CALIFORNIA
ENERGY
COMMISSION

Thermal Distribution Systems in Commercial Buildings

CONSULTANT REPORT

DECEMBER 2002
P500-02-077F

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Funding Statement

This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, of the US Department of Energy under Contract No. DE-AC03-76SF00098.

Acknowledgements

Our largest debt of gratitude is to our Energy Performance of Buildings Group staff and students, who worked long hours in the lab and at the site, often late into the night, in order to perform the necessary measurements for this project. They are Bass Abushakra, Brian Smith, Iain Walker, Tengfang Xu, Rozy Brar, Allan Cheng, Matt Dubrovich, Jeff Guasto, Alan Ropers, Prabu Segaran, and William Watts. John Wunderlich, LBNL Facilities, also provided valuable assistance guiding us through the EMCS system of the large commercial test building.

The building management staff at the site was extremely cooperative and supportive of our work. We would like to thank Bob Young, Scott Kutylowski, Andy Rhoades, Pat Lewis, Carlos Isquierdo, Ian Chan, Simi Rossi, Gary Spencer, and Don Scott from Thomas Properties.

Our Project Advisory Committee (PAC) members contributed at several critical junctures, and we would like to acknowledge their support and input. The PAC members are:

Ed Becker, Southern California Gas Company; Karl Brown, California Institute for Energy Efficiency; Grant Brohard, Pacific Gas and Electric Company; Charles Eley, Eley Associates; Glenn Friedman, Taylor Engineering; Mark Hydeman, Taylor Engineering; Eli Howard, Sheet Metal and Air Conditioning Contractors' National Association; John Kesselring, Electric Power Research Institute; Jon Leber, California Energy Commission; Esher Kweller, U.S. Department of Energy; Henry Lau, Southern California Edison Company; Kurt Mankell, Certainteed Corporation; Mohammad Mirseyedi, Los Angeles Department of Water & Power; David Sellers, Portland Energy Conservation Inc.; Maziar Shirakh, California Energy Commission; Bruce Vincent, Sacramento Municipal Utility District; Joseph Wang, California Energy Commission; Tom Webster, Center for Environmental Design Research, University of California at Berkeley; Rick Wiesner, Sacramento Municipal Utility District.

This project evolved from the ideas and work of Mark Modera, the original Principal Investigator for the project. Even after he left the project, Mark continued to provide contributions and was a valuable resource to the entire project team.

Esher Kweller, Program Manager, U.S. Department of Energy provided co-funding for this research, as well as important technical and programmatic suggestions.

Lastly, we would like to acknowledge the support and contributions of the PIER Contract Manager, Martha Brook, and the Buildings Program team under the leadership of Nancy Jenkins: Don Aumann, Chris Scruton, and Phil Spartz.

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 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:

- Residential and non-residential buildings end-use energy efficiency
- Industrial, agricultural, and water end-use energy efficiency
- Renewable energy technologies
- Environmentally preferred advanced generation
- Energy-related environmental research
- Energy Systems Integration

What follows is the final report for the Thermal Distribution Systems in Commercial Buildings project, Contract Number 500-98-026, conducted by the Energy Performance of Buildings Group, Environmental Energy Technologies Division of the Lawrence Berkeley National Laboratory. The report is entitled Thermal Distribution Systems in Commercial Buildings. This project contributes to the PIER Building 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.

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Executive Summary

Introduction

Previous research suggests that HVAC thermal distribution systems in commercial buildings suffer from thermal losses, such as those caused by duct air leakage and poor duct location. Due to a lack of metrics and data about the potentially large energy savings from reducing these losses, the California building industry has mostly overlooked energy efficiency improvements in this area.

Purpose and Objectives

The purpose of this project is to obtain the technical knowledge needed to properly measure and understand the energy efficiency of thermal distribution systems in commercial buildings. We expect that this new information will assist the California building industry in designing better thermal distribution systems for new commercial buildings and in retrofitting existing systems to reduce their energy consumption and peak electrical demand.

The specific technical objectives for this project were to:

- Develop metrics and diagnostics (“yardsticks” and measurement techniques) for determining the efficiencies of commercial thermal distribution systems.
- Develop information that the California building industry (e.g., HVAC system design engineers and installers) can use to design new thermal distribution systems, estimate energy efficiency, and prevent or reduce the incidence of problems that have been identified in existing commercial thermal distribution systems.
- Determine the energy impacts associated with duct leakage airflows in an existing large commercial building, which could be mitigated by applying duct retrofit technologies.

