OVERVIEW OF PIER-FUNDED EXISTING BUILDING COMMISSIONING AND DIAGNOSTICS RESEARCH

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ABSTRACT

The California Energy Commission's Public Interest Energy Research (PIER) Program supports research and development that helps improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. The PIER Program awards up to $62 million annually and has funded some of the most promising energy research in the U.S. The PIER Buildings program area seeks to decrease building energy use through research that develops or improves energy efficient technologies, strategies, tools, and building performance evaluation methods. This paper summarizes the accomplishments of projects within the PIER Buildings Program related to existing building commissioning and diagnostics between 1999 and 2003.

BACKGROUND

The PIER Buildings Program supports research and products for both new and existing buildings, residential and non-residential. PIER places great emphasis on the practical use of all research activities. As a result, PIER has looked increasingly to commissioning as a practice with great potential, both in terms of the energy savings it can produce and the room for growth in the industry. In the last six years, PIER has directed over five million dollars towards existing building commissioning and diagnostics research. In 1999, PIER made multi-year awards to many projects with strong market connections at various stages of development. These projects have resulted in many products that are on the path to commercialization, while other products are already positioned for market adoption.

Below we provide an overview of several of these successful projects, organized into two areas:

- Fault Detection and Diagnostic (FDD) Tools
- Guides for Commissioning and Controls

For each project, we list the developers, their objective, the results, and their recommendations for future work. The purpose of this paper is to give the reader a broad understanding of the status of existing building commissioning research efforts in California, and to alert readers to resources for further information on these research projects. Interested scientists, engineers, and managers will find useful information applicable to their work, as well as recommended areas for additional work. It is the authors' hope that this paper will help facilitate connections between PIER research and others working in the existing building arena.

FAULT DETECTION AND DIAGNOSTIC TOOLS

Centralized High-Speed Meters for Fault Detection

Lead Researcher: Les Norford, Massachusetts Institute of Technology

Objective: The objective of this task is to develop and deploy high-speed electrical load monitoring capable of providing component-specific load information from a centralized location (motor-control center, HVAC service entrance, or whole building), thereby substantially reducing the cost of obtaining information. This metering technique, called Non-intrusive electrical load monitoring (NILM), is one new fault detection and diagnostics (FDD) method.

Results: A significant outcome of the PIER NILM research was to further develop the software algorithms in detecting equipment scheduling and cycling events. In particular, a method that detects variable speed drive (VSD) loads via the higher harmonics unique to VSDs represents a significant advance. The method estimates the power drawn by all VSD devices. It was not yet determined whether it is possible to discern individual VSD loads.

Additional NILM advancements include an upgraded method for detecting changes in steady state loads and analyzing short-term start-up transients, and other procedures that improve load identification.

The NILM is now capable of tracking all HVAC loads except constant-speed chillers. Work to develop an approach for chillers is underway.

This project has also documented a number of faults found with the NILM, artificially introduced (at the Iowa Energy Center's Energy Resource Station) or naturally occurring (in a pilot San Francisco office building). These faults can be identified by analysis of the power data produced by the NILM.

Recommendations: As the NILM software is further developed, it becomes a viable approach for savvy building operators and managers or for energy service companies that do such diagnostic work. At the present time, testing of the NILM to determine its commercial value has not been started. This testing requires an analysis of whether NILM power signatures associated with faults has value to customers. Additionally, further research is needed to automate NILM-based fault detection. Automatic fault detection will aid those potential users who have limited time or ability to analyze NILM data. Hands-off testing of the NILM should be performed in several buildings in conjunction with an assessment of the value of the NILM.

Download: A full report is available at http://buildings.lbl.gov/hpcbs/Element_5/02_E5_P2_2_3.html

Fault Detection Techniques and Tools

Lead Researchers: Michael Brambley, Battelle Northwest Division; and Stuart Waterbury, Architectural Energy Corporation (AEC)

Objective: This research aims to develop techniques that automate the detection and diagnosis of faults. These rule-based diagnostic techniques are based on a comparison of plots of good and bad system performance, obtained from both simulation and actual field measurements for a broad number of faults. A commercially available diagnostic tool that makes use of this approach, but with expert interpretation applied manually, is AEC's ENFORMA® software. This project will automate this expert interpretation so that diagnostic results are presented immediately to the user.

