. Using the annual cost savings of $63 for a 12 percent savings from tight ducts alone, the average estimated costs from the survey of $214 to fabricate and install the tight ducts and $131 to test the ducts for leaks (total incremental cost $345), the simple pay back for these improved ducts is 5.5 years. The cost estimates from the survey are likely conservative (high), and with experience and competition, the industry will likely find that the marginal cost of improved fabrication, installation, and testing the ducts is closer to $250. If this turns out to be the case, the simple pay back for duct sealing alone falls to 4 years, without any downsizing or additional savings from improved cooling coil efficiency.

If the industry accepts that the HVAC systems can be downsized because the ducts are not losing capacity through leakage, an additional three percent energy savings can be obtained, as well as a cost savings. The air conditioner and air handler downsizing likely from tight ducts is estimated at approximately one-half ton in a typical California home with air conditioning (15 percent savings from a 3 to 3.5 ton air conditioner), which would produce a cost savings of approximately $100. The combination of sealing and downsizing due to sealing increases the potential energy savings to 15 percent or $79 annual savings. The associated cost drops to $150 ($250 for sealing minus $100 cost savings from downsizing), producing a simple payback of 1.9 years.

If the experimental aerosol-based sealing technique invented and developed by LBNL proves successful, and our cost estimate of $100 to $150 proves to be accurate, then the simple pay back for the 12 percent energy savings from duct sealing is 1.6 - 2.4 years, without downsizing or other effects. If this technique is successful, it should reliably produce total system leakage of 50-60 cfm at 50 Pa (or 0.03 times floor area in ft^2), increasing the savings by 24 percent and decreasing the payback by 20 percent.

Combined Duct Sealing and System Design Cost-Effectiveness

The survey results clearly indicated that the majority of the California HVAC subcontractors currently do not use procedures such as the ACCA Manual J, D, and S to size ducts and equipment. If the industry can more broadly adopt these procedures, air flow across the air conditioner coil will be improved producing a 6 percent to 10 percent increase in energy efficiency. This will be accompanied by a 10 percent decrease in air conditioner size, producing a $60 cost savings. The energy savings from duct sealing and the resulting downsizing coupled with that from improved air flow across the coil due to improved design and construction, increase the annual savings for the typical house to $101 (15 percent heating savings, 23 percent cooling savings). Assuming that the industry has moved to the lower $250 cost for sealing and testing, that the cost of the ACCA calculations is amortized over 25 homes for a cost of $10 per home, and that there is cost savings from downsizing due to sealing ($100, see previous section) and due to improved coil air flow ($60), the total cost is $100 and the simple pay back improves to 1 year. In addition, if the ducts were sealed and tested with the aerosol technique, with downsizing the there is an immediate cost savings.

A different method to view the value of the energy savings is using a present value analysis of the future cost savings, such as a life cycle value (LCV) calculation. The life cycle chosen could range from 15 years (representing a short life for an HVAC system) to 25 years or more (representing the duration of the mortgage). The following table summarizes the Title 24 estimated energy and energy-cost savings resulting from tight ducts, demonstrating the considerable value of the discounted future savings.

Table 3: Cost Savings from Improved Ducts

Duct sealing only (12% heating & cooling savings)

	Therm	kWh	Total	Net Present Value
saved	38	239		($250 cost est.)
annual value	$30	$33	$63	-$187 (first year)
15yr LCV	$358	$409	$768	$518
20yr LCV	$443	$508	$951	$701
25yr LCV	$516	$594	$1,109	$959

Sealing and downsizing due to sealing (15% heating, 15% cooling savings)

	Therm	kWh	Total	Net Present Value
saved	48	299		($150 cost est.)
annual value	$37	$42	$79	-$71 (first year)
15yr LCV	$448	$512	$960	$810
20yr LCV	$555	$635	$1,190	$1,040
25yr LCV	$645	$743	$1,388	$1,238

Sealing and downsizing and improved coil air flow (15% heating, 23% cooling savings)

	Therm	kWh	Total	Net Present Value
saved	48	459		($100 cost est.)
annual value	$37	$64	$101	-$1 (first year)
15yr LCV	$448	$785	$1,233	$1,133
20yr LCV	$555	$973	$1,528	$1,428
25yr LCV	$645	$1,139	$1,784	$1,684

Table 3 notes:

1. The annual value of savings assumes values of $0.14/kWh and $0.78/Therm, which were calculated using 1995 PG&E, SCE, SCG and SDG&E rates averaged using 1990 CEC utility market weightings.
2. The lifecycle value (LCV) assumes the same average values for kWh and Therms and a 3.2% annual inflation and 3.0% real discount rate. If the annual inflation rate is increased to 5.0% and real discount rate increased to 4.0%, the LCVs are extended by about 5 years.

Section 5:Strategies for implementation of suggested procedures

There are several methods that could be used to implement the procedures for improved duct systems that were developed under this project. A basic tenet of the recommended strategy is that a simple, energy-code (Title 24) based strategy will not result in rapid market transformation from current practices to the proposed practices. While Title 24 has been very effective in increasing the energy efficiency of California housing, its major successes have been limited to those that are easily and quickly inspected by builders and building officials.

As discussed in Section 3, some of the duct leakage problems that exist today could be resolved by close adherence to the requirements of the UMC. However, these requirements are not easily inspected and discrepancies often go without being inspected and/or they are not noticed. The only certain method to assure proper HVAC system performance is to have the systems tested. Testing could be done by building officials, but it is not likely that they could afford to staff such a requirement, even on a limited basis. Therefore, some alternate method needs to be devised that will result in better designs, use of better materials, improved installations, and testing of the installation. This alternate method needs to both encourage these improved practices, and compensate builders for additional costs that will occur during market transformation.

Such an approach has been successfully employed by two California utilities through demand-side management (DSM) programs, which provided incentives that covered the incremental cost of the improvements and testing, and provided marketing support for participants. While this might have been an effective implementation pathway, these programs have been eliminated or severely curtailed and do not provide a likely method for the near future. Thus some alternate strategy that has similar components is required.

Toward this end, a market-driven strategy is recommended that establishes value in the market for improved HVAC systems. It includes code-based elements for inspectable materials and market-based credits for improved design and installation. This strategy combines additions to Title 24 mandatory features for duct-connection materials, changes in Title 24 assumptions to support credit for improved HVAC systems, changes in home energy rating system (HERS) requirements to include diagnostics, and adoption of energy efficiency mortgages (EEMs) to demonstrate value and help finance a market transformation. The steps in implementing this strategy are:

Immediately:

1. Fix HERS reference house duct efficiency at 72%,
2. Adopt HERS testing protocols for duct testing,
3. Permit the HERS proposed house duct efficiency to be increased if prescribed tests are performed and criteria passed: 81% heating and cooling if ducts are adequately sealed, (12% savings from sealing only); 81% heating and 87% cooling if have adequate air flow across the cooling coil (additional 8% cooling savings).
4. Encourage energy efficiency mortgages (EEMs) that will provide market value for improved HVAC systems and cover the incremental cost to improve them.

In the next version of Title 24:

1. Change the default Title 24 duct efficiency to 72%,
2. Add duct-closure material requirements to Mandatory Measures,
3. Add procedures to obtain credit for installation of improved HVAC systems.

Once a criterion residential new construction market penetration has been achieved:

1. Change the default Title 24 duct efficiency to an appropriate figure based on the then current state-of-the-art,
2. Update the Mandatory Measures as appropriate to reflect use of key duct and duct-closure materials.

Each element of this strategy is described and discussed in the following sections.

