Data from control systems and dataloggers are useful for quantifying the performance of HVAC systems

Capturing and Using Building-Generated Data

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We are in the midst of a data-driven, decision-making society. Today, more than ever, HVAC professionals *must* quantify the performance of their systems and provide cost-benefit analyses supporting their requests for new equipment, software, and training.

No problem.

For operations and maintenance support, commissioning, real estate transactions, performance contracting, utility rate negotiations, and other purposes, the burgeoning field of diagnostics addresses many quantification issues with a wide variety of special equipment and software. The basis of diagnostics is measurement, and measurement is the basis of verification. HVAC systems are perfectly capable of being measured, and sensors connected to dataloggers and building automation systems are perfectly capable of measuring them.

There are a number of diagnostic approaches, each requiring special hardware, software, and techniques. This article describes diagnostic approaches based on selected papers and presentations from the workshop, Diagnostics for Commercial Buildings: Research to Practice, held in San Francisco on June 16 and 17 at the Pacific Energy Center. The workshop was hosted by Lawrence Berkeley National Laboratory (LBNL), Pacific Gas & Electric (PG&E), and the California Institute for Energy Efficiency. Additional support was provided by HPAC Engineering, ASHRAE Golden Gate Chapter, and BOMA San Francisco.

The papers and presentations have been published on a Website maintained by LBNL at *http://poet.lbl.gov/*. (Please note that this address does not begin with the usual "www.") Access to the proceedings is free. The topics of the papers include introductory lessons on diagnostics, descriptions of commercially available products, and updates on cutting-edge research being conducted at universities and national laboratories. Some of the presentations at the workshop discussed automated diagnosticians and model-based methods. For brevity, this work is not covered in this article; instead, emphasis is placed on techniques, equipment, and software utilizing commercial controls and dataloggers as sources of diagnostic information.

DIAGNOSTIC METHODS

There are two levels or stages of diagnostics: fault detection and fault diagnosis. These are often lumped together and discussed as fault detection and diagnosis (FDD).

Fault detection is the determination that the operation of the building is incorrect or unacceptable in some respect. Unacceptable behavior may occur over the whole operating range or be confined to a limited region and, hence, only occur at certain times. Detection can be accomplished either by:

- assessing the performance of all or part of the building over a period of time (*e.g.*, from utility bills or complaint frequencies) and then comparing that performance to what is expected; or
- monitoring the temperatures, flow rates, and power consumption and continuously checking for incorrect operation or unsatisfactory performance.

Fault diagnosis is the identification or localization of the cause of faulty operation. It involves determining which of the possible causes of faulty behavior are consistent with the observed behavior. Automated fault diagnosis relies entirely on sensors and so may not be able to identify the nature of the fault unambiguously, although it may be able to eliminate some of the possible causes.

In addition to establishing the physical cause of faulty operation (*e.g.*, fouled coil, over-ridden control function), it is desirable that automated diagnosticians be capable of estimating the cost of fixing the fault and the cost of delaying fixing it. This helps administrators and operators set priorities for maintenance actions.

Fault Types

Faults can arise at every stage in the building life cycle, for example:

- planning; *e.g.*, actual building occupancy incorrectly anticipated or specified;

Datalogger Methods

We are familiar with the concept of short-term monitoring as it applies to medical diagnostics such as EKGs, MRIs, etc. The same concept applies to buildings. We can apply dataloggers and specialized software to collect data that are subsequently used in diagnostic analyses performed by specialists (Figure A).

Diagnostics based on short-term monitoring can reveal and unravel problems created over time that would be very difficult to identify in a typical service call. The premise is that by looking at graphs that represent key relationships of how the system operates over time, operating efficiencies can be clearly identified. Figure B is a graph of data taken from a 60,000 sq ft office building where high energy bills resulted in an investigation using datalogger methods. Simultaneous heating and cooling was one of the reasons for higher-than-expected energy consumption.