Results: Based on the systems and components covered in other PIER fault detection and diagnostics (FDD) projects, the research team selected chillers, boilers, and pumps (circulation and cooling towers) for development of FDD methods. Determination of how an expert analyzes the data for chillers and

boilers led to adoption of a rule-based method for detecting faults. A spreadsheet with a graphical user interface was developed to implement FDD algorithms for the selected building system components. Testing was performed using real data collected from buildings in other projects. A fully documented software specification was produced, which will guide future efforts to more completely develop a FDD tool.

The results of tests on the diagnostic algorithms validate that the rules are effective for automating the tool diagnostic process. In addition, testing revealed the need to develop a method by which to detect short-term anomalous chiller behavior. This research also led to recognition of the importance of carefully deciding what information should be presented to users and what should be filtered to prevent over-burdening building operators with information.

Recommendations: The rule-based diagnostic approach could be implemented in existing building control systems or component controllers. Additional research on the effect of sensor calibration and sensor placement is needed to understand the impact of these factors on false alarms and missed faults.

Built-up Fan System Diagnostics

Researchers: Tom Webster, University of California, Berkeley; Allen Barth, Nexant Energy Management Group

Objective: The objective of the project is to develop and demonstrate diagnostic methods and protocols based on short term monitoring techniques for built-up air handling systems.

Results: The AHU Toolkit developed from this project is composed of eight Excel spreadsheet tools with over 30 charts and tables for a semi-automatic way to calculate various performance metrics and display correlations and trends. These tools standardize data analysis and unburden the analyst from computations. The following areas of analysis are covered:

Fan Analysis & Benchmarking. This tool compares the design intent to estimated peak load operation based on actual measurements. A new method was developed for determining the maximum operating point for VAV systems. The tool also includes the structure for a fan performance database that allows benchmarking of a subject fan to other similar fans in the database population. The three buildings analyzed for this project serve as the initial

population for the database.

System Temperature Analysis. This tool includes an economizer analysis to determine the minimum outside air fraction. It also helps to identify sensor calibration errors and problems with the supply air temperature controls through manual graphical analysis.

Fan Power Analysis. The distribution of fan power (as percent of full load) is graphed by this tool to help identify problems with VAV control (e.g., lack of turndown) and unexpected off-hours fan operation. The tool also includes a projection of annual fan energy consumption.

Motor Efficiency. In-situ motor efficiency is calculated to identify fan motor problems.

As an additional area of research to support the Toolkit, procedures for tracer gas calibration of airflow monitoring stations were developed. Airflow monitoring stations were calibrated for all three sites using tracer gas techniques. These calibrations resulted in a 17% average error that was applied to all airflow data.

Recommendations: New methods for airflow measurement need to be developed or additional research conducted to prove that manufacturers' fan curves are accurate enough in actual installations to be used to determine airflow from static pressure and speed measurements. To accurately identify problems with fans, efficiency must be measured in the field-installed condition. Alternatively, methods should be investigated for determining the maximum operating point from a normalized system operating curve characterized by field test data for particular fan types.

Download: The AHU Toolkit is publicly available at: http://buildings.lbl.gov/hpcbs/Element_5/02_E5_P2_2_1.html

FDD of Rooftop Air Conditioners

Lead Researcher: James Braun, Purdue University

Objective: The purpose of this project is to demonstrate the extension of a fault detection and diagnosis (FDD) system for rooftop air conditioners to families of manufacturers' rooftop units through laboratory and field testing. The potential for commercialization and the economic benefits of applying the FDD system in California are being evaluated.

Results: Two laboratory test units, four quick service restaurants, four K-12 classrooms, and two retail drugstores were field test sites for the project. Field test data revealed that many units have multiple concurrent faults, confirming evidence from other PIER studies that maintenance of rooftop units is generally lacking.