IMMEDIATE ISSUES:

Changes to California Home Energy Ratings Requirements

Consumers would demand better HVAC systems if they understood how poorly typical ducts currently perform and how much better they could be. One good way to improve the public understanding of duct issues is through home energy ratings that include diagnostic testing of the HVAC system as described in the proposed procedures. Such ratings of both new and existing homes will help educate the public, provided that the ratings contain results of HVAC diagnostics or identify that HVAC improvements would be cost-effective.

California HERS with incorporation of performance diagnostics provides an immediate mechanism for consumers to identify and quantify the quality of the HVAC system. HERS ratings that include duct diagnostics will produce a significantly lower rating for a home with leaky (typical) ducts than for a home with tight ducts. In addition, sealing the ducts should be one of the most cost-effective, and therefore highest priority changes to the home.

The largest HERS organization in California, CHEERS, is currently piloting the voluntary addition of home diagnostics to its ratings. Some raters have been trained in testing procedures that include duct diagnostics. These are valuable to both new and existing homes, and typically should result in duct improvements listed as a cost-effective option. The recurrence of this option, and the industry response that it should evoke, could, over time, drive new home builders to anticipate consumers' requests for tight ducts by incorporating tight ducts into all of their homes.

For California HERS to encourage tight duct systems, the reference house needs to assume typical, leaky ducts. For new construction, our best estimate of the mean efficiency value is approximately 72 percent (with considerable variation, see CEC, 1995, Jump, et. al., 1996), which can be improved by 12 percent (to 81 percent efficient) when sealed to leak a cfm value equal to less than 0.07 times the conditioned floor area (in sq. ft., as specified in the proposed procedures), and an additional eight percent for cooling (to 87 percent efficient) when the currently restricted air flow across the coil is increased to approximately 400 cfm per ton. Our estimated average 72 percent efficiency value is comparable to the 71 percent overall efficiency measured in ducts in crawl spaces in the Pacific Northwest (Olson, et. al., 1994). A similar study in California measured delivery efficiency of 64 percent ±10 percent for attic duct systems (Jump, et. al., 1996), as compared to 56 percent delivery efficiency measured in the Pacific Northwest homes with crawl-space duct systems. Delivery efficiency is the ratio between the heating or cooling delivered at the registers to the heating or cooling supplied by the HVAC. It does not include any recovery of lost heat or cool from the buffer zones to which it was lost. These delivery efficiencies compare reasonably well considering both the large variability among measured delivery efficiencies, and that recovery in efficiency due to recovery from the buffer zones is greater for the crawl-space ducts systems as compared to the attic duct systems. HERS ratings should assume the low efficiency (72 percent) unless they are tested to leak no more than the criterion amount. Such diagnostic test procedures are outlined in the proposed procedures, and need to be incorporated into California HERS certification protocols and procedures. Coordination is also required between the CEC, CHEERS and other California

HERS organizations to ensure that California home energy ratings are quickly capable of rating HVAC systems in homes and that they are consistent in how that is done. There is currently an ASHRAE Standard under development that should provide a long-term defensible basis for the efficiency estimation procedures, including a protocol for dealing with houses that have yet to be built (ASHRAE 1996).

The California Energy Commission can also help promulgate this by encouraging or requiring all home energy rating systems operating in California to be able to provide home diagnostics and to integrate the results into suggested upgrades. While it may not be appropriate to require all ratings to have diagnostics (due to the likely increased cost of a diagnostic rating), it would be beneficial to have all raters trained and competent in such diagnostics.

Consumers will need to become more aware of HERS ratings, and know to ask for them. Because they are already aware of other consumer labels, such as on cars and certain appliances, it should not be difficult for them to grasp the importance and information contained in a home energy rating – they just need to know to ask for one. This sort of public awareness could be developed with assistance from the CEC.

Energy Efficiency Mortgages (EEM)

HERS ratings alone will not promulgate improved HVAC systems in new construction because of their initial incremental cost. This cost will discourage builders from utilizing HERS ratings unless the ratings have a demonstrable value. For improved duct systems to be installed in new homes, a mechanism is required to pay the initial costs of materials, installation, and testing. Both of these issues can be resolved quickly through improved EEM products.

HUD recently announced a new EEM lending guideline for new construction. Previously, the only EEM was a two percent stretch in qualifying ratios, which has had no impact on energy efficiency features in new construction because all homes that comply with Title 24 (and the MEC) are eligible, and most lenders are already stretching two percent or more to qualify borrowers for new California homes. The new lending guidelines allow the borrower, after qualifying for the home, to borrow up to an additional $8,000 or five percent of the mortgage amount (whichever is less) to cover the cost of additional energy features that are cost-effective over the life of the loan, without any additional qualification. Duct improvements easily fit within these guidelines, and, as demonstrated in Section 4, improving duct integrity is one of the most cost-effective features available.

To obtain this additional financing, a home energy rating or similar certification is required to estimate the energy and cost savings due to duct sealing, and to certify that the improvement is cost effective. Thus, if the California HERS requirements include the capability for HVAC system diagnostics, it can provide the certification mechanism required for this mortgage. The combination of HERS and EEMs form the basis of a funding mechanism that can help produce consumer pull-through of high efficiency duct systems.

If utilized, these new EEM loans could be used immediately to sell "more home" (one with a superior HVAC system, for instance) to the buyer for no additional monthly cost to the consumer – i.e., the consumer’s combined monthly mortgage and utility bills are less than they would be for the non-EEM qualifying home. The CEC could help educate builders that tight ducts are the most cost-effective additional feature to add to their homes and that it will improve the comfort (and possibly sales) of the homes, without changing the listing price of the homes if any incremental construction cost is wrapped into this new EEM, keeping them affordable.

Builders will find that they can add value, comfort, and salability to their homes through improved HVAC systems funded through EEMs. As builders become aware of these mortgages, they will quickly grasp that they can add features to their homes without loosing potential buyers due to increased prices. The buyer need only qualify for the basic home; by using the EEM he or she can still buy the improved home because the cost of the improvement is counterbalanced by the energy-bill savings. The building industry needs to be educated in the use of these mortgages (as has begun under an existing CEC contract), and the industry also needs to appreciate the value and cost-effectiveness of the improved HVAC system as a primary enhancement, as can be demonstrated by a HERS rating with integrated diagnostics.

For this strategy to work, the HVAC subcontractors need to be trained in the proper installation of HVAC systems to achieve improved system performance. This project developed procedures that will result in an improved system cost-effectively. The combination of HVAC subcontractor training in these procedures, linked with the builder motivation through EEMs and quality assurance certification through the HERS with diagnostics, could result in rapid promulgation of improved HVAC systems.

Title 24 Assumptions and Mandatory Measures

At the next opportunity, the Title 24 default assumption for residential new construction duct efficiency should be set equal to the HERS reference house duct efficiency – approximately 72 percent. This should be done so that Title 24, HERS, and the market are aligned, and to provide the potential for credit to builders who build homes with more energy-efficient duct systems than is current practice. However, as this would allow builders to trade off other energy efficiency features against duct sealing, it is important to assure that the duct improvements have adequate longevity. Thus, any credit for improving duct efficiency must include a requirement with respect to the longevity of the sealing materials. Our recommendation is that this requirement on sealing materials become a mandatory measure (i.e., independent of whether a high-efficiency credit is being taken).

For tight ducts to be acceptably effective, proper materials need to be used at duct connections to provide good longevity. Currently, the most common material used in duct connections is duct tape, usually inexpensive duct tape. While there have not been definitive studies comparing longevity of different types of duct tapes and mastics, there is considerable field evidence that inexpensive cloth duct-tape dries out and within a few years fails, but that mastic lasts as long as the flexduct. There are other duct tapes being used that are claimed to last longer than the common tapes; testing and rating of these tapes for adhesive properties and longevity would be very useful. A first step has come from UL who has drafted a standard for duct tapes (UL 181 B) that will help rate tapes for their adhesive properties. This UL Standard 181 B is proposed in the procedures as a requirement for any tape closures of duct connections, and as such should become a Mandatory Measure within Title 24.