Outcomes

Based on the project objectives, the project has three primary outcomes:

- **Metrics & Diagnostics.** The most important metric that we identified and defined characterizes the overall efficiency of the thermal distribution system in large commercial buildings: transport energy (e.g., total energy used to transport air) per unit thermal energy delivered. This metric is useful for comparing the relative performance of various types of thermal distribution systems. We recommend that California’s Title 24 compliance process for large commercial buildings include quantification of this metric.

  Our field tests of diagnostics focused on measurements of duct leakage airflows, fan airflows, and fan power. In particular, of the two duct leakage diagnostics that we tested, only one reliably determined duct leakage airflows: it involves accurately measuring airflows entering and exiting the duct system—the difference is the duct leakage. With further development and testing, we expect this diagnostic will be useful in developing a database that characterizes the distribution of duct leakage airflows in California's large commercial buildings.

- **Characterization.** Because there has been very little characterization of the actual performance of thermal distribution systems in large commercial buildings, we carried out an extensive characterization of one of these systems. The test building showed every indication of a "tight" thermal distribution system: good application of mastic, metal bands at joints, and overall high quality. To demonstrate duct leakage impacts, we installed temporary calibrated leaks and monitored their effects on the system energy consumption and demand.

- **Energy impacts.** The principal outcome from this project is that duct leakage airflows can have a significant energy impact in large commercial buildings. Our measurements indicate that adding 15% duct leakage at operating conditions leads to an increase in fan power of about 25 to 35%. These findings are consistent with the impacts of increased duct leakage airflows on fan power that have been predicted by previous simulations.

Conclusions

The primary outcome from this project is the measured confirmation that duct leakage airflows can significantly increase fan energy consumption in large commercial buildings. In addition, we have defined a new metric for distribution system efficiency, demonstrated a reliable test for determining duct leakage, and developed new techniques for duct sealing. The parallel story in the residential and small commercial sector has shown that from the comparable stage in that research to maturity of technology adoption (e.g., commercialization and inclusion in standards) was approximately ten years. We conclude that a concerted effort will be necessary to make the same—or better—progress for the large commercial sector.

Recommendations

Based on the project findings, our recommendations for further work are to:

- Further develop the duct leakage airflow diagnostic and submit it to the American Society for Testing and Materials (ASTM) for adoption as a standard method of test.

- Work with California's Title 24 staff to introduce a requirement for quantifying and reporting the "overall efficiency of the distribution system" metric for new large commercial buildings. Once we have a good understanding of the range of duct system efficiencies from reported data, we could then use these data to set guidelines for minimum acceptable levels.

- Develop specifications for maximum allowable duct leakage airflows and for duct sealing in new construction.

- Continue collaborative work with the U.S. Department of Energy, University of California, and private sector (e.g., Carrier, Eley Associates, Taylor Engineering) to transfer information to the building industry.

- Evaluate the performance of the thermal distribution system at the demonstration building over a heating season, with and without the added duct leakage. The investment of time and equipment at the demonstration building makes it worthwhile to continue monitoring the system in order to look at energy savings over the year.

- Survey additional sites to start a database of duct leakage characteristics in large commercial buildings. This work is currently planned with funding from the U.S. Department of Energy and would benefit from co-funding by the CEC.

Benefits to California

We have identified several benefits that result directly from this study or that will accrue over time as necessary information and infrastructure develops further:

- **Benefits in electricity savings.** The primary benefits from having tight duct systems are electricity savings. We estimate that eliminating duct leakage airflows in half of California's existing large commercial buildings has the potential to save about 560 to 1,100 GWh annually (about $60-$110 million per year or the equivalent consumption of about 83,000 to 170,000 typical California houses), and about 100 to 200 MW in peak demand.

- **Benefits to future buildings**. The identification of a metric for characterizing distribution system performance allows us to recommend its inclusion in the next round of California's Title 24 as a way of characterizing the new building stock. Once we have a good database of new duct system characteristics, we can set reasonable targets for distribution system performance, which will ultimately lead to further energy savings in this sector.

- **Benefits to new buildings in the UC system**. As an outgrowth of our work on this project, we have been working with members of the design team on duct specifications for the new University of California at Merced campus. In particular, we have reviewed the draft design documentation for their duct systems and recommended changes to the specifications. While we don't have a specific energy saving calculated for this work, we see the benefits extending to other UC campuses once others use these specifications.

- **Benefits in building operations and maintenance**. A willing partner in this work has been Thomas Properties, a major manager of buildings, both public and private. Through this study, they have seen the benefits not only of improvements in duct diagnostics, but also in feedback on their HVAC system performance via the EMCS. By working closely with the private sector, we have seen the transfer of knowledge and the improvements in building operation in a major public facility.