A new method for decoupling at least three simultaneous faults was developed and tested using laboratory and field test data. Significant improvements in the FDD models for detecting single faults were also made, including a new steady-state detector for filtering transient data, a new modeling approach for predicting normal operation variables, and new FDD classifiers that streamline calculations. The revised FDD tool also incorporates overall performance models, which act as virtual sensors to estimate some system performance variables that cannot be economically measured. These system variables can be used to access the impact of the fault on the system performance in order to evaluate whether the diagnostic service should be performed.

Recommendations: With successful field tests, further development of this promising FDD technology is recommended. Field Diagnostic Services, Inc., a supporting contractor involved in developing FDD products, and Honeywell, Inc., a match fund provider on other projects within the program, participated in the field activities of this project. Both companies have expressed interest in further development of the automated FDD technology.

FDD of Air Handlers and VAV Boxes

Researchers: Jeffrey Schein, Steve Bushby, and Natascha Castro, National Institute of Standards and Technology; John House, Iowa Energy Center

Objective: The purpose of this research effort is to develop, test, and demonstrate FDD methods that can detect common mechanical faults and control errors in air-handling units (AHUs) and variable-air-volume (VAV) boxes. The tools are intended to be sufficiently simple so that they can be embedded in commercial building control systems and rely upon only sensor data and control signals that are commonly available in commercial building automation and control systems.

Results: AHU Performance Assessment Rules (APAR) and VAV box Performance Assessment Control Charts (VPACC) have been designed from

the ground up to be embedded in commercial HVAC equipment controllers. In laboratory testing, the APAR and VPACC tools were both found to be successful at finding a wide variety of faults including stuck or leaking dampers and control valves, sensor drift, and improper control sequencing. Some faults could not be detected under certain operating conditions because the control system was able to mask the problem or because sensor data needed to detect the fault is not commonly available in commercial systems.

The field research involved collecting AHU and VAV box data from several field sites, including an office building, a restaurant, and community college and university campuses, featuring constant- and variable-air-volume systems. The effectiveness of these tools in detecting commonly found mechanical faults and control problems, the reliability of the tools across several seasons, and the robustness of the tools in handling data from a variety of system types and configurations were investigated. Several faults were successfully detected and confirmed by building operations staff. Every site was found to have at least one fault.

Even though the sample size is small, these results appear to confirm the hypothesis that faults can commonly be detected by these tools. Both APAR and VPACC appear to be suitable for embedding in commercial control products. The research results have not been deployed commercially, but there is a high likelihood that controls manufacturers will adopt the technology. Several commercial partners provided control products for embedding the APAR and VPACC diagnostic rules.

Recommendations: For these automated fault detection procedures to be packaged within HVAC control products, more work is needed in three main areas. First, it is impractical to expect trend data to be evaluated to determine the necessary parameters and thresholds for each site, as was done in this study. Additional field data from a wide variety of systems must be collected in order to determine robust parameters and thresholds.

The FDD tools developed were embedded in the controllers using generic mathematical functions available in the languages in which the controllers are programmed. Although this approach is suitable for a technology demonstration, built-in APAR and VPACC functions would greatly simplify the task of embedding FDD in a control program. Finally, more work is needed to develop ways to interpret FDD results and deliver this information to the building

operator. A mechanism is needed to resolve conflicting fault reports before reporting them to the operator.

Field Performance of Small HVAC Systems

Lead Researchers: Don Frey and Pete Jacobs, Architectural Energy Corporation (AEC)

Objective: The goal of this research is to identify problems with rooftop heating, ventilating, and air conditioning (HVAC) systems in the field including controls, distribution systems, and operation/maintenance practices that lead to poor system performance. Problems will be identified through short-term monitoring and on-site surveys of current practice.

Results: A total of 75 buildings and over 200 rooftop HVAC systems were studied. The project identified a number of problems with field installation and operations including broken economizers, improper refrigerant charge, fans running during unoccupied periods, fans that cycle on and off with a call for heating and cooling rather than providing continuous ventilation air, low airflow, inadequate ventilation air, and simultaneous heating and cooling. Correcting these problems represents a major opportunity for improvements in energy efficiency, operations, and indoor comfort. Preliminary findings revealed that:

- 70 percent of units have economizers that do not function optimally

- 40 percent of units have low air flow

- 45 percent of units have fans that run during unoccupied periods

- 28 percent of units have problems with cycling fans

To avoid the problems identified in the study in the future, design teams and contractors should ensure rooftop HVAC systems are properly sized and the appropriate components selected and properly installed. The distribution, ventilation, thermostat and control systems should be integrated. Also, the entire HVAC system should undergo commissioning to ensure it performs as designed and regular maintenance checkups should be scheduled. As a result of this research, the Small HVAC System Design Guideline was developed.