In the longer term, once improved duct systems are relatively common within the marketplace, we recommend moving the required (or standard house) efficiency back up to 81 percent to 85 percent, which would reflect the fact that improved duct installations had become common practice (and that the marginal cost should be minimal - see chart on pages 3-4). The question that remains is how to determine when we have transformed the marketplace to this point, or more specifically, when the short-term implementation strategy has become successful.

At the most basic level, this implementation strategy should be considered successful once a criterion market segment has changed their design and installation practices to result in efficient

HVAC systems. Some discussion of market saturation that is beyond the scope of this report needs to occur to determine the criterion market saturation. Nonetheless, when significant market saturation occurs, the strategy should be considered successful, and what now needs to be considered as added value should then become a requirement.

By the time significant market penetration has occurred, competition and new methods will have decreased the cost of these higher efficiency HVAC systems. In addition, the industry will have learned how to cost-effectively test and certify that their systems are as efficient as they need to be to qualify for EEMs. At that point, which is likely to occur before two Title 24 code-cycle changes, Title 24 should be changed to require the more efficient HVAC systems that the industry will have embraced. That change in Title 24 should increase the required efficiency to be whatever that significant market segment has achieved (expected to be approximately 85 percent), it should include a reasonable method to ensure that the ducts are as efficient as specified (some kind of testing), and should update the prescriptive requirements for materials that ensure the longevity of the improved system.

Section 6:Discussion and future directions

The analysis presented in this report of how to improve the performance of duct systems in California houses has focused on two basic technical issues: 1) reducing duct leakage and 2) using current industry tools to improve designs, including the impacts on equipment sizing and the flows across air conditioner coils. In addition, several shortcomings of those industry tools were uncovered. However, there are a number of other technical and implementation improvements that could and should be pursued as means of improving the quality of residential HVAC installations. Although detailed analyses of these options are beyond the scope of this project, they need to be mentioned and discussed briefly.

Duct-system efficiency is a function of duct leakage, insulation level, duct surface area, duct location, the thermal conditions surrounding the ducts, and the impact of the duct system on equipment efficiency. The protocols developed in this project address the first and the last of these sources of inefficiency. There are additional practical options that could be employed to improve duct efficiency above the current 72 percent by addressing the other sources of inefficiency.

Increasing duct insulation levels can be considered an alternative or compliment to reducing duct leakage. The typical duct insulation level in California is R-4.2; increased duct insulation levels of R-6 and R-8 are readily available, and R-11 is also available. A recent study by LBNL analyzed the cost effectiveness of increasing duct insulation levels in new construction (Treidler et al. 1996). The most pertinent result from that study was the finding that increasing supply-duct insulation up to R-8 was cost-effective for attic ductwork.

Another way to decrease conduction losses from ductwork is to install the duct system in conditioned spaces. This type of a change can produce a dramatic increase in duct efficiency (resulting in efficiencies above 87 percent) because any losses are to the conditioned space and are therefore not considered losses. There are however four issues that need to be dealt with in terms of implementing such an option: 1) there needs to be a way to assure that the ducts are truly located in conditioned space (such as the house-pressure duct leakage diagnostic in the CHEERS rating tool and ASHRAE 152P), 2) the change in construction practice is much more significant as compared to sealing ductwork or adding insulation, 3) the current credit for conditioned-space ductwork within the Title 24 regulations effectively requires the use of a condensing furnace (Jump 1995), and 4) there still needs to be some requirement for high-longevity duct sealing, because if leaks remain, then the conditioned air does not end up where it is supposed to go, and leaks hidden behind walls and in between floors are much harder to access. Conditioned-space ductwork without leak sealing and adequate insulation results in a home that does not perform as designed, and is not as comfortable as it should be.

Duct surface area could also be decreased to improve duct efficiency. Field measurements in California houses has shown that actual duct surface area are approximately twice what is assumed in the current Title 24 compliance tool (CEC 1995). Those same field studies showed dramatic variations in duct surface area, the smallest system having a surface area equal to approximately six percent of the house floor area, and the largest system having a surface area of 65 percent of the house floor area. Surface areas could be systematically reduced by improving the placement of the HVAC system, changing placement of registers, and other design changes. Specifically, as envelopes and windows have improved, the need to install registers under windows on exterior walls may no longer exist. The ability to provide credit for such changes would require some research to determine typical designs, average surface areas, and reasonable metrics to determine credit. Some reasonable method of field inspection and credit should also be developed to ensure that the installation does, in fact, have a decreased surface area and the resultant decreased conductive losses.

Finally, conductive losses can also be decreased by reducing the temperature difference between the conditioned air inside the ducts and their surroundings (typically attic conditions). This could be achieved for cooling through the use of radiant barriers above the attic air space. Recent studies demonstrate considerable decreases in attic temperature with the use of attic radiant barriers, and resultant decreased duct conductive losses (Hageman and Modera, 1996). Reasonable credits would need to be determined for such installations.

Alternative Title-24 Strategies

Lowering the Title 24 default assumption to 72 percent may not be immediately acceptable to some energy-code stakeholders because it may be seen as giving away energy efficiency that has been believed to be inherent in new construction. However, changing this assumption to reflect reality is what will allow Title 24 to work with other market drivers, such as EEMs to provide value for improved duct systems. The goal of the recommended strategy is to achieve real energy savings from improved HVAC systems; if Title 24 is not adjusted to reflect reality, then it denies providing builders and consumers any real value for the cost of improved HVAC systems.

It might be argued that we now understand that duct systems are not as efficient as previously assumed in Title 24, and that the energy code should simply mandate the increased efficiency by holding the standard house assumption at its current level. The basic problem with this argument is that there is currently no workable mechanism within Title 24 to enforce such a mandate. Specifically, the only effective way to ensure that the duct system is working efficiently is to test it. Testing will not be done by building officials; they do not have the staff, expertise, or budget. It is also not realistic to assume that testing could be immediately embraced by the building or HVAC industries if they are required to certify duct efficiency. The problem is that there are too few people who are qualified to test duct leakage, and therefore the most likely outcome is that the leakage certification will become meaningless, as most contractors will not know what to do, and there will be no mechanism for training them or policing their performance. An example of the problems associated with mandating duct testing in the short term can be taken from the insulation certificate. Insulation subcontractors are currently required to certify the installed insulation on a form. A recent study of homes found that 100 percent of the homes were certified to have the correct insulation, but that an independent inspection determined that 70 percent of the homes had significantly less insulation than was certified (CEC, 1995-2). For the industry to change in the short term, there needs to be a value associated with that change. That value can come from EEMs and HERS ratings. Title 24 could then capitalize on the change at a future date.