- **Benefits to future engineers.** A key aspect of our research team has been the inclusion of numerous students. While they may not have appreciated the long hours at the field site, they are now familiar with a number of important lessons about the performance of thermal distribution systems. As future engineers—not all of who may practice in California—we expect that some will become leaders in this area.

Abstract

Previous research suggests that HVAC thermal distribution systems in commercial buildings suffer from thermal losses, such as those caused by duct air leakage and poor duct location. Due to a lack of metrics and data about the potentially large energy savings from reducing these losses, the California building industry has mostly overlooked energy efficiency improvements in this area. The purpose of this project is to obtain the technical knowledge needed to properly measure and understand the energy efficiency of these systems. This project has three specific objectives: to develop metrics and diagnostics for determining system efficiencies, to develop design and retrofit information that the building industry can use to improve these systems, and to determine the energy impacts associated with duct leakage airflows in an existing large commercial building. The primary outcome of this project is the confirmation that duct leakage airflows can significantly impact energy use in large commercial buildings: our measurements indicate that adding 15% duct leakage at operating conditions leads to an increase in fan power of about 25 to 35%. This finding is consistent with impacts of increased duct leakage airflows on fan power that have been predicted by previous simulations. Other project outcomes include the definition of a new metric for distribution system efficiency, the demonstration of a reliable test for determining duct leakage airflows, and the development of new techniques for duct sealing. We expect that the project outcomes will lead to new requirements for commercial thermal distribution system efficiency in future revisions of California's Title 24.

Keywords: Buildings, HVAC, ducts, fans, energy, metrics, diagnostics, retrofits

1.0 Introduction

1.1. Background

Heating, ventilating, and air conditioning (HVAC) equipment in California commercial buildings consumes approximately one quarter of the electrical energy used by these buildings and accounts for about half of their peak electrical demand (Brook 2002). Previous research suggests that the HVAC thermal distribution systems in these buildings suffer from a number of problems, such as thermal losses due to duct air leakage and poor duct location (Xu et al. 1999, 2002). Despite the potential for large energy savings by reducing thermal losses in commercial buildings (Franconi et al. 1998), the California building industry has mostly overlooked this area as a target for energy efficiency improvements. One reason is that metrics for determining the efficiencies of commercial thermal distribution systems are poorly defined. Another reason is that the utility of duct diagnostic and retrofit technologies to identify and reduce duct leakage, duct conduction losses, and associated energy consumption and demand remains undetermined.

As an example of the complexities involved in understanding thermal distribution system performance, consider a variable-air-volume (VAV) HVAC system in a large commercial building. Although the conditioned air that leaks from supply ducts is captured in the return air, and may be regained from a thermal viewpoint, the leakage airflow does not reach the conditioned spaces directly. To maintain the main duct static air pressure at its set point, all leakage upstream of the VAV boxes must be made up by an increase in the supply fan airflow. Leakage downstream of the VAV boxes must be made up by supplying more air to the VAV boxes. To deliver more supply air, VAV box primary air dampers need to open further. Consequently, to maintain the main duct static pressure at its set point, an increase in the supply fan airflow is also needed to compensate for the downstream leakage airflows. Because the relationship between fan power and airflow is somewhere between a quadratic and cubic function, the increase in supply airflow means that supply fan power consumption increases, with a large fraction of this fan power used just to move the leaking air. Note that some of the thermal losses associated with duct leakage are not entirely recaptured during periods of economizer use, because relief fans discharge some of the return air directly to outdoors to maintain building envelope pressure differentials that would otherwise increase due to the increased outdoor airflows entering the building through the economizer.

The overall goal of this project is to obtain the technical knowledge needed to properly measure and understand the energy efficiency of thermal distribution systems in commercial buildings. We expect that this new information will assist the California building industry in designing better thermal distribution systems in new commercial buildings and in retrofitting existing systems to reduce their energy consumption and peak electrical demand.

This project contributes to the PIER program objective of improving the energy cost and value of California’s electricity in two ways. One is by demonstrating through measurements how leaky or poorly designed thermal distribution systems in commercial buildings waste the energy that is used to condition air (e.g., cooling, heating, dehumidification). The other is by developing methods to identify and correct these problem systems. We expect that the knowledge gained from this research will be used to craft new requirements for commercial duct system efficiency in future revisions of California's Title 24.