Recommendations: The Consortium for Energy Efficiency's staff is surveying member commercial

program managers to identify interest in supporting a new specification that improves in-field performance by using factory-installed components and on-board diagnostics. AEC and the New Buildings Institute are jointly working to develop an advanced package rooftop unit specification, partnering with Carrier to achieve changes in the market for small commercial rooftop units.

Download: A design brief based on this research (Integrated Design for Small Commercial HVAC) is available through Energy Design Resources website http://216.98.139.76/resource/162/

GUIDES FOR COMMISSIONING AND CONTROLS

Diagnostic and Energy Information Tools

Objective: This task was designed to evaluate current diagnostic tools and systems to help improve future implementations of these tools for both energy and peak demand analysis. The research resulted in two guides that detail the currently available options for diagnostic tools and web-based energy information systems (EIS). The final few months of the project has included reviewing the costs and benefits of EIS including a review of GSA buildings, UC Santa Barbara, and buildings that have Lawrence Berkeley National Laboratory's Information Monitoring and Diagnostic Systems.

1) Comparative Guide to Emerging Diagnostic Tools for Large Commercial HVAC Systems

*Researchers***:** Hannah Friedman and Mary Ann Piette, Lawrence Berkeley National Laboratory (LBNL)

Results: This guide compares emerging diagnostic software tools that aid detection and diagnosis of operational problems for large HVAC systems. The diagnostic tools summarize relevant performance metrics, display plots for manual analysis, and perform automated diagnostic procedures. There are two main purposes in writing this guide: 1) to help potential tool users gain an understanding of key diagnostic capabilities that could affect tool implementation with EMCS data, and 2) to provide tool developers with feedback by identifying important features and needs for future research.

The six diagnostic tools included in the guide are:

- ENFORMA® Portable Diagnostic Solutions, Architectural Energy Corporation
- AHU Toolkit for Built-up Fan Systems, University of California, Berkeley
- Universal Translator (UT), Pacific Gas and Electric
- Whole Building Diagnostician (WBD) outdoor air economizer module and whole building energy module, Pacific Northwest National Laboratory
- Performance And Continuous Recommissioning Analysis Tool (PACRAT), Facility Dynamics Engineering
- Enterprise Energy Management Suite, Silicon Energy Corp.

Nine tables summarize the tool scope, development history, market issues, set-up, diagnostic capabilities, level of automation, and development plans. An evaluation of specific system diagnostics focuses on the air-side economizer, since this is the most common diagnostic area across the tools. Sample diagnostic screens for each tool are presented.

Download: The full report is available at http://buildings.lbl.gov/hpcbs/pubs/r_48629.html

2) Web-based Energy Information Systems for Energy Management and Demand Response in Commercial Buildings

Researchers: Naoya Motegi, Mary Ann Piette, Satkartar Kinney, and Karen Herter, LBNL

Results: Energy Information Systems (EIS) for buildings are becoming widespread in the U.S., with more companies offering EIS products every year. As a result, the quickly expanding portfolio of EIS features and options often overwhelms customers. The objective of this report is to provide a technical overview of currently available EIS products.

In particular, this report focuses on web-based EIS products for large commercial buildings, which allow data access and control capabilities over the Internet. EIS products combine software, data acquisition hardware, and communication systems to collect, analyze and display building information to aid commercial building energy managers, facility managers, financial managers and electric utilities in reducing energy costs in buildings. Data types commonly processed by EIS include: energy consumption data, building characteristics, building HVAC and lighting system data, weather data, energy price signals, and demand-response event information.

This project involved an extensive review of research and trade literature to understand the motivation for

EIS technology development. This study also gathered information on currently commercialized EIS. This review is not an exhaustive analysis of all EIS products; rather, it is a technical framework and review of current products on the market.