An argument can also be made that some intermediate value should be set for Title 24 duct efficiency that is between the current typical efficiency and the current assumed efficiency – as a compromise between mandates and voluntary programs. Such a strategy serves to decrease the value of change to the builder or contractor by reducing the value that can be obtained from HERs ratings for homes with improved ducts for EEMs. For EEMs to be effective in moving the new construction market from its current practices to efficient duct systems, the change needs to be cost-effective. An intermediate duct-efficiency assumption in Title 24, which if adopted should be reflected in the California HERs guidelines, would diminish the value, sending the wrong message to the industry and potentially making such a change not cost-effective. Care

need be taken to ensure that HERs assumptions and Title 24 assumptions become aligned and that they provide sufficient value to improved practices so that they are cost-effective.
Another alternative strategy would be to keep the Title 24 standard house at the current level of duct efficiency, or at some intermediate efficiency level, and to allow multiple alternative means for the builder and contractor to achieve the mandated efficiency level. These alternative means are likely to have a one-to-one correspondence with the other technical improvements discussed in this section. This strategy is attractive in many ways, as it would allow the most flexibility for compliance, while sending the right signals with respect to the performance of duct systems. There are however two problems with this strategy: 1) it requires more detailed analyses of each of the alternative compliance routes, and 2) it diminishes the market forces for making duct sealing an integral part of the residential HVAC industry. Nonetheless, we would support this strategy in the longer term (i.e., once duct sealing has reached critical mass), as the proposed ASHRAE Standard 152P should take much of the technical burden for evaluating these alternatives off of the just the state of California.

Draft Evaluation Guidelines

If a program is put in place to implement improved HVAC systems, it will likely need to be evaluated as to its effectiveness. In such an evaluation, there are several issues that need to be addressed. The major issues and the corresponding variables to be measured are:

Issue	Variable
Has duct leakage decreased?	Duct leakage
Are systems sized correctly?	System size
Are ducts sized correctly?	Duct size, air flow
What energy savings have been achieved?	Energy use
What has been the cost to the builder; to the homeowner?	Costs
What is the market penetration of improved HVAC systems?	Market penetration
Has comfort improved?	Consumer surveys

To evaluate program effectiveness, additional research will be required, both to determine the current basis, as well as to track effectiveness. How this is done is obviously highly dependent on the chosen implementation strategy. This discussion of evaluation procedures assumes that the strategy suggested in Section 5 is followed. While there is a considerable amount of data available for some of the required baseline information, other data will need to be collected; all data for evaluation of improvements will require new research. The following table lists the potential sources of information for each of the key variables, both for baseline and improvements, as well as the estimated status of baseline information (other sources could be developed – this list is not intended to be comprehensive; formal research proposals will likely be required to obtain most of this information and to integrate it into a final opinion):

Variable	Sources	Baseline Status
Duct leakage	LBNL, CHEERS, Utilities	Adequate
Sealant longevity	LBNL	Research required
System size	CHEERS	Research required
Duct size	LBNL	Research required
Air flow	LBNL, CHEERS	Research required
Exit air temp	LBNL, CHEERS	Research required
Energy use	CEC, CHEERS, Utilities	Adequate
Costs	LBNL, CEC	Adequate
Market penetration	CHEERS, CBIA	(assumed minimal)

When an evaluation plan is developed, target values for each variable must be developed. Many of these targets are included in the procedures developed in this project, which are discussed in Section 1 and included as Attachment A. For instance, the procedures provide test criteria for duct leakage, coil air flow, supply and return air flows, and system sizing. If these are promulgated as appropriate, then the evaluation need only track whether they are being obtained. Such tracking could be achieved as part of a large research project where all aspects are evaluated by a single contractor, or a smaller project could track information available from the participating groups. For example, CHEERS may be an integral part of the implementation plan, providing duct leakage and airflow testing so that the builder can qualify for the EEMs. If so, CHEERS could provide some of the information required, in this example, the duct leakage values, system size information, air flow results, energy use estimates, and program participation estimates. This would likely involve a research contract with CHEERS (in this example), as well as some oversight group to provide third-party evaluation and integration, but would likely be a more cost-effective method to obtain evaluation information than to have it done entirely by a non-participating external organization.

SECTION 7: Conclusion

This study has resulted in a set of buildable, cost-effective procedures for improved design, fabrication, installation and testing of residential HVAC systems that have been reviewed by a number of builders, HVAC subcontractors, as well as staff from the CEC, NRDC, and CBIA. An analysis of the cost of implementing these procedures and the resultant energy savings has shown that, in the short term there will be some cost to the builder, but that it will result in a cost-effective improvement to the consumer. In the longer term, as builders and HVAC subcontractors improve their techniques, the costs can drop to zero, or even provide some savings in construction costs. In addition, as these implementation improvements occur, there are additional savings to the consumer, making this change in construction techniques even more cost-effective to the consumer.

This project has also resulted in the development of an implementation strategy that utilizes existing market vehicles, primarily home energy ratings with integrated duct diagnostics and energy efficiency mortgages, to produce initial market value and acceptance of improved HVAC systems. This would be followed in the next Title 24 code change with alignment of the Title 24 assumptions regarding duct system efficiency with the California HERs assumptions. The authors feel that this change will reinforce the market value of improved duct systems and allow the driving forces of HERs coupled with EEMs to continue. After significant market penetration has been achieved, we suggest that the Title 24 assumptions be raised to a higher efficiency, recognizing that construction practices have changed.

The final conclusion is that this project has also identified a number of alternative or supplementary means for improving the quality, energy efficiency and performance of residential duct systems that should also prove to be cost-effective. However, the analysis required prior to including those options into the proposed implementation plan was beyond the scope of this project. The options identified included: 1) practical encouragement of ductwork in conditioned spaces, 2) added duct insulation, 3) reducing duct surface by means of better layouts and register locations, and 4) reducing attic temperatures with radiant barriers above the ductwork.

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ATTACHMENT A
PROCEDURES FOR HVAC SYSTEM DESIGN AND INSTALLATION

The goal for a HVAC system is to provide proper airflow, heating, and cooling to each room. This page sets out key criteria that describe a quality system, and key design and installation considerations that should be met to achieve this goal. The pages following contain more detailed information on design, fabrication, installation, and performance testing.

Criteria for a Quality HVAC System

An HVAC system should:

1. Be properly sized to provide correct air flow, and meet room-by-room calculated heating and cooling loads;
2. Be installed so that the static air pressure drop across the handler is within manufacturer and design specifications;
3. Have sealed supply ductwork that will provide proper airflow;
4. Be installed with a return system sized to provide correct return airflow;
5. Have sealed return ductwork that will provide proper airflow to the fan, and avoid air entering the HVAC system from polluted zones (e.g., fumes from autos and stored chemicals, and attic particulates);
6. Have balanced airflows between supply and return systems to maintain neutral pressure in the home;
7. Minimize duct air temperature gain or loss between the air handler and room registers, and between return registers and the air handler;
8. Be properly charged with refrigerant;
9. Have proper burner operation and proper draft.

Procedures to Design and Install an Air Distribution System

The following steps should be followed in the design and installation of the HVAC system to ensure efficiency and comfort (for details, see Appendix A):

1. Determine room-by-room loads and air-flows using ACCA Manual J calculation procedures (or substantially equivalent);
2. Layout duct system on floor plan, accounting for the direction of joists, roof hips, fire-walls, and other potential obstructions. Determine register locations and types, duct lengths, and connections required to produce layout given construction constraints;
3. Size duct system according to ACCA Manual D calculation procedures (or substantially equivalent);
4. Size HVAC equipment to sensible load using ACCA Manual S procedures (or substantially equivalent);
5. Install equipment and ducts according to design specifications, using installation requirements and procedures from the Uniform Mechanical Code, the Air Diffusion Council, SMACNA, California Residential Energy Efficiency Standards (Title 24), and manufacturers' specifications; Using these procedures and those in Appendix A, the duct system should be substantially air tight;
6. Charge the system appropriately, and verify charge with the evaporator superheat method or subcooling method (or substantially equivalent);
7. Check for proper furnace burner operation and fire-box drafting;
8. Test the system to ensure that it performs properly by determining (1) that the system is properly sized, (2) it does not leak substantially, and has (3) proper room and return air flows, and proper plenum static pressures. (Procedures are detailed in Appendix A.)

