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Assessing in Situ Performance of Advanced Residential Heat Recovery Ventilator Systems: A Case Study of Monitoring Protocol

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ABSTRACT

A federal regional power administration (BPA) has sponsored the Residential Construction Demonstration Project to demonstrate and evaluate energy-conserving innovations in energy-efficient new houses. Incremental energy measure cost and thermal performance of 165 houses have been monitored. This paper is a case study of the planning process and accomplishment of field monitoring in a subsample of 12 occupied houses equipped with automatic data loggers to record heat recovery ventilator performance and other information in real time.

Project organization was necessarily complex and it invited problems. However, some very beneficial steps were taken during project planning and execution. Inevitably, certain problems occurred. Fortunately, the worst potential consequences were averted by foresight and flexible planning during the design and data acquisition phases of the project.

INTRODUCTION

Since 1986 a federal regional electric power broker in the Northwest has sponsored a major residential construction demonstration project. The project's purpose is the demonstration of energy-conserving innovations, but it has contained a strong research component. Part of this research has involved field monitoring of heat recovery ventilators in 12 houses distributed over four northwestern states. This paper is a case study of the planning process and the monitoring.

The 12 houses were a subsample within a larger population of new houses that had both heat recovery ventilators and state-of-the-art envelope construction. Circumstances of the project complicated planning. Funding and major direction were provided by the sponsor, a large federal body that must be responsive to diverse constituencies with changing needs. Project management was provided by the state of Washington's energy agency (hereafter referred to as "managing contractor" or simply "contractor"), under contract to the sponsor. Finally, data acquisition system design, installation, and data retrieval and archiving were performed by a subcontractor. The sponsor, the state agency managing contractor, and three other state energy agencies were all partners in planning.

The managing contractor in the state of Washington operated the project in the four northwestern states. As subcontractors, three other northwestern states—Idaho, Montana, and Oregon—carried out planning and implementation aspects of the project.

During the first phase of the project, which ended in September 1987, 165 new homes were built and occupied. All were required to meet the current standards of the sponsor's new energy-efficient construction programs, which prescribe low U-value envelope construction, tight sealing, and heat recovery ventilators. In addition, each house was to have at least one of several alternative special energy innovations. Some of these innovations involved envelope measures and some pertained to the heat recovery ventilator installations.

There were two levels of field thermal performance data acquisition in the project. All the houses were instrumented to record thermal performance with weekly or more resolution. The 12-house subsample discussed in this paper represented a higher time resolution experiment with more data points per house monitored. The heat recovery ventilator monitoring effort conducted on this 12-house subsample is referred to as the "data logger project."

The overall demonstration project is broad in its scope and objectives. This paper does not pertain to the entire project, only to the experimental design and data acquisition methods for the 12-house data logger project.

CONSTRAINTS

When the project was being conceived in 1985, monitoring protocol and the knowledge of involved parties was less than it is today. However, members of the sponsor's and managing contractor's staffs had attended a landmark workshop on building energy monitoring in 1985, sponsored by the U.S. Department of Energy and a national laboratory. Those in charge of implementing the project were informed about planning and managing such projects. From the beginning, however, it seemed impossible to design and implement the research "by the book." Some of the constraints were unique to the project. Others were likely to be endemic to all such projects. Planning constraints included:

- Tight schedule
- Complex bureaucratic structure

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- A major demonstration goal that was sometimes incompatible with research goals, and
- Knowledge and significant issues continuing to evolve after critical planning stages passed.

Implementation constraints included:

- Widely dispersed field locations
- Use of human subjects
- Dissimilar house and ventilator designs, and again
- Knowledge and significant issues continuing to evolve after critical implementation stages passed.

Early awareness of the constraints and a flexible approach helped to mitigate problems.

PLANNING

By the summer of 1985, the project had been conceived as a test and demonstration of several energy-saving innovations. All of the more than 200 targeted houses were to have heat recovery ventilators. Some of the innovations involved the heat recovery ventilators. It had been decided that basic energy consumption data, including air-to-air heat exchanger run time and weekly average "sensible effectiveness," would be monitored in all houses. "Sensible effectiveness" was eventually defined to mean the ratio of exhaust air temperature drop to the indoor to outdoor temperature differential. Engineers were frustrated that there was no easy way to measure heat recovered by the heat recovery ventilators. It was decided that a subsample of homes needed to be monitored, at a higher level, to truly understand their field performance. The paramount need was for a protocol to measure recovered heat.