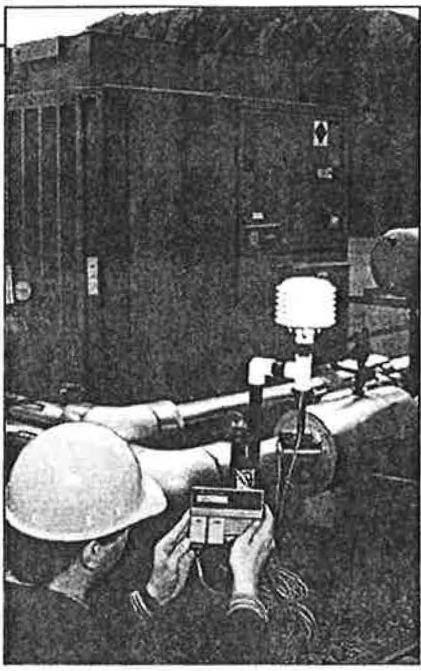

FIGURE A. Ambient temperature and RH being monitored from building rooftop.

A procedure for using datalogger methods is outlined below. The full paper presents a detailed case study of the office building, where a $22,000 investigation resulted in annual energy savings of $57,000.

PROCEDURE

The short-term monitoring process is divided into three steps: project planning, measurement of system data, and data analysis. After the data are analyzed, corrective measures are taken. The short-term monitoring process can be re-applied if the effectiveness of the measures needs to be ascertained, for example, for payback analysis or contractual performance assurance.

Planning. The objective of the planning step is to establish the data streams that need to be collected by the data acquisition equipment. The person responsible for the diagnostic activity conducts all of the tasks necessary to determine what measurements should be made and prepares the monitoring equipment. Activities in this process include:

- state the goals and objectives of the monitoring and diagnostic processes, including any "data products" required;
- obtain copies of mechanical plans and specifications, including control drawings and sequences of operation;
- tour the building with the operations staff to gather information about the building and its systems;
- interview operations staff to discuss obvious or chronic problems, operating and occupancy schedules, operation of the EMCS, and any other information they can provide;
- determine the methods that will be used to analyze the data;
- develop a list of data requirements based on the plans and building tour and determine where all the measurements will be made in the building;
- assemble the dataloggers and sensors;
- program the dataloggers.

Measurement. The objective of the measurement step is to collect the data needed for analysis. The building should be operated in a normal manner during the monitoring period. Activities in this process include:

- install data acquisition equipment in the building (central plants, systems, and zones);
- verify the correct operation of all equipment;
- operate the building in a normal manner;
- retrieve the loggers and sensors at the completion of the monitoring period;
- patch holes and restore the site to the condition it was found.

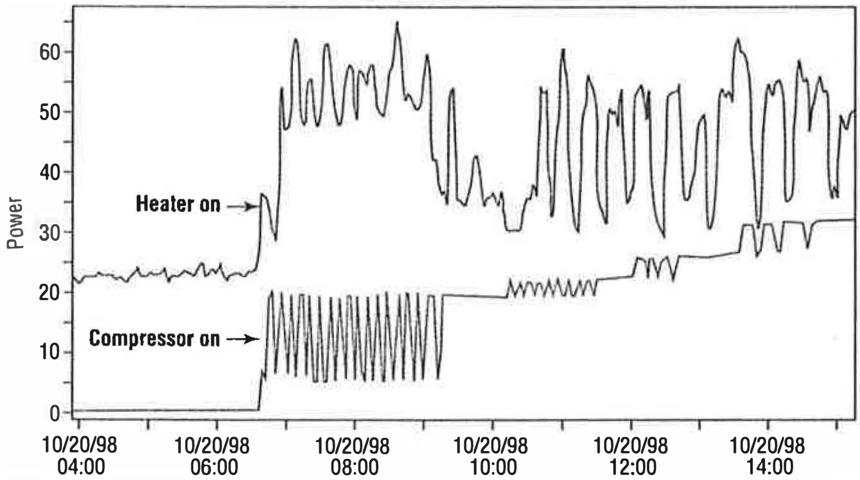

FIGURE B. Diagnostic graph showing simultaneous heating and cooling.