APPENDIX A

Recommended Details for an HVAC System: Materials, Fabrication, Design, Installation, and Performance Testing

MINIMUM MATERIALS SPECIFICATIONS

The following are minimum materials specifications recommended to achieve a substantially tight installation that will last:

<u>All Materials</u>

- Shall have a minimum performance temperature ratings per UL181 (ducts), UL181A (closure systems for rigid fiberglass ducts), UL181B (closure systems for flexible ducts) and / or UL 181BM (mastic);
- Shall have a flame spread rating of no more than 25 and a maximum smoke developed rating of 50 (ASTM E 84);

<u>Factory-Fabricated Duct Systems</u>

- All factory-fabricated duct systems shall include UL 181 listed ducts with approved closure systems including collars, connections and splices;
- All pressure-sensitive and heat-activated tapes used in the manufacture of rigid fiberglass ducts shall be UL 181A listed;
- All pressure-sensitive tapes and mastics used in the manufacture of flexible ducts shall be UL 181B (tape) or UL 181BM (mastic) listed.

<u>Field-Fabricated Duct Systems</u>

- Ducts:
  - Factory-made ducts for field-fabricated duct systems shall be UL 181 listed.
- Mastic sealants and mesh:
  - -Sealants shall be UL 181BM listed, non-toxic, and water resistant;
  - Sealants for interior applications shall pass ASTM tests C 731 (extrudability after aging) and D 2202 (slump test on vertical surfaces);
  - Sealants and meshes shall be rated for exterior use;
  - Sealants for exterior applications shall pass ASTM tests C 731, C 732 (artificial weathering test), and D 2202.
- Pressure-sensitive tapes:
  - Cloth-backed, rubber-adhesive tapes (typical duct tape) shall not be used even if UL 181B rated;
  - Tape used for flexduct shall be UL 181B listed;
  - Tape used for duct board shall be UL 181A listed and so indicated with a UL 181A mark.
- Drawbands:
  - Shall be either stainless-steel worm-drive hose clamps or UV-resistant nylon duct ties;

- Shall have a minimum performance temperature rating of 165 degrees Fahrenheit (continuous, per UL 181A-type test) and a minimum tensile strength rating of 50 pounds;
- Shall be tightened as recommended by the manufacturer with an adjustable tensioning tool.

DESIGN, FABRICATION, AND INSTALLATION

The following are design, fabrication, and installation guidelines that, if carefully followed, will provide a duct installation that is substantially airtight and that will provide proper airflow to each room of the house:

General Issues

- • Ducts, plenums, and fittings should be constructed of galvanized metal, duct board, or flexible duct. Building cavities may not be used as a duct or plenum without a sealed duct board or metal liner.
- • The air handler box should be airtight;
- • Air filters should be easily accessible for replacement, and evaporator coils should be easily accessible for cleaning;
- • Ducts should be configured and supported so as to prevent use of excess material, prevent dislocation or damage, and prevent constriction of ducts below their rated diameter;
- • Flexible duct bends should not be made across sharp corners or have incidental contact with metal fixtures, pipes, or conduits that can compress or damage the ductwork;
- • Flexible ducts should not have bends that exceed 90º unless specified and accounted for in the design;
- • Sheet metal collars and sleeves should be beaded to hold drawbands.

DESIGN HVAC SYSTEM

<u>Loads and CFM Calculation</u>

- ACCA Manual J Load Calculation or equivalent required;
- Calculate heat loss and heat gain for each room;
- Total room loads to determine system requirements.

<u>Lay Out Air Distribution System</u>

- Lay out duct system on floor plan and determine register positions and duct paths to optimize room air circulation and minimize actual duct length as well as equivalent lengths of fittings, bends, etc.;
- Duct paths must account for locations and directions of joists, roof hips, fire-walls, and other potential obstructions;
- Duct paths must be planned to avoid sharp turns of flexduct that will kink the duct.

<u>Size Air Distribution System</u>

- ACCA Manual D Duct Design or equivalent required;
- Calculate correct cfm for each room and total for building for both supply and return;
- Size ducts according to Manual J loads, Manual D air flows, and final layout on plans;
- Choose registers to optimize air distribution and duct static pressure;
- Size and locate returns to optimize airflow per ACCA Manual T;

- For return-filter grills, calculate minimum return filter area per ACCA Manual T.

Select System

- • ACCA Manual S Residential Equipment Selection or equivalent required;
- • From Manual J loads and Manual D cfm, determine appropriate equipment;
- • Equipment should be sized to sensible loads;
- • Equipment sensible capacity should not be more than 15 percent larger than the total sensible design load (as specified in Manual S).

FABRICATE AND INSTALL AN AIRTIGHT DUCT SYSTEM

All Duct Types

- All joints and seams of duct systems and their components should be sealed with mastic, mastic and embedded mesh, or pressure-sensitive tape approved for use by the duct manufacturer and meeting UL181 specifications, excluding cloth-backed rubber-adhesive tapes ("approved tape"); cloth-backed rubber-adhesive tapes shall not be used to attach or seal ducts.
- Junctions of collars to distribution boxes and plenums should be sealed with mastic;
- All sealants should be used in strict accordance with manufacturer's installation instructions and within sealants moisture and temperature limitations;
- All tapes used as part of duct system installation should be applied to clean, dry surfaces and sealed with manufacturer's recommended amount of pressure or heat. If oil is present, taped surfaces should be prepared with a cleaner / degreaser prior to application;
- All register boxes should be sealed to the drywall or floor with caulking or mastic.

Flexible Ducts

- Flexible ducts should be joined by a metal sleeve, collar, coupling, or coupling system. At least 2 inches of the beaded sleeve, collar, or coupling must extend into the inner core while allowing a 1 inch attachment area on the sleeve, collar, or coupling for the application of tape;
- The inner core should be mechanically fastened to all fittings, preferably using drawbands installed directly over the inner core and beaded fitting. If beaded sleeves and collars are not used, then the inner core should be fastened to the fitting using #8 screws equally spaced around the diameter of the duct, and installed to capture the wire coil of the inner liner (3 screws for ducts up to 12" diameter, and 5 screws for ducts over 12" diameter);
- The inner core should be sealed to the fitting with mastic or approved tape;
- Tape used for sealing the inner core should be applied with at least 1 inch of tape on the duct lining, 1 inch of tape on the fitting of flange, and wrapped at least three times;
- The outer sleeve (vapor barrier) should be sealed at connections with a drawband, and either mastic or three wraps of approved tape;
- The vapor barrier should be complete. All holes, rips, and seams must be sealed with mastic or approved tape.

Metal Ducts and Plenums

- Metal-to-metal connections should be cleaned and sealed in accordance with manufacturer's specifications;
- Openings greater than 1/16 inch should be sealed with mastic and mesh or approved tape;
- Openings less than 1/16 inch should be sealed with mastic or approved tape;
- Special attention should be paid to collar connections to duct-board and/or sheet metal; seal around the connection with mastic;
- Connections between collars and distribution boxes should be sealed with mastic;
- At least three equally-spaced #8 screws should be used to mechanically fasten round ducts (3 screws for ducts up to 12" diameter, and 5 screws for ducts over 12" diameter);
- Crimp joints should have a contact lap of at least 1½ inches;
- Square or rectangular ducts should be mechanically fastened with at least one screw per side.

<u>Duct Board</u>

- • Duct board connections should be sealed with adhesive, mastic, or approved tape in accordance with manufacturer's specifications.