1.2. Project Objectives

The specific technical objectives for this project are to:

- Develop metrics and diagnostics ("yardsticks" and measurement techniques) for determining the efficiencies of commercial thermal distribution systems.
- Develop information that the California building industry (e.g., HVAC system design engineers and installers) can use to design new thermal distribution systems, estimate energy efficiency, and prevent or reduce the incidence of problems that have been identified in existing commercial thermal distribution systems.
- Determine the energy impacts associated with duct leakage airflows in an existing large commercial building, which could be mitigated by applying duct retrofit technologies.

There are two overall economic performance objectives of this project. One is to lower the cost for building owners of performing diagnostic services on commercial thermal distribution systems, by developing quick field measurement techniques. The second is to lower space conditioning and ventilating costs to commercial-building electric ratepayers, by developing duct retrofit technologies that improve the performance of thermal distribution systems.

1.3. Report Organization

This report presents our findings and recommendations that have resulted from investigating the impacts of thermal distribution systems on energy use in commercial buildings. Most of the work focuses on large commercial buildings rather than on small commercial buildings, because much less is known about thermal distribution system performance in large commercial buildings.

In **Section 2 Project Approach**, we discuss the tasks that we undertook and our approach to the research to accomplish our objectives. In particular, we discuss changes to the testing procedures that we undertook and the need for system modifications during those tests.

In **Section 3 Project Outcomes**, we present the key results from our investigations.

In **Section 4 Conclusions and Recommendations**, we present what we learned from the research and what we recommend for future activities.

Following the **Glossary** and **References**, there are four technical Appendices:

- "Appendix I. Metrics and Diagnostics" provides a starting point in the development of a set of metrics and diagnostics that describe thermal distribution system performance in both small (thermally dominated) and large (fan-power dominated) commercial buildings. The appendix discusses energy (consumption and demand) metrics, as well as environmental indices (e.g., health, comfort, and safety). It also outlines several one-time and short-term diagnostics that can be used to quantify these metrics.
- "Appendix II. In-Situ Characterization" provides a general description of the large commercial building and its thermal distribution system that we characterized; a

description of our monitoring and diagnostic activities; a summary of our preliminary duct leakage findings; a description of the HVAC system airflow diagnostics that we carried out prior to and during our duct leakage intervention tests; and a summary of our HVAC fan power measurements and other field study findings.

- "Appendix III. Duct Sealing Techniques" discusses the need for duct sealing techniques that reach duct leaks in existing commercial buildings without having to access and seal every joint manually. It then describes the development and laboratory testing of a mobile aerosol-sealant injection system (MASIS) that can use multiple injectors simultaneously to seal multiple duct sections. To help the reader understand the multiple injector system, the appendix includes a description of the aerosol sealing technology. At the end of the appendix, we also discuss whether there is a need to develop field retrofit techniques for sealing duct system components such as VAV boxes and supply grilles.
- "Appendix IV. Production Readiness Plan" discusses our production readiness plan for retrofitting thermal distribution systems in large commercial buildings. In particular it summarizes our market transfer work to date, discusses steps needed to commercialize the aerosol sealing technology for use in large commercial buildings, and provides recommendations for future work.

2.0 Project Approach

In the original project plan, as part of obtaining the technical knowledge needed to properly measure and understand the energy efficiency of thermal distribution systems in commercial buildings, much of the work was intended to focus upon the utility of aerosol-based duct sealing technologies, for both small and large commercial buildings. Technical tasks were divided into three groups that addressed multiple project objectives in some cases:

- Develop metrics and diagnostic approaches for small and large commercial buildings.
- Carry out in-situ characterizations of two commercial buildings (one small and one large) using the metrics and diagnostics approaches defined in the project, before and after sealing the ducts using aerosol-based duct sealing technologies, and determine the energy savings associated with reducing the duct leakage.
- Develop aerosol-based duct sealing technologies, test them in the laboratory, and then apply them in the field to retrofit the duct systems in the buildings selected for the in-situ characterization task.

As in any research effort, the results along the way also shaped the work. Based on input from the PAC team and the PIER Buildings Program team, the project evolved. Changes included:

- We acquired additional funding from the U.S. Department of Energy to develop and test the aerosol-sealing technology itself. This meant that the CEC project could narrow its focus to developing protocols and control algorithms for field applications in large commercial buildings, which require the use of multiple injectors to achieve acceptable sealing efficiencies.