Analysis. The objective of the data analysis step is to understand the operation of the systems and distinguish the systems that are working properly from those that are working improperly or inefficiently. Activities in this process include:

- download the data from the loggers to the computer;
- use software-based automated analysis tools or spreadsheets to create the graphs needed to detect problems; and
- calculate the energy and cost savings that can be achieved through repairs, modifications, and equipment replacements.

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- design—design basis fails to meet design specification; *e.g.*, under-sizing or over-sizing;
- incorrect installation; *e.g.*, motor phases wired incorrectly;
- commissioning; *e.g.*, poor control loop tuning;
- changes made by the operator that may improve operation under a limited set of conditions; *e.g.*, disabling mixing box dampers;
- equipment failure; *e.g.*, broken fan belt;
- equipment degradation; *e.g.*, coil fouling.

To be able to detect a fault, *i.e.*, to know that the observed operation is incorrect or unsatisfactory, it is necessary to have some reference, or baseline, to which actual performance may be compared. Possible sources of this baseline include:

- design brief; *e.g.*, provide comfort at given occupancy level;
- codes and standards; *e.g.*, California's Title 24;
- rules of thumb—'standard practice';
- design basis; *e.g.*, heating coil should provide a particular duty under particular conditions;
- manufacturer's specification; *e.g.*, chiller performance map;
- performance of comparable buildings; *e.g.*, whole building energy consumption (Btu per sq ft per yr);
- *in situ* test performance; *e.g.*, results of acceptance test during commissioning
- 'normal' operating data, collected when system is assumed to be operating correctly.

The choice of baseline depends on the kinds of faults that need to be detected. For example, comparing the current capacity of a cooling coil to the capacity observed during commissioning can show that it is fouled but cannot show that the wrong coil was selected. The earlier in the life-cycle a particular fault arises, the more restricted is the choice of baseline that can be used to detect the problem, since the baseline has to originate earlier in the life cycle than the fault for it to be detectable.

Physical faults in HVAC systems can be divided into two classes: abrupt faults; *e.g.*, broken fan belt; and degradation faults; *e.g.*, coil fouling. Abrupt faults are easier to detect because they generally result in a sudden failure of some part of the plant, although they are not necessarily easier to diagnose. In the case of degradation faults, it is necessary to define a threshold below which the fault is considered insignificant and above which it is considered desirable to detect the fault.

Performance Verification and Performance Monitoring

Diagnostic methods can be applied either during on-going operation or at specific critical phases in the building life cycle; *e.g.*, commissioning, retrofit, or change of ownership.

Short-term testing, sometimes known as performance verification, involves deliberate exercising of the appropriate systems; *e.g.*, by changing set points or introducing artificial heat loads to get as much information as possible about the behavior of the system in a limited period of time—usually when the building is unoccupied.

Long-term performance monitoring involves passive observation of the behavior of the systems of interest, waiting for operating conditions to change so as to reveal particular faults. Long-term monitoring requires the use of an energy management and control system (EMCS) or a dedicated monitoring system. An approach that falls between these two extremes is to install special monitoring hardware, such as dataloggers with internal memory, for a limited period; *e.g.*, two weeks. This produces a 'snapshot' of building operation that can be analyzed to check for those faults that manifest themselves under the operating conditions encountered during the monitoring period.

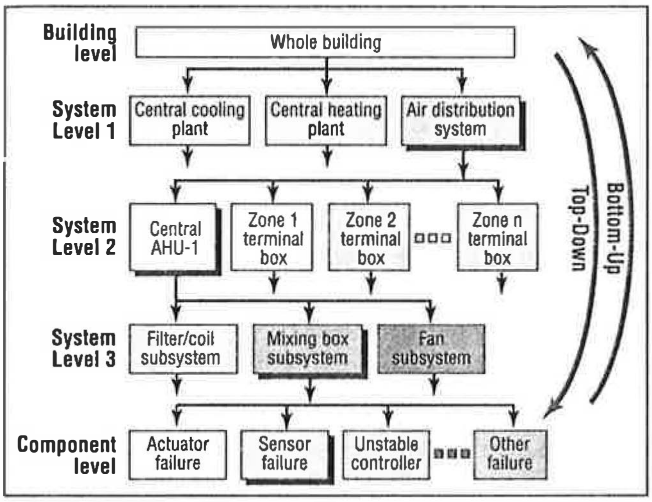

FIGURE 1. Top-down and bottom-up approaches to diagnostic reasoning. (Adapted from IEA Annex 25, 1996, Building Optimization and Fault Diagnosis Source Book, *Eds. J. Hyvärinen and S. Kärki, Technical Research Centre of Finland)*