An additional part of the study examined the practical experiences of using web-based Energy Information Systems to improve building operation at three sites, as described in Montegi's "Energy Management Case Studies using Energy Information Systems" within these proceedings:

Download: The full report is available at:
buildings.lbl.gov/hpcbs/pubs/E5P2T1b5_LBNL52510.pdf

Functional Testing Guide For Air Handling Systems

Researchers: David Sellers, Hannah Friedman, and Tudi Haasl, Portland Energy Conservation Inc. (PECI), Mary Ann Piette and Norman Bourassa, LBNL

Objective: This project supplies commissioning providers with details about how to perform functional tests for air handling systems. Pacific Gas & Electric's *Commissioning Test Protocol Library* (CTPL) was recently developed to bring together all of the publicly available commissioning test procedures in the industry in effort to improve the cost-effectiveness of commissioning services. The test library provides the necessary forms, but does not provide information on why a test is important and other details about how to execute the test. For these reasons, the *Functional Testing Guide for Air Handling Systems: From the Fundamentals to the Field* (FT Guide) was developed.

*Results***:** The FT Guide allows users to directly access the pre-functional and functional test procedures compiled within the CTPL. In a uniquely practical way, the FT Guide describes the fundamentals of air handling systems as they relate to these commissioning tests. The educational information assists users in better understanding the benefits of each test, instrumentation, test conditions, time required to test, acceptance criteria, and potential problems that may occur during air handling system test procedures. Additionally, common operational problems and their solutions are explained, with spreadsheets included to help quantify energy implications. This information has been developed for the following air handler subsystems:

1. Outdoor Air Intake
2. Fan Casing
3. Economizer and Mixed Air
4. Filtration
5. Preheat
6. Cooling
7. Humidification
8. Reheat
9. Warm-Up
10. Fans and Drives
11. Distribution
12. Terminal Equipment
13. Return, Relief and Exhaust
14. Scrubbers
15. Management and Control of Smoke and Fire
16. Integrated Operation and Control

Initial feedback on the FT Guide has been highly positive as the industry recognizes the need for greater understanding of commissioning procedures and the need to disseminate the standardized procedures in the CTPL. At the National Conference of Building Commissioning in May 2003, almost 200 copies were distributed on CD-ROM. Additionally, over 100 copies were downloaded from LBNL's website, a demand that greatly exceeded expectations. PG&E's Pacific Energy Center will also be providing training based on the guide.

*Recommendations***:** The following tools and training should be developed that draw upon the current level of FT Guide development:
- Commissioning providers should pilot the guide in real functional testing situations and give feedback for future revisions.
- Gaps in publicly available functional test procedures should be gathered by surveying commissioning providers. Tests should be written to fill these gaps, and the tests incorporated into the FT Guide.
- The effectiveness of the FT Guide should be enhanced by providing training based on the Guide. Commissioning provider training workshops would focus on describing how to use the FT Guide to improve functional testing. Creating and performing a functional test during the workshop will solidify concepts learned.
- To facilitate the use of the FT Guide, a tool could be developed that outputs a checklist of appropriate functional tests based on project criteria entered by the user.

Download: The Functional Testing Guide is publicly available for download at:
http://buildings.lbl.gov/hpcbs/FTG

Persistence of Commissioning Benefits

Researchers: Hannah Friedman, Amanda Potter, and Tudi Haasl, PECI; David Claridge and Soolyeon Cho, Texas A&M Energy Systems Laboratory

Objective: The objectives of this task are to:
- Investigate whether mechanical system performance in buildings degrades over time
- Study how significant degradation is over time
- Investigate the reasons for persistence or lack of persistence
- Determine methods for improving persistence

Although the success and cost-effectiveness of commissioning activities depend on how well the benefits of commissioning persist over time, this aspect of commissioning is not well understood.

Results: As the first study of persistence of savings from retrocommissioning, ten buildings at the Texas A&M campus were analyzed. Two years after retro-commissioning, the savings were 83% of the initial retro-commissioning savings. Although savings decreased, the facilities still saved about 34% of their total energy usage compared to before retrocommissioning. Three fourths of the decrease in savings was due to component failures in two buildings. The remainder of the changes in consumption was shown to be quantitatively consistent with specific control changes in the buildings following commissioning. These results emphasize the importance of ongoing tracking of consumption to identify the presence of problems that decrease efficiency without causing comfort problems.