The sponsor's engineers and state agencies visualized an automatic hourly data logger to record recovered heat. They were familiar with other programs using real-time monitoring equipment, including an earlier one funded by the sponsor and operated by a national laboratory (Mazzucchi 1985), and a similar project sponsored by a northwestern state and a non-profit research organization and conducted by a private contractor (Fowlkes 1985). It was felt that a similar program could monitor air flow rates and temperature differences and, with appropriate algorithms, compute heat recovery in real time.

Much of the planning at this stage took place in large meetings attended by the sponsor and state personnel, including program personnel as well as engineers. Agendas covered all aspects of the overall project, not just the data logger project. Many people had experience with building energy monitoring projects, but there was limited *technical* knowledge about higher level real-time monitoring and related problems. Opinions and goals varied. Some felt it better to capture all information that might be useful in case it was needed after the program cycle was over. Others were skeptical about the research component altogether, since it had the potential to conflict with demonstration goals. There was also very legitimate concern that securing high-resolution data on a small number of houses would consume resources that could better be used to increase the overall sample size. A large sample was considered important for statistical validity and for meeting the demonstration goals of the overall project.

The managing contractor's engineers had the lead role in field data acquisition and, as such, they held a research orientation. Their perspective was to generate information sufficient to facilitate an engineering understanding of the heat recovery ventilators' performance in the field. It should provide an in-situ performance record in great enough detail to reconcile field performance to that which was anticipated based upon theory and lab testing. Any performance disappointments should be detected, understood, and explained from the data. They wanted to know more than how well equipment performed; they wanted to know *why* it performed at observed levels. It was envisioned that this would be valuable information for manufacturers in refining or developing new generations of products.

No research objectives, questions, or analysis plans were formalized specific to the data logger project until the data retrieval was almost completed in March 1988. These were finally prepared by the managing contractor after the sponsor indicated that a proposal, from the contractor, to perform analysis, would be considered. There were, however, formal objectives for the overall project:

1. To develop and refine predetermined conservation techniques and innovations.

2. To examine predetermined conservation techniques and innovations by gathering specific data on reliability, cost effectiveness, and marketability.

3. To expand the use of innovations that show potential to be reliable, cost-effective, and marketable.

Several methods were developed to accomplish each objective. Those that necessitated this data logger project fall under objective number two. They are:

- Establish thermal monitoring procedures and collect information on the energy use of project homes so that an analysis of the innovations' impacts on energy use can be conducted.
- Collect site-specific data on project homes and innovations such as airtightness of the envelope (blower door test), air changes of the home (perfluorocarbon test), ventilation flow rates, and indoor air quality testing/monitoring in homes with exhaust air heat pumps.

The objectives and methods seemed to dictate that a recording of useful heat recovery and ventilation rates be made in at least a subsample of homes. Heat recovery seemed to dictate a system to sense and integrate upstream and downstream enthalpies with mass flow rates. To determine whether the heat recovered was *useful* necessitated knowing something about the time varying demand for space heating. Because of thermal mass effects and the cyclic nature of heating systems, mere absence of coincident space heat use would not be a reliable indicator of non-useful recovered heat. Various parameters needed to be recorded in real time in order for analysts to deduce the need for space heat and, thus, the usefulness of recovered heat. It was recognized that recording heat recovery and other parameters in real time would be costly. Mainly upon this basis, it was decided by the sponsor, with the contractor and other states' input, to perform the data logger monitoring on a small subsample (initially 20 houses).

In the beginning, well before a monitoring protocol was developed, it was decided to allocate a subsample of

20 homes to the high-resolution monitoring or what had come to be called the data logger project. Ten homes were to have a supply air preheater (duct heater) innovation and 10 were to have an exhaust air heat pump (EAHP) innovation. This was soon revised to change five of the supply air preheater homes to "air-to-air heat exchanger (AAHX) integrated with furnace" homes. The description of these innovations is as follows:

1. Supply Air Preheaters—The supply air preheater was an innovation directed at a condition reported by some house occupants in a prior demonstration program sponsored by the same federal agency. There were reports of cool drafts near the heat exchanger supply registers. The duct heater was intended to temper the air enough to prevent any discomfort.

2. Integration with Furnaces—Integrating the heat exchanger with a forced air furnace was aimed at reducing cool drafts by mixing heat exchanger supply air with furnace return air. It was also directed at cost savings by eliminating redundancy of supply ducting systems. Most heat exchangers were indirectly connected to the furnace system through a single heat exchanger supply point located very near a furnace system cold air return. The furnace fans were to be wired to always run when the heat exchangers operated. Direct connection to furnace ducting was not allowed unless the unit was UL-rated for direct connection.