The baseline that is used as a reference in performance monitoring can either be derived from design information and manufacturers' data or from performance data measured when the system is correctly operating. In the case of performance verification at commissioning time, only design information and manufacturers' data can be used, since the system has not yet operated.

Whole Building and Component-Level Diagnostics

Most current R&D in diagnostics can be categorized as either:

• whole building level—a 'top down' approach in which the main focus is on the energy consumption of the whole building and the major systems (chilled water, lighting, fans);

- component level—a 'bottom up' approach focussing on the operation of individual items of equipment and performance at the local loop level.

The ultimate goal is to link these two approaches (Figure 1).

At the whole building level, the baseline against which performance is compared can either be a database of the energy consumption of different buildings or a simulation model such as DOE-2, which defines the performance expected by the designer. Simulation models are starting to be used as the basis of performance contracts.

At the component level, the baseline can be provided by design calculations, the manufacturer's performance data (corrected for allowed tolerances), or performance measured either during commissioning or during a period of 'correct' operation. A presentation by Karl Stum (PECI) described how diagnostic methods could benefit the commissioning process.

Manual and Automated Procedures

Manual procedures rely on a human operator to initiate the collection and display of data and to perform the subsequent analyses. Manual methods include setting up an EMCS trend log or installing portable dataloggers and using the data to troubleshoot an occupant complaint or an energy bill that is higher than expected. There are many other uses as well. Papers on manual methods were presented by Mary Ann Piette (LBNL), Don Frey (Architectural Energy Corporation), Todd Rossi (Field Diagnostics Services), and Steve Blanc (PG&E).

Automated procedures use pre-programmed procedures to collect and analyze data on a routine basis and report conclusions without being prompted; *e.g.*,. monitoring mixing box temperatures and damper control signals at different operating points and diagnosing a leaking recirculation damper. Products in this category are sometimes called "automated diagnosticians." Papers describing these methods were presented by Tim Salsbury (LBNL), Michael Brambley (PNNL), and Rob Pratt (PNNL).

Semi-automated procedures use a combination of manual and automated methods; *e.g.*, monitoring chiller efficiency and displaying a graph of KW per ton vs. tons, and checking if the KW per ton significantly exceeds the value expected for the current operating conditions. Papers on these methods were presented by David Claridge (Texas A&M), Leslie Norford (MIT), and Jim Braun (Purdue University).

Work on manual performance monitoring procedures for use during normal operation has focused on graphical methods of displaying the measurements to the operator to allow efficient fault detection and then fault diagnosis. Displaying information to an operator is also an issue for automated tools, because such tools are unlikely to be accepted unless they can display the evidence and provide justification for a

Whole Building Methods

Whole-building diagnostics may be considered a 'top-down' approach. The performance of the whole building is examined to determine whether there are indications of problems in the way the building or its systems are operating. This approach can be expected to spot large problems; *e.g.,* problems that typically lead to increases of 5 percent or more in energy use. It can not be expected to locate an office where the occupants never turn off the lights! However, many, many buildings have problems that are amenable to whole building diagnostics; we argue that the first stage of any diagnostic program should install the equipment needed to identify major problems. Then, refinements may be added as needed to operate a building or buildings in the most economically efficient and effective way.

Most whole-building diagnostic procedures can be split into two major categories—examination of time series data, and use of physical or empirical models in the analysis of whole-building data streams. The examination of time series data is described below; the full paper discusses of the use of models.