<u>Duct Support</u>

- Supports should be installed per manufacturer's specifications and UMC requirements;
- Supports for flexible ducts should be spaced at no more than 4-foot intervals;
- Flexible ducts should be supported by strapping having a minimum width of 1½ inches at all contact points with the duct;
- Supports should not constrict the inner liner of the duct;
- Flexible ducts should have maximum of ½ inch sag per foot between supports;
- Flexible ducts may rest on ceiling joists or truss supports as long as they lie flat and are supported at no more than 4 foot intervals.

<u>Boots</u>

- After mechanically attaching the register boot to floor, wall, or ceiling, all openings between the boot and floor, wall, or ceiling should be sealed with caulk, mastic, or butyl-adhesive tape.

<u>Seal Air Handler</u>

- • Openings greater than 1/16 inch should be sealed with mastic and mesh, or butyl adhesive tape;
- Openings less than 1/16 inch should be sealed with mastic or UL 181A listed tape;
- Unsealed access doors should be sealed with UL 181A listed tape.

CHECK REFRIGERANT CHARGE

- For systems with fixed metering devices use evaporator superheat method:
  - indoor coil airflow must be <u>greater</u> than 350 cfm/ton;
  - refrigerant system evacuation must be complete (all non-condensables must be removed from the system;

  - in hot, dry climates be cautious to be within range of superheat charging chart or use a different method.
- For systems with thermostatic expansion valves (TXV) use the subcooling method.
- Install an access door for field verification of the TXV.

CHECK COMBUSTION PERFORMANCE

- Check each chamber for correct flame;
- Check for proper drafting.

TEST SYSTEM PERFORMANCE

The following are testing requirements and procedures that must be followed to ensure that the HVAC system has been properly installed. The tests are designed to determine whether:

1. *Room-by-room airflows are correct;*
2. *Total supply is as designed;*
3. *Total return = total supply;*
4. *Ducts, plenum, and air handler are tight;*
5. *Static pressure is correct.*

- Test the system to ensure that it performs properly, by (1) verifying HVAC equipment sizes installed are those specified, (2) measuring duct leakage, and measuring (3) supply and return flows and plenum static pressures:

1. Air conditioner sensible capacity must be no more than 15 percent greater than the calculated sensible load; fan flow must be greater than 350 cfm/ton; check that the correct size air handler is installed.
2. Ensure that the duct system does not leak substantially:
    a. A rough system, including both supply and return but without the air handler, must leak less than 4% of specified fan flow (cfm leakage measured with HVAC system pressurized to 25 Pa);
    b. The finished installation, including supply, return, the air handler and finished registers, must leak less than 6% of measured fan flow or of measured return flow (cfm leakage measured with HVAC system pressurized to 25 Pa);
3. Supply and return air flow, and static pressure requirements: Ensure that supply and return flows are correct, and that the static pressure across the fan is correct:
    a. Measure room-by-room air flows to ensure that each register is within 15 percent of Manual D design air flow, and that the entire supply is within five percent of design;
    b. Measure return airflow to ensure that it is within five percent of the total supply airflow;
    c. Test static pressure drop across the blower to ensure that it is within 0.1 inch water gauge of design and manufacturer specifications.

- Duct leakage can be determined using a pressurization or depressurization technique; for details, California Energy Commission ACM Manual Appendix F, Minneapolis Duct Blaster™ manual, or manuals for other commercially available duct pressurization or depressurization devices;

- Fan flow, supply flow and return flow measurements, see Minneapolis Duct Blaster™ manual (or equivalent); alternatively for supply and return flows, use a calibrated flow hood. Do not use a Pitot tube, or any type of anemometer to determine these airflows;
- Static pressure drop across the fan is measured using static pressure probes in the return plenum and in the supply plenum.

REFERENCES

1991 Uniform Mechanical Code Sections 1002 - 1005 and Appendix A, Standard No. 10-5.

Air Diffusion Council	Flexible Duct Performance & Installation Standards.
ACCA	Air Conditioning Contractors of America, 1515 16th St., NW, Washington, DC 20036, (202) 483-9370
ACCA	Manual J, Seventh Edition, 1986
ACCA	Manual D, New Edition, 1995
ASHRAE	1791 Tullie Circle, N.E., Atlanta, GA 30329, (404)636-8400
ASTM E 84	Test for Surface Burning Characteristics of Building Materials
ASTM C 731	Extrudability After Aging
ASTM C 732	Artificial Weathering Test
ASTM D 2202	Slump Test on Vertical Surfaces
CEC	California Energy Commission, 1516 9th Street, Sacramento, CA 95814-5512, (800) 772-3300
SMACNA Manual	Installation Standards for Residential Heating and Air Conditioning Systems
UL Standard 181	Standard for Factory-Made Air Ducts and Air Connectors
UL Standard 181A	Standard for Closure Systems for Use with Rigid Air Ducts and Air Connectors
UL Standard 181B	Standard for Closure Systems for Use with Flexible Air Ducts
UL Standard 181BM	Standard for Mastic Materials

ATTACHMENT B

PROBLEMS WITH ACCEPTED PRACTICE SIZING METHODS:

Relationship Between Duct System Performance, ACCA Design Procedures, and Installed-System Quality

Background
The Air Conditioning Contractors of America (ACCA) association publishes four manuals related to residential heating and air conditioning that address many of the issues associated with residential duct systems. ACCA Manual J (Load Calculation for Residential Winter and Summer Air Conditioning, Copyright 1986) is the industry-standard design-load calculation procedure for residences. ACCA Manual S (Residential Equipment Selection, 2/92) provides procedures for choosing residential heating and cooling equipment based on the loads calculated with Manual J. ACCA Manual D (Residential Duct Systems, Copyright 1995, 2nd Printing) provides design procedures for residential duct systems, focusing on how to produce the desired air delivery at each register, as well as discussions of the magnitudes and impacts of duct-system inefficiencies. ACCA Manual T (Air Distribution Basics for Residential and Small Commercial Buildings, UPB592-10M) addresses room air motion issues, focusing on the impacts of register/grille location and diffuser performance.

Treatment of Duct Performance in ACCA Manual J

ACCA Manual J addresses residential duct system performance in three ways: 1) it provides room-by-room loads, which are intended to be used to calculate the energy that needs to be transported by the ducts to each room, 2) it provides a table of duct-loss multipliers that are used to calculate the extra design load associated with conduction losses from the ducts, and 3) it provides a table of recommended levels of duct insulation, and states that "All ducts should have their seams sealed with tape".

In calculating the energy load impacts of ducts and room-by-room loads, Manual J makes two fundamental assumptions: 1) that there is no duct leakage, and 2) that the load due duct conduction is independent of the length and design of the ducts. The implication of the first assumption is that the actual load associated with duct losses is in general significantly higher than that assumed in Manual J. The second assumption implies that even if the average conduction losses in the duct-loss multipliers are correct, the calculated room-by-room loads are incorrect due to non-uniform conduction losses.

A significant body of research performed over the past five years in California and other states that install ductwork in attics and crawlspaces demonstrates that duct leakage increases space-conditioning energy use by 15-20 percent on average, even in new construction. This loss needs either to be eliminated, or to be added to the losses associated with conduction gains to obtain correct loads seen by the equipment. Field research has also demonstrated the effective increase in heating and cooling system capacity associated with improving duct performance (Modera and Jump, 1995). Those studies show reduced fractional on-times and increased cycling under the same weather conditions after duct retrofit.