3. Exhaust Air Heat Pumps—Exhaust air heat pumps are heat pump water heaters that exhaust cold evaporator air outside the home instead of into a confined conditioned or tempered space. This allows them to provide necessary mechanical ventilation to tightly constructed houses. Air is exhausted a few degrees above freezing regardless of outside temperature. This accomplishes considerable latent and sensible heat recovery even on moderate days. The units, used in the project, were configured to supply domestic hot water on a priority basis and contribute to space heating as a secondary priority. Some were convertible to the summer cooling mode by ducting reconfiguration.

It is clear that the real-time capability of the data logger approach was necessary to capture EAHP performance. In fact, real-time monitoring was not essential to capture performance of supply air preheaters or the AAHX furnace integration innovation. These innovations were directed toward cost, comfort, and ventilation distribution effectiveness. They were not devised to (or expected to) significantly change heat recovery patterns from those of a conventional heat exchanger installation. For these two innovations, real-time monitoring was to provide high-resolution data on useful AAHX heat recovery that would be meaningful for AAHX installations whether or not associated with preheaters or furnaces. The data logger project lent visibility to the two innovations. The innovations provided justification to study AAHX field performance, which was controversial, although conventional AAHX installations were not identified as innovations under the project.

The managing contractor had insufficient in-house capability to perform the actual field data acquisition. This was to be contracted out. Great care was exercised in the subcontractor selection process. In November 1985, the contractor's staff searched trade journals and conferred with colleagues and other agencies to assemble a list of all firms that might have the capability to perform the monitoring. They were all advised by letter that RFPs would eventually be issued. They were invited to submit their company descriptions for inclusion on a field data acquisition bidders list. The same letter described the project, as currently envisioned, and invited suggestions for the RFP.

At this point the schedule was tightening. Houses were being built. Data logger wiring and plumbing accommodations (for EAHPs) needed to be placed inside walls before drywall installation. A prewiring and preplumbing specification had to be prepared before monitoring subcontractor selection. This was far from ideal. No one knew what kind of sensors the selected subcontractor would be using. The anticipated number and location of field monitoring data points was still evolving.

As a hedge against the unknown, the managing contractor tried to be conservative and flexible in prewiring and preplumbing. The contractor's engineers reviewed prior projects and specified an instrumentation cable and wiring instructions. What was thought to be an ample surplus of cable runs was specified to allow for damaged runs or increases in anticipated data points. An extra phone line was specified, and empty conduit was installed between the main breaker box and data logger location. The overriding concern was that no demands of the yet-to-be-designed monitoring system would necessitate surface wiring or relocated plumbing.

A large list of bidders was assembled and, in March 1986, the RFP was issued asking for 20 houses to be monitored for a year with a budget ceiling not to exceed $126,500. It briefly articulated a monitoring objective to "generate data from which the following can be determined:

- Energy consumption and/or recovery by the innovations and the systems they affect, on an annual basis and temporally in relation to weather.
- Impact of the innovations on the overall thermal integrity of houses in which they are installed, and annual and weather-correlated space heating energy requirements of those houses."

Engineering personnel had learned that such projects were prone to poor data retrieval rates even when centrally located and well attended by technical staff. Accordingly, the RFP forewarned that the contract would contain monetary penalties for loss of data.

There were a number of questions from potential bidders, mostly about schedule, budget, location of houses, and data loss penalty. In early April 1986, the managing contractor issued a clarification to the RFP which answered most of the questions. It instructed bidders, if they could not meet the budget ceiling, to bid within the ceiling but reduce the number of houses proposed for monitoring. It included a copy of the prewiring specification and instructed bidders to advise the managing contractor immediately if it was not compatible with the system they would propose.

Eleven proposals of varying quality from firms distributed over the United States and Canada were received by the deadline in late April 1986. Bids varied from three houses to 20 houses. The contractor convened a panel of nationally recognized experts in field data acquisition and representatives of the sponsor and the other states to review the proposals. Based upon those comments and its own judgment, the contractor selected three for interviews. The entire review panel met in Olympia, WA, for the interviews. The national experts not only evaluated interviews, but provided copious suggestions regarding monitoring protocol. They made immeasurable contributions to the quality of the project. Following the review process, a subcontractor with a well-established national reputation in the field was selected. The selected subcontractor had proposed to monitor 11 houses for the budget ceiling. The subcontractor was headquartered outside the region, but at the time also had a small office in Bellevue, WA, from which field operations were conducted. Following negotiations, a contract was finally signed in August 1986. The contracted scope of work was essentially identical to that sought in the RFP. There were only minor exceptions at the detail level.

IMPLEMENTATION

System Configuration

Not long after the contract was signed in September 