Diagnostics with Time Series Data . The simplest form of diagnostics with whole-building data is manual or automated examination of the data to determine whether prescribed operational schedules are followed. The normal minimum set of whole-building data required for diagnostics are separate channels for heating, cooling, and other electrical uses. With these data streams, it is possible to identify probable opportunities for HVAC system shutoffs, excessive lighting operation, etc. It is also possible to monitor the effects of energy conservation strategies implemented using modified building operations, equipment upgrades, and repairs.

Blink tests—a valuable way in which whole-building data can be used to identify the

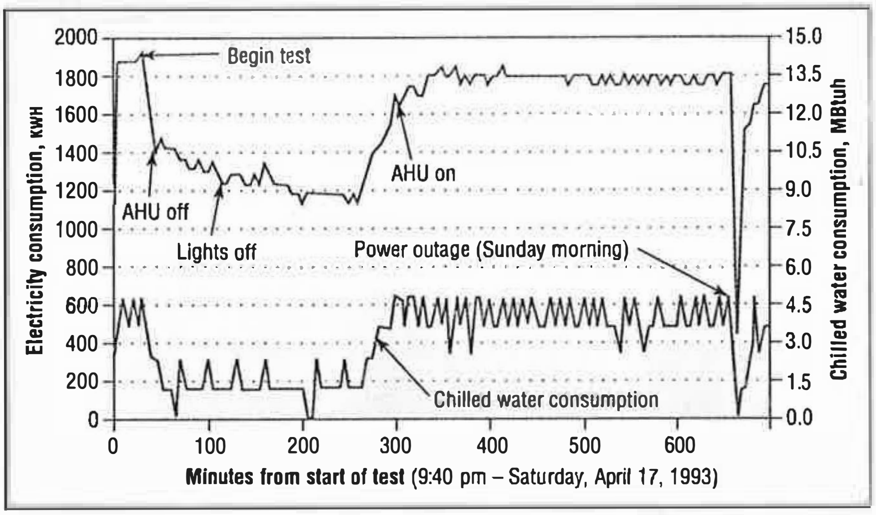

FIGURE C. Data from a short-term (blink) test at a Texas office building.

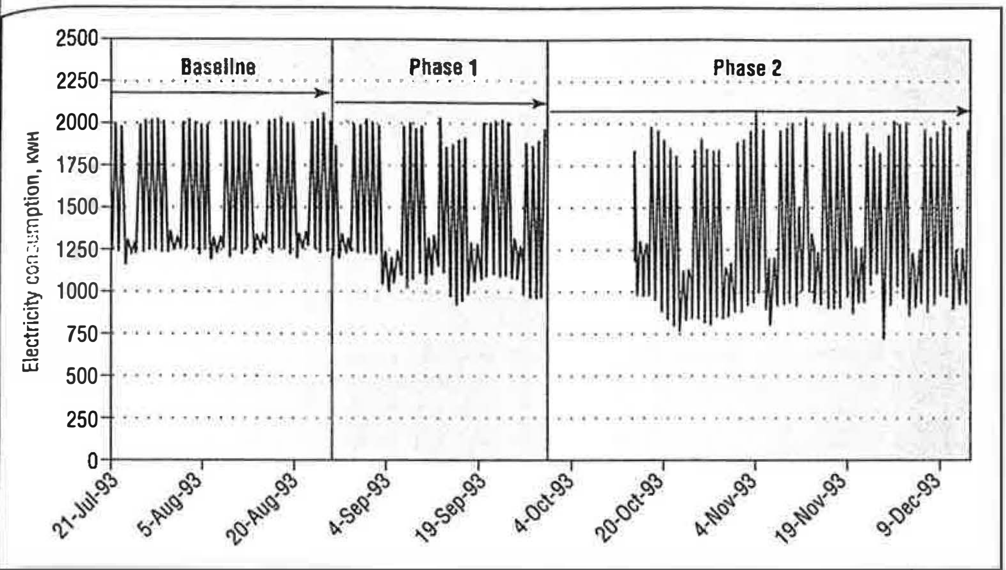

FIGURE D. Whole building lights, receptacles, and air handler electricity use at a Texas office building during progressive shutdown of selected AHUs.

size of various equipment loads such as switchable connected lighting load, AHU consumption, etc., is the use of short-term "blink" tests. Blink tests that last only a few hours can reveal useful data such as the data from an AHU shutdown and lighting turn-off test performed in a Texas office building (Figure C). The plot shows a reduction of three million Btuh in chilled water consumption and 600 kW in electrical load.