A logical question that arises with respect to these duct leakage losses is why Manual J is not resulting in significantly undersized systems because of the fact that it does not include these duct leakage losses. The reasons for why this is not the case seem to stem principally from the application of Manual J, rather than the manual itself. In general, Manual J leaves quite a bit to the discretion of the user, leaving numerous opportunities for increasing the size of the unit. Some of the common points at which safety margins seem to creep in are:

- The use of the worst house orientation for load calculations,
- The choice of the next size up in the piece of heating / cooling equipment,

- The assumption of 50 percent RH indoor conditions in most manufacturer's capacity data, which is higher than what is found in much of California, and which results in a lower estimated sensible capacity for a piece of equipment as compared to the sensible capacity the equipment would have at a lower indoor humidity level,
- Using a somewhat lower indoor design temperature,
- Using a higher outdoor design condition, such as one percent, or utility-peak outdoor design temperature rather than the 2.5 percent values recommended in Manual J.
- Using the next-highest outdoor-temperature rating point, rather than interpolating manufacturer's capacity data.
- The recommendation of 0-15 percent oversizing of sensible capacity in Manual S.

To be fair, it should also be noted that there are some factors that tend to decrease the size of the equipment chosen with the ACCA procedures, including:

- ARI capacities are normally quoted at 80°F, whereas Manual J requires capacities at 75°F, which will be smaller.

It is very difficult to quantify exactly how much the above trends influence equipment sizing. A contractor survey performed in Florida indicated that there is a large variability in the equipment-sizing practices used by contractors (Home Energy 1995). It is safe to say that there are numerous opportunities for a contractor to increase equipment size within the ACCA procedures so as to maintain the sizing with which they are comfortable. A related study of equipment sizing and ACCA manuals is published in Home Energy magazine (Proctor et al. 1995).

The assumption of constant duct-loss multipliers for all duct sections (or in other words, that duct loads scale with room load, and not with duct design or length) is more of a design-flaw and comfort problem, rather than an energy-use or equipment-sizing problem. Namely, after calculating room-by-room loads including constant duct-loss multipliers, the air flow required for each room is calculated from the loads, the duct system is laid out, and the cross-sectional area of the ductwork is calculated and checked with Manual D based upon the ability of the system to supply the required air flow. This implies that the percentage energy loss from the longest duct run is the same as that from the shortest run. It seems clear that this is not a realistic assumption, however the magnitude of the resulting disparity, based upon field measurements, is striking. Namely, the bedroom closest to the furnace for an R-4 duct system in a Sacramento attic was measured to have 12 percent of the duct energy lost by conduction on the way to the register. The equivalent losses for the master bedroom at the end of the duct run were more than 40 percent (Modera and Jump, 1995). The 12 percent loss is line with the losses that are calculated from the Manual J duct loss multipliers, and the 40 percent loss clearly indicates that the master bedroom duct is most likely undersized. Sure enough, the homeowner commented on the improvement in master-bedroom conditions after the retrofit. The end result of this disparity is that the entire duct-design process is skewed so as to provide far less than optimal distribution of heating and cooling.

There is another assumption within Manual J that is likely to result in inaccurate estimates of room-by-room loads. Namely, it is assumed that the infiltration load is split between rooms based on the estimated relative external leakage area of that room. The problem with this assumption is that it ignores the fact that a significant fraction of residential air infiltration is driven by the stack effect. The implication of ignoring the stack effect in two-story houses is that in general the upstairs flows will be oversized for heating, resulting in unnecessary stratification and discomfort in the winter. This upstairs-duct oversizing should actually help reduce stratification in the summer.

In addition, it is also worth noting that the duct loss multipliers for an attic and a crawlspace are the same, which is clearly inconsistent with intuition and field experiments. The result is that cooling equipment with attic ductwork is likely to be relatively undersized as compared to cooling equipment with crawlspace ductwork.

Treatment of Duct Performance in ACCA Manual D

As noted above, the principal function of Manual D is to assure that a given duct layout delivers the appropriate air flows to each room, based upon the room-by-room loads calculated with Manual J. Thus, if the total load seen by the duct run to a given room is not correct, the size of the ductwork leading to that zone will not be correct, resulting in poorly designed system (i.e., one that does not provide uniform heating or cooling, and which is difficult or impossible to balance).

There is however a disconnect within Manual D. Namely, Manual D contains an entire, fairly complete section on duct-system energy efficiency, however this section is not connected to the load calculation procedures used to size the equipment and ductwork.

Treatment of Duct Performance in ACCA Manual T

As noted above, Manual T focuses on the room-air motion aspects of air distribution systems. The way that this relates to duct performance and quality HVAC installations is through the performance of the diffusers. In particular, if a diffuser is designed to provide a given throw at a specific air flow rate, that throw will be reduced (potentially significantly) by supply-duct leakage or by flow restrictions within the ductwork (e.g., flexduct that is not fully extended, that is bent at hangers, or that is bent at too sharp of a radius).

Recommended Strategy for California

Based upon the discussion above, a two-phase strategy for improving the quality of HVAC installations is recommended. The first phase of the strategy simply addresses the issue of duct leakage, focusing on the interaction between duct leakage and equipment sizing with Manual J and Manual S. The second phase addresses the quality of the design, focusing on a methodology for accurately laying out and sizing ductwork so as to provide better occupant comfort.

The essence of the Phase-I strategy is to develop a modification to Manual J duct loss/gain multipliers that takes into account duct leakage losses, and to combine this with an appropriate training course designed to help contractors take some of the oversizing trends out of their Manual-J calculations.

The essence of the Phase-II strategy is to address the duct-design problems in the combination of Manual J and Manual D. This can be accomplished by inserting an overall duct-loss calculation procedure for each register in the house into the process. This may require some iteration between the duct-sizing procedure and the duct-loss calculation procedure, however one or two iterations will most likely be adequate, and the final design will not only provide better comfort, but should ultimately result in better energy efficiency. This overall duct-loss calculation procedure should most-likely be based on the simplified procedure developed by Palmiter (1995) that is likely to be adopted into the proposed ASHRAE Standard 152P. This procedure should be used separately for heating and cooling operation.

Detailed Results of Cost/Benefit Analysis

A parametric analysis of energy-efficiency features was performed using MICROPAS4. The home used for this analysis was the California Energy Commission (CEC) typical home used for energy standards analysis. The home has 1761 square foot conditioned area and different glazing percentage (of conditioned floor area) based on Title 24 package requirements for each climate zone. In Climate Zones 3, 4, 6-10 the home has 20 percent glazing, and in Climate Zones 1, 2, 5, 11-16 it has 16 percent glazing. This file is available from both the CEC and Enercomp, the distributor of MICROPAS4.

The base-case home had Title 24 package features for each climate zone and a duct efficiency of 75 percent. Each feature was individually increased above these minimums to determine a difference in energy budget. The sealed duct case (R-4.2 ‘TIGHT’) had a duct efficiency of 84 percent.