- We acquired funding from the Sacramento Municipal Utility District to carry out a duct leakage intervention – energy impact study on several small commercial buildings. This meant that the CEC project could shift its focus away from small commercial buildings and toward large commercial buildings, where less is known about the performance of their thermal distribution systems.
- Once planning began for the in-situ characterization and duct leakage intervention study in a large commercial building, it quickly became apparent that this effort would consume most of the resources planned for these activities, leaving none to address a second large building. In particular, our experimental design called for extensive characterization of the HVAC system operation on an intervention floor before and after modifying duct leaks on this floor; plus less detailed characterization of a separate floor within the same building (used as a control floor with no changes to the HVAC system, as a basis for comparison to the intervention floor). Based on consultations with the PIER Buildings Program team, the decision was made to study one building in detail and understand it well, rather than diverting resources to two buildings and being less thorough in each building.
- During our in-situ characterization efforts in the large commercial building, we found that the duct leakage diagnostics gave disparate results. In particular, although pressurization tests indicated the duct system was leaky, in reality it was tight (small leakage airflows). This meant that using aerosol sealing to reduce duct leakage was not an option as an intervention method, and that leaks would need to be added to assess the energy impact of duct leakage. To support that effort, additional funding was acquired from the U.S. Department of Energy to add calibrated duct leaks both upstream and downstream of VAV boxes. This meant that we could separately determine the impact of each set of leaks. Given that the multiple injector aerosol-based sealing technology is ready to deploy and may be the most practical method for retrofit duct sealing applications, we had still hoped to seal the installed leaks using aerosol sealing, as a field demonstration of this technology. However, we were unable to obtain approval for such sealing in the test building.

Appendices I through IV describe our research efforts in detail.

3.0 Project Outcomes

This section presents the key results from our investigations, in the same order as the three objectives.

- **Objective #1:** Develop metrics and diagnostics ("yardsticks" and measurement techniques) for determining the efficiencies of commercial thermal distribution systems.

  Metrics. As described in Appendix I, we identified and defined eleven metrics for characterizing the thermal performance of distribution systems in large commercial buildings. The most important of these metrics characterizes the overall efficiency of the distribution system: transport energy (e.g., total energy used to transport air) per unit thermal energy delivered. This metric is useful for comparing the relative performance of various types of thermal distribution systems. Calculating this parameter for a building on paper or using a computer is relatively straightforward, excluding any impacts of improper installation or operation. Determining this parameter in a building that has already been built is somewhat more difficult because measuring the total heating or cooling energy delivered to each zone requires air temperature and flow sensors at every grille and temporally continuous measurements. We recommend that California's Title 24 compliance process for large commercial buildings include quantification of this metric.

Diagnostics. We field tested six diagnostics that can be used to quantify the performance of existing thermal distribution systems, with a focus on diagnostics to measure duct leakage airflows, fan airflows, and fan power. As we discuss in Appendix II, only one of the two duct leakage diagnostics that we tested could reliably determine duct leakage airflows: it involves accurately measuring airflows entering and exiting the duct system—the difference is the duct leakage. A significant barrier to the widespread use of this diagnostic is the need to rapidly measure the flows exiting the duct system at many supply grilles. Through our field tests of several commercially available flow hoods, we found one that can give the same results as our reference research-grade device, within the uncertainty specification of the reference (bias and RMS errors less than 2%). Our tests also indicated that this hood could measure 100 grille airflows in less than two hours, which is rapid enough to make the diagnostic practical. Because hood accuracy depends on grille type, further development and testing is needed, but we expect this diagnostic will be useful in developing a database that characterizes the distribution of duct leakage airflows in California's large commercial buildings.

- **Objective #2:** Develop information that the California building industry (e.g., HVAC system design engineers and installers) can use to design new thermal distribution systems, estimate energy efficiency, and prevent or reduce the incidence of problems that have been identified in existing commercial thermal distribution systems.

Characterization. Because there has been very little characterization of the actual performance of thermal distribution systems in large commercial buildings, we carried out an extensive characterization of one of these systems. Of particular note, we used duct pressurization techniques similar to those described by SMACNA (1985) to determine duct leakage areas. Our initial measurements of leakage area and pressures in the ducts indicated that the duct system downstream of VAV boxes was leaky: about mid-range compared to the leakage (58 to 606 cfm at 1 in. w.c. pressure per 100 ft^2 of duct surface area) of branch ducts that we have tested in other large commercial building systems (Xu et al. 2002). However, this was only part of the story. Using the duct leakage airflow diagnostic described above, we determined that the actual airflow through the duct leaks was small (about 5% of total air-handler supply airflow at operating conditions), and consequently less significant. The test building showed every indication of a "tight" thermal distribution system: good application of mastic, metal bands at joints, and overall high quality.

- **Objective #3**: Determine the energy impacts associated with duct leakage airflows in an existing large commercial building, which could be mitigated by applying duct retrofit technologies.

Energy impacts. Because the duct system in the study building was extremely tight, we installed temporary calibrated leaks to demonstrate duct leakage impacts. Specifically, we added 15% duct leakage to make a total of 20% at operating conditions. We feel that the added leaks represent what we might find in other buildings, but need to validate this assumption by making duct leakage airflow measurements in more buildings.

During the cooling season, the amount of electrical power required by the HVAC system to transport conditioned air includes the power to drive the air-handler supply fans, relief fans, and VAV box induction fans. In reviewing the patterns of fan operation, we found that the supply fan and induction fan airflows and operation are impacted by the introduction of additional duct leakage. The relief fans are operated to maintain building pressure set points and run as needed during pre-cooling and economizer modes. As a result, the relief fans have an irregular operational pattern. We did not see a correlation between duct leakage and relief fan operation. As such, we only discuss the impact of duct leakage on the air-handler supply fans and the induction fans, and not on the relief fans.

The principal outcome from this project is that the energy impact of duct leakage in large commercial buildings can be substantial. We found that the added leakage leads to an increase in air-handler supply fan power of about 37%, and an overall increase in total fan power (air-handler supply fans plus induction fans) of about 26%. The total fan power increase is lower because the added duct leakage causes induction fans to operate less often.

Previous simulations (Franconi et al. 1998) have suggested that the energy impacts of 20% duct leakage are larger: on the order of 60% to 70% of the total fan energy consumption. However, the duct leakage fraction in the simulations is normalized by nominal design supply airflow rather than by operating supply airflow. Redefining our duct leakage fraction to match the definition used in the simulations means that the duct leakage that we added was about 10% of the nominal design supply airflow. Given that our leakage fractions were about 50% of those used in the simulations, and assuming that fan power is somewhere between a quadratic and cubic function of airflow, our measurements are consistent with the simulation results.

4.0 Conclusions and Recommendations

4.1. Conclusions

The primary outcome from this project is the measured confirmation that duct leakage airflows can significantly increase fan energy consumption in large commercial buildings. In addition, we have defined a new metric for distribution system efficiency, demonstrated a reliable test for determining duct leakage airflows, and developed new techniques for duct sealing. The parallel story in the residential and small commercial sector has shown that from the comparable stage in that research to maturity of technology adoption (e.g., commercialization and inclusion in standards) was approximately ten years. We conclude that a concerted effort will be necessary to make the same—or better—progress for the large commercial sector.

4.2. Commercialization Potential

Market Transfer Efforts. Our project activities have already resulted in market transfer efforts:

- **Codes and Standards**. California's Title 24 currently has no performance criteria for duct systems in large commercial buildings. We have identified a metric for characterizing duct system efficiency that Title 24 reports should include for all new commercial buildings. Once we have a good understanding of the range of duct system efficiencies, we could then set guidelines for minimum acceptable levels.
- **CA Public Sector**. University of California staff is already asking for the development of duct tightness criteria for the new buildings at UC Merced. They are also interested in the measurement and verification procedures to ensure that these criteria have been met. These criteria could be adopted for new construction at University of California and California State University campuses throughout the state.
- **PIER-related activity**. Taylor Engineering, Eley Associates, and the Center for the Built Environment at UC Berkeley have all come on board this project as interested co-participants. The work at the test building in Sacramento has been a fertile test bed for several groups interested in sharing our monitoring capabilities to do unique measurements of HVAC systems in commercial buildings.
- **Synergistic funding with US DOE**. This project has benefited from over $400k of support from the Building Technologies office at the U.S. Department of Energy. DOE plans to continue supporting work in this area, including continued efforts at the test building in Sacramento to further assess duct leakage diagnostics, as well as measurements of duct leakage at different sites.

Production Readiness Plan. In addition to the market transfer work identified above, there is one specific aspect of the study that has large commercialization potential: the aerosol sealing technology. There are some development tasks that may be appropriate for the public sector to pursue, given the lack of R&D that is currently done in the building's sector. Once this work is done, we expect the private sector to fully commercialize this technology. The steps needed for its commercialization are:

- Document the health and safety performance for the aerosol sealant, to eliminate barriers that may prevent adoption of this technology to seal ducts in large commercial buildings.
- Characterize the energy savings potential of existing large commercial buildings, by determining the actual range of leakage distributions in these buildings.
- Demonstrate aerosol sealing in a sample of commercial buildings.
- License technology to the private sector, which could then train contractors and produce equipment to reach the market.

Appendix IV describes these steps in more detail.