Shutoff opportunities—this is often the most intuitive of all diagnostic procedures. However, the use of whole-building data, even with heating and cooling removed, can cause some confusion because nighttime electric use in many buildings is 30 to 70 percent of daytime use. Our experience indicates that while many EMCSs have implemented equipment shutoff opportunities, analysis of time series data can still find opportunities in 10 to 20 percent of buildings. Figure D shows a plot of time-series data where progressive shutoff strategies were employed in the office building depicted in Figure C.

Operating anomalies—a slightly different category of opportunities can be identified using the same techniques. Mistakes in implementing changes in thermostat setup/setback schedules sometimes result in short-time simultaneous heating and cooling, which shows up as large spikes in consumption, which last only an hour or two. Time series plots of motor control centers often show that variable air volume (VAV) systems seldom operate above their minimum box settings—and hence are essentially operating as constant air volume (CAV) systems. Comparisons between typical weather-independent operating profiles from one year to the next will often reveal "creep" in consumption that is often due to addition of new computers or other office equipment.

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fault detection and diagnosis.

The main benefit of automated performance monitoring tools is that they can pre-filter data from many points—avoiding the need for manual inspection of all the measurements from every point. By acting as smart alarms, automated performance monitoring tools have the potential to allow a building operator to spend less time keeping on top of performance and allow remote operators and service companies to monitor multiple buildings efficiently. Ultimately, automated tools may be able to make reliable diagnoses and automatically contact service contractors and direct them to replace particular components.

EMCS or Dedicated Data Acquisition System?

Some diagnostic systems are intended to use data from the EMCS, and some use dedicated data acquisition systems, which may either be installed permanently or temporarily. When considering which method to employ, the following issues apply:

- purpose of monitoring (control performance, energy performance);
- number and type of sensors;
- sensor quality (accuracy, reliability, drift);
- sampling frequency and timestamp accuracy (15 min intervals may be too long);
- data archiving (many EMCSs have limited storage and retrieval capabilities);
- data visualization (many EMCSs have limited manipulation and display capabilities);
- cost (installing a separate monitoring system adds significantly to first cost and also adds to maintenance costs).

Monitoring energy performance requires additional sensors that are not required for control purposes; *e.g.*, electric power meters and fluid flow meters, and requires some sensors to be more accurate; *e.g.*, chilled water flow and return temperature sensors when used to determine evaporator duty. A presentation by Steve Blanc (PG&E) outlined some of these issues.

REMOTE ACCESS TO DIAGNOSTICIANS

Accessing diagnostic software through the Internet is possible in much the same way that access to building automation systems is facilitated by modems and RS-232 connections. At the diagnostics workshop, a password-protected diagnostician developed by LBNL was "toured" using a Web browser.

The recent updates to the BACnet standard allow connections using the Internet Protocol (IP) instead of RS-232. A presentation by Steve Bushby, National Institute for Standards and Technology (NIST), described the two methods by which remote access to controls networks is granted by BACnet. One method, "IP message tunneling" allows BACnet to link buildings without BACnet devices having to understand IP. BACnet/IP, the second method, requires that BACnet devices "speak" using IP directly. HPAC Engineering will publish a separate article on this topic in 2000.

CAVEATS

There are a lot of caveats associated with diagnostic methods and technologies. One large concern is the apprehension that exists among some HVAC professionals, particularly service technicians, who believe that computers are infringing on their turf. Diagnostic systems can operate continually for brief or extended periods of time—they don't have to sleep, take breaks, or respond to distractions such as leaky roofs, office relocations, or chemical spills.

This issue is not limited to functionality but privacy. Automated diagnosticians can detect faulty installations and repairs or maintenance actions that introduce new problems. In other words, they not only monitor the performance of systems, they indirectly monitor the performance of operators and service technicians.