A second study focused on the performance over time of buildings that were commissioned as new construction. The findings reveal that for new building commissioning, a majority of items identified as problems and fixed during commissioning continued to show benefits many years after commissioning. In new buildings, the longest lasting benefits came in two areas: modifications to equipment that did not require further adjustments, and control system programming changes that are not easily accessed through the workstation user interface. However, every building studied had fixes that did not persist. The most problematic and least durable fixes were control strategies like schedules and setpoints that were modified through the workstation interface.

As a result of this study, a guide was developed to inform building owners, managers, and operators about strategies for improving the persistence of commissioning benefits. The strategies described include:
- Design review
- Building documentation
- Operator training
- Building benchmarking
- Utility tracking
- Trend analysis
- Recommissioning
- Continuous Commissioning

This guide is a practical document where each persistence strategy is described in detail: why it is important, what is involved, who performs the work and what other resources are available. This guide is available for distribution to building managers and operators that are interested in improving the long-term performance of their buildings (Friedman et al., 2003).

*Recommendations***:** This initial persistence study has attracted considerable interest from California utility program managers assessing the value of commissioning as well as those interested in ensuring the persistence of the benefits of commissioning. However, this initial study had limited funding, with only ten new construction commissioning sites and ten existing building commissioning sites studied. In addition, there was a lack of documentation on how building occupancy, use, and conservation strategies changed since commissioning. As a result, the study provided mainly qualitative information on the persistence of commissioning.

More research on the persistence of commissioning benefits is needed, involving a larger population of buildings that have well-documented commissioning processes. The California Commissioning Collaborative (CCC) is interested in using their Commissioning Case Study Database as a means to collect the information necessary to study persistence in a standardized way in California.

Download: Reports are available at http://buildings.lbl.gov/hpcbs/Element_5/02_E5_P2_2_5

Implementation of Monitoring Systems in Existing Buildings

Developers: Yasuko Sakurai and Charles Culp, Energy Systems Laboratory, Texas A&M University

Objectives: The objective of this research is to develop guides for owners and building engineers that specify how to use existing control systems as an accurate energy monitoring system. In addition, the project focused on developing sensor fault detection technology that can be used to determine when specific sensors have drifted out of calibration.

Results: Guides for the implementation of monitoring systems were created for three control systems: TAC-Americas, Andover Controls, and Siemens systems. The results of this research effort showed that EMCS systems can be brought up to a functional level which allows data logging of critical energy use. The Guides can also be used for general sensor selection with other manufacturers' systems. The available Guides provide the steps to perform these upgrades, covering the system functionality and the specific sensors needed.

The sensor fault detection technology developed through this research requires that sensor values have interdependencies - most energy systems in buildings satisfy this requirement. Synthetic chiller data was used to test this concept at 1%, 5% and 10% noise levels. The auto-associative neural network (AANN) detected the drifting sensor value even at 10% noise level.

Recommendations: The monitoring system guides should be disseminated as widely as possible, so that building owners and operators can take the necessary steps to ensure that building control systems can provide energy performance information. Further work is recommended for sensor fault detection technology development, as this may have far reaching impact.

Download: The monitoring guides are available at http://buildings.lbl.gov/hpcbs/Element_5/02_E5_P2_2_2.html

CONCLUSION

The PIER buildings research has already led to the development of existing building commissioning and diagnostics tools that have proven their worth in the field. Several control system manufactures have participated as industry partners in this research and now have the opportunity to incorporate diagnostics and monitoring capabilities into their control products. The comprehensive reviews of existing diagnostic tools and energy information systems have been used by building owners and operators to make key decisions to improve ongoing building operations. Designers, commissioning providers, building operators, and facility managers have used guides for commissioning and controls to improve the performance of existing buildings.

These PIER-funded automated tools and resources help commissioning providers improve the quality their services and increase the persistence of commissioning benefits. Through further dissemination efforts, the benefits of the PIER research will be far-reaching – beyond California to the national and international commissioning industry.

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