4.3. Recommendations

Based on our findings, our recommendations for further work are as follows, arranged in the same order as the three objectives:

- **Objective #1**: Develop metrics and diagnostics (“yardsticks” and measurement techniques) for determining the efficiencies of commercial thermal distribution systems.
  - **Recommendation #1**: Further develop the duct leakage airflow diagnostic and submit it to the American Society for Testing and Materials (ASTM) for adoption as a standard method of test.
  - **Recommendation #2:** Work with California’s Title 24 staff to introduce a requirement for quantifying and reporting the “overall efficiency of the distribution system” metric for new large commercial buildings. Once we have a good understanding of the range of duct system efficiencies from reported data, we could then use these data to set guidelines for minimum acceptable levels.
- **Objective #2:** Develop information that the California building industry (e.g., HVAC system design engineers and installers) can use to design new thermal distribution systems, estimate energy efficiency, and prevent or reduce the incidence of problems that have been identified in existing commercial thermal distribution systems.
  - **Recommendation #3:** Develop specifications for maximum allowable duct leakage airflows and for duct sealing in new construction.
  - **Recommendation #4:** Continue collaborative work with the U.S. Department of Energy, University of California, and private sector (e.g., Carrier, Eley Associates, Taylor Engineering) to transfer information to the building industry.
- **Objective #3:** Determine the energy impacts associated with duct leakage airflows in an existing large commercial building, which could be mitigated by applying duct retrofit technologies.
  - **Recommendation #5:** Evaluate the performance of the thermal distribution system at the demonstration building over a heating season, with and without the added duct leakage. The investment of time and equipment at the demonstration building

makes it worthwhile to continue monitoring the system in order to look at energy savings over the year.

- **Recommendation #6:** Survey additional sites to start a database of duct leakage characteristics in large commercial buildings. This work is currently planned with funding from the U.S. Department of Energy and would benefit from CEC co-funding.

The final Project Advisory Committee meeting in November 2002 also generated 11 recommendations for further work. These recommendations are in the form of desired outcomes for improving thermal distribution systems in large commercial buildings, both new and existing, by 2010. Many of these outcomes reflect our recommendations, but they also represent a broader scope. The desired outcomes are as follows:

- Stock Characterization and Energy Savings Potential
  - *Stock Characterization***.** An assessment of thermal distribution systems in the large commercial building stock (e.g., magnitude and location of leakage airflows).
  - *Current Practice***.** Characterization of existing practices for duct installation.
  - *Energy Impacts***.** An expanded understanding of the energy impacts of thermal distribution system characteristics (e.g., impacts related to duct leakage and thermal conduction) and a ranking of the issues that warrant further study.
- Design and Construction
  - *Design Guides*. Duct design and construction guidelines that focus on the most important issues in terms of their impacts on energy performance.
  - *Simulation Tools*. Mainstream simulation programs that can be used as design tools to predict distribution system performance.
  - *Technology Adoption*. Use of low-leakage duct components and joints, which will reduce or eliminate the need for widespread duct leakage testing.
  - *Specifications*. Specifications for achieving tight ducts within the normal building delivery process.
  - *Design Intent Linkage*. Improved communications between design intent, field construction, and operation.
- Codes and Standards
  - *Metrics*. Further development of proposed metrics for system characterization (i.e., expanded definitions of what each metric includes, and how each is determined or measured).
  - *Standards*. Defined standards for distribution system installation.
  - *Test Procedures*. A standard test procedure for flow hoods.
- Operations & Maintenance, Diagnostics, and Commissioning

- *Commissioning Toolkit*. A toolkit for commissioning ducts.
- *Real-Time Diagnostics*. A diagnostic method for measuring the energy use of distribution systems during operation, so that building operators can detect and rectify deficiencies in space conditioning energy delivery.
- *Information Transfer*. Dissemination of our current knowledge to the critical players.

5.0 Benefits to California

We have identified the following benefits that result directly from this study or that will accrue over time as necessary information and infrastructure develops further:

- Benefits in electricity savings. The primary benefits from having tight duct systems are electricity savings. Based on CEC Year 2000 estimates (Brook 2002), site electricity consumption for commercial buildings in California was 91,771 GWh that year, with a peak demand of 20,150 MW; 27% (25,185 GWh) of this energy and 51% (10,180 MW) of this peak demand were related to HVAC (heating, ventilating, and cooling) equipment operation in these buildings. The CEC also estimates that 39% (9,822 GWh) of this HVAC consumption and 21% (2,138 MW) of this HVAC demand was associated with fan operation; central system supply and return fans represented 56% (5,460 GWh) of this fan-related consumption and 47% (1,010 MW) of this fan-related demand.

  Using CEC Year 2000 estimates (Rohrer 2000), there was about 5,690 million ft^2 of commercial building floor area that year in California. Assuming that the fraction of large commercial buildings in California for the Year 2000 is the same as in the entire US Pacific region for Year 1999 (78%, EIA 2002), then there was about 4,440 million ft^2 of large commercial building floor area in California during the Year 2000. Assuming that central system supply and return fans are only used in large commercial buildings, this means that the average normalized fan power associated with peak demand for these fans was about 0.23 W/ft^2. This value is similar to the peak demand values that we measured for air-handler supply fans in the Sacramento test building (0.20 to 0.25 W/ft^2).

  We estimate that eliminating duct leakage airflows in half of California's existing large commercial buildings has the potential to save about 560 to 1,100 GWh annually (about $60-$110 million per year or the equivalent consumption of about 83,000 to 170,000 typical California houses), and about 100 to 200 MW in peak demand. It is important to recognize that these potential savings estimates are crude, particularly because we do not have good data yet to define the distribution of duct leakage airflows in the large commercial building sector. Our estimates assume that the duct leakage that can be eliminated ranges from 10 to 20% of the nominal design supply airflow in each building and that the fan power increases associated with this duct leakage are 26% to 70% respectively (eliminating this duct leakage translates to fan power savings of 21 to 41%). The lower bound is based upon our measurements in the Sacramento test building; the upper bound is based upon predictions by Franconi et al. (1998). Dollar savings are based on an electricity price of $0.10 per kWh. The representation of savings in terms of residential electricity consumption are based upon California residential electricity use projections for Year 2000 (Rohrer 2000), which indicate that the average California house used about 6,740 kWh that year.

Rufo and Coito (2002) assessed technical and economic potentials for 28 energy efficiency measures that could be implemented now in California's commercial buildings. Compared to their estimates of energy consumption and demand savings for the 28 measures (45 to 2,539 GWh, 0 to 769 MW), our energy consumption savings estimates for duct sealing rank somewhere between the 4th and 8th highest savings; our demand savings estimates rank between 6th and 13th.

- Benefits to future buildings. The identification of a metric for characterizing distribution system performance allows us to recommend its inclusion in the next round of Title 24 as a way of characterizing the new building stock. Once we have a good database of new duct system characteristics, we can set reasonable targets for distribution system performance, which will ultimately lead to further energy savings in this sector.
- Benefits to new buildings in the UC system. As an outgrowth of our work on this project, we have been working on duct specifications for the new University of California at Merced campus with members of the design team. In particular, we have reviewed the draft design documentation for their duct systems and recommended changes to the specifications. While we don't have a specific energy saving calculated for this work, we see the benefits extending to other UC campuses once others use these specifications.
- Benefits in building operations and maintenance. A willing partner in this work has been Thomas Properties, a major manager of buildings, both public and private. Through this study, they have seen the benefits not only of improvements in duct diagnostics, but also in feedback on their HVAC system performance via the EMCS. By working closely with the private sector, we have seen the transfer of knowledge and the improvements in building operation in a major public facility.
- Benefits to future engineers. A key aspect of our research team has been the inclusion of numerous students. While they may not have appreciated the long hours at the field site, they are now familiar with a number of important lessons about the performance of thermal distribution systems. As future engineers—not all of who may practice in California—we expect that some will become leaders in this area.

6.0 Glossary

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
APT	Automated Performance Testing
CEC	California Energy Commission
cfm	Cubic feet per minute
CIEE	California Institute for Energy Efficiency
DOE	U.S. Department of Energy
EIA	Energy Information Administration
ELA	Effective Leakage Area
EMCS	Energy management control system
GWh	Gigawatt hours, 10^9 Wh, 10^6 kWh
HVAC	Heating, ventilating and air conditioning
IAQ	Indoor air quality
LBNL	Lawrence Berkeley National Laboratory
MASIS	Mobile aerosol-sealant injection system
MW	Megawatt, 10^6 W
PAC	Project Advisory Committee
PIER	Public Interest Energy Research
RD&D	Research, Development, and Demonstration
RMS	Root mean square
SMACNA	Sheet Metal and Air Conditioning Contractors' National Association
TDS	Thermal distribution system
UC	University of California
VAV	Variable air volume

7.0 References

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Appendix I
Metrics and Diagnostics

Appendix II
In-Situ Characterization

Appendix III
Duct Sealing Techniques

Appendix IV
Production Readiness Plan