These issues were discussed in a paper presented by Kristin Heinemeier, PhD, Honeywell Technology Center, following a market analysis for an automated diagnostician.

CONCLUSIONS

The upside of all of this is that computer-assisted diagnostic tools are available for facility managers, building owners, and staff engineers—and more are on the way.

That these tools are so well developed at this time is fortunate. The need for them is immense and growing. The HVAC industry is trying hard to change the mindset of building owners, property managers, and other financial decision makers so they view HVAC investments more seriously and set aside ample budgets for good design, quality equipment, and high performance over the life cycle of the building.

IT Gives Building Operators What They Want

LBNL is leading a multi-institutional project to develop, introduce, and evaluate state-of-the-art information technology to enhance building energy performance by focusing on the continual improvement of O&M. An Information Monitoring and Diagnostic System (IMDS), designed by Supersymmetry, Inc., has been installed in a 100,000 sq ft office building located at 160 Sansome Street in San Francisco. The system records 90 points of data each minute. The scope of the data includes HVAC paramenters such as chiller, cooling tower, fan, and pump power; chilled water flows and temperatures; wet-bulb and dry-bulb outdoor air measurements, and lighting, whole-building, and miscellaneous power.

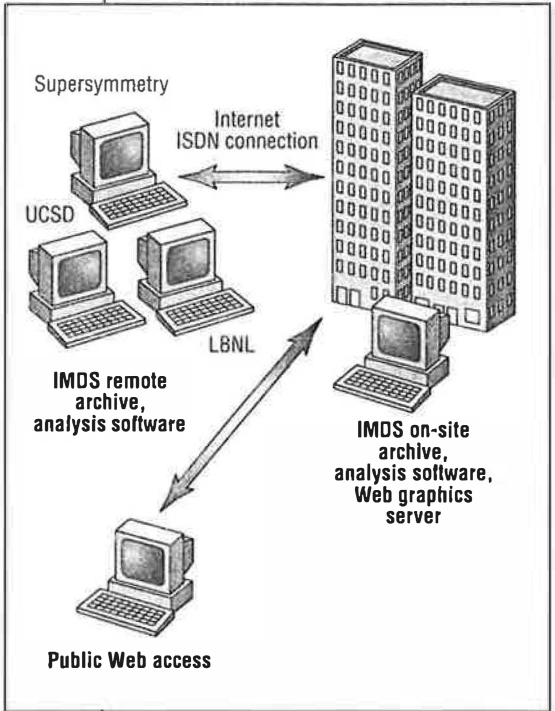

FIGURE E. Illustration shows the data management structure of the IMDS project. The PC at 160 Sansome operates on a Linux system, with an ISDN connection for remote access. For more information about this project, visit http://eetd.lbl.gov/EA/IIT/diag/.

The IMDS uses a data visualization system called Electric Eye that can display eight points of 1 min data collected simultaneously over 18 months, far exceeding what building operators can handle with simple spreadsheets. Building operators select the parameters they want to view and the software automatically plots the trends.

The building operators have used the system to evaluate the overall performance of the building, and report that they have reduced complaint calls from 20 per month 3 per month. Fredric Smothers, technical manager, Kennedy Wilson (a property management company) uses the password-protected, Web-based remote access system almost daily. He and the on-site operator, Glen Starkey, have been able to improve the overall automation of the current controls.

Smothers is designing an EMCS retrofit to capture the large energy savings he thinks he'll obtain based on his new understanding of the performance problems at the building. Other activities within the project include efforts by UC San Diego and LBNL to deploy evolutionary programming and model-based automated diagnostic techniques on the IMDS platform.

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Meanwhile, the societal trend is toward a data-driven, decision-making economy rather than one that relies on expert opinion and judgement.

Diagnostic methods play into this trend nicely because they make building-generated data available for so many uses—from commissioning new buildings to detecting faults and recommending solutions in existing ones—from baselining a building's performance before entering into a utility rate negotiation to verifying the performance of a contracted O&M service. **HPAC**

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