	CLIMATE ZONE 3			
RUN **DESCRIPTION**	**ENERGY BUDGET** **(kBtu/sf-yr)**	**FEATURE IMPACT** **(kBtu/sf-yr)**	**COST** **($)**	**COST EFFECTIVENESS** **(kBtu/$100)**
BASE CASE FEATURES	24.00	n/a	n/a	n/a
R-38 CEILING	23.80	0.20	$131	0.15
R-49 CEILING	23.48	0.52	$323	0.16
R-15 WALL	23.62	0.38	$190	0.20
R-19 WALL	22.69	1.31	$607	0.22
'R-21' WALL	22.37	1.63	$811	0.20
'R-24' WALL	22.02	1.98	$906	0.22
'R-25' WALL	21.79	2.21	$962	0.23
'R-25' WALL#2	21.84	2.16	$1,000	0.22
'R-26' WALL	21.63	2.37	$1,057	0.22
R-30 FLOOREXT	23.96	0.04	$9	0.44
R-5 SLAB (24")	23.01	0.99	$497	0.20
R-10 SLAB (24")	22.58	1.42	$568	0.25
ALTB (0.65)	23.13	0.87	$504	0.17
WOOD (0.55)	22.43	1.57	$2,098	0.07
VINYL (0.45)	21.36	2.64	$588	0.45
LOW-E (U=.65)	23.28	0.72	$420	0.17
LOW-SC	25.30	-1.30	$534	-0.24
LOW-E & LOW-SC	24.66	-0.66	$954	-0.07
HEAT-MIRROR 66	24.94	-0.94	$1,526	-0.06
BRONZE or GREY	24.56	-0.56	$324	-0.17
R.SHADES @ BACK	23.90	0.10	$116	0.09
M.BLINDS @ BACK	23.93	0.07	$170	0.04
R.SHADES @ ALL	23.37	0.63	$324	0.19
2' OVERHANG	23.77	0.23	$385	0.06
20% EXP.SLAB	23.74	0.26	$474	0.05
RADIANT BARRIER	23.81	0.19	$167	0.11
80% AFUE	23.76	0.24	$50	0.48
90% AFUE	22.75	1.25	$550	0.23
11.0 SEER	23.81	0.19	$155	0.12
12.0 SEER	23.66	0.34	$300	0.11
13.0 SEER	23.53	0.47	$475	0.10
15.0 SEER	23.32	0.68	$1,100	0.06
HYDRONIC #1	24.28	-0.28	$25	-1.12
HYDRONIC #2	23.79	0.21	$175	0.12
R-6.3 DUCTS	23.74	0.26	$113	0.23
R-11 DUCTS	23.56	0.44	$312	0.14
R-4.2 'TIGHT'	21.00	3.00	$384	0.78
EF=0.62	23.19	0.81	$150	0.54

EF=0.65	22.66	1.34	$350	0.38
EF=0.62 w/R12	22.06	1.94	$165	1.18
PIPE INSUL.	23.33	0.67	$95	0.71

	CLIMATE ZONE 10			
RUN **DESCRIPTION**	**ENERGY BUDGET** **(kBtu/sf-yr)**	**FEATURE IMPACT** **(kBtu/sf-yr)**	**COST** **($)**	**COST EFFECTIVENESS** **(kBtu/$100)**
BASE CASE FEATURES	37.12	n/a	n/a	n/a
R-38 CEILING	36.65	0.47	$131	0.36
R-49 CEILING	36.15	0.97	$323	0.30
R-15 WALL	36.52	0.60	$190	0.32
R-19 WALL	35.18	1.94	$607	0.32
'R-21' WALL	34.68	2.44	$811	0.30
'R-24' WALL	34.14	2.98	$906	0.33
'R-25' WALL	33.79	3.33	$962	0.35
'R-25' WALL#2	33.87	3.25	$1,000	0.32
'R-26' WALL	33.56	3.56	$1,057	0.34
R-30 FLOOREXT	37.09	0.03	$9	0.33
R-5 SLAB (24")	36.14	0.98	$497	0.20
R-10 SLAB (24")	35.72	1.40	$568	0.25
ALTB (0.65)	36.26	0.86	$504	0.17
WOOD (0.55)	33.60	3.52	$2,098	0.17
VINYL (0.45)	33.22	3.90	$588	0.66
LOW-E (U=.65)	35.94	1.18	$420	0.28
LOW-SC	33.96	3.16	$534	0.59
LOW-E & LOW-SC	32.30	4.82	$954	0.51
HEAT-MIRROR 66	29.61	7.51	$1,526	0.49
BRONZE or GREY	35.67	1.45	$324	0.45
R.SHADES @ BACK	34.72	2.40	$116	2.08
M.BLINDS @ BACK	35.87	1.25	$170	0.74
R.SHADES @ ALL	33.16	3.96	$324	1.22
2' OVERHANG	36.08	1.04	$385	0.27
20% EXP.SLAB	36.61	0.51	$474	0.11
RADIANT BARRIER	36.54	0.58	$167	0.35
80% AFUE	36.93	0.19	$50	0.38
90% AFUE	36.10	1.02	$550	0.19
11.0 SEER	35.58	1.54	$155	0.99
12.0 SEER	34.30	2.82	$300	0.94
13.0 SEER	33.21	3.91	$475	0.82
15.0 SEER	31.47	5.65	$1,100	0.51
HYDRONIC #1	37.35	-0.23	$25	-0.92
HYDRONIC #2	36.96	0.16	$175	0.09
R-6.3 DUCTS	36.56	0.56	$113	0.49
R-11 DUCTS	36.25	0.87	$312	0.28
R-4.2 'TIGHT'	30.96	6.16	$384	1.60
EF=0.62	36.31	0.81	$150	0.54

EF=0.65	35.78	1.34	$350	0.38
EF=0.62 w/R12	35.18	1.94	$165	1.18
PIPE INSUL.	36.45	0.67	$95	0.71

	CLIMATE ZONE 12			
RUN **DESCRIPTION**	**ENERGY BUDGET** **(kBtu/sf-yr)**	**FEATURE IMPACT** **(kBtu/sf-yr)**	**COST** **($)**	**COST EFFECTIVENESS** **(kBtu/$100)**
BASE CASE FEATURES	41.26	n/a	n/a	n/a
R-49 CEILING	40.73	0.53	$323	0.16
'R-21' WALL	40.67	0.59	$811	0.07
'R-24' WALL	39.99	1.27	$906	0.14
'R-25' WALL	39.53	1.73	$962	0.18
'R-25' WALL#2	39.64	1.62	$1,000	0.16
'R-26' WALL	39.23	2.03	$1,057	0.19
R-30 FLOOREXT	41.21	0.05	$9	0.55
R-5 SLAB (24")	39.77	1.49	$497	0.30
R-10 SLAB (24")	39.10	2.16	$568	0.38
WOOD (0.55)	38.79	2.47	$2,098	0.12
VINYL (0.45)	37.64	3.62	$588	0.62
LOW-E (U=.55)	39.81	1.45	$420	0.35
LOW-SC	39.61	1.65	$534	0.31
LOW-E & LOW-SC	37.68	3.58	$954	0.38
HEAT-MIRROR 66	36.57	4.69	$1,526	0.31
BRONZE or GREY	40.64	0.62	$324	0.19
R.SHADES @ BACK	38.48	2.78	$116	2.40
M.BLINDS @ BACK	39.82	1.44	$170	0.85
R.SHADES @ ALL	37.29	3.97	$324	1.22
2' OVERHANG	40.16	1.10	$385	0.29
20% EXP.SLAB	40.96	0.30	$474	0.06
RADIANT BARRIER	40.81	0.45	$167	0.27
80% AFUE	40.88	0.38	$50	0.76
90% AFUE	39.21	2.05	$550	0.37
11.0 SEER	40.07	1.19	$155	0.77
12.0 SEER	39.08	2.18	$300	0.73
13.0 SEER	38.24	3.02	$475	0.64
15.0 SEER	36.90	4.36	$1,100	0.40
HYDRONIC #1	41.72	-0.46	$25	-1.84
HYDRONIC #2	40.92	0.34	$175	0.19
R-6.3 DUCTS	40.62	0.64	$113	0.56
R-11 DUCTS	40.22	1.04	$312	0.33
R-4.2 'TIGHT'	33.97	7.29	$384	1.90
EF=0.62	40.45	0.81	$150	0.54
EF=0.65	39.92	1.34	$350	0.38
EF=0.62 w/R12	39.32	1.94	$165	1.18
PIPE INSUL.	40.59	0.67	$95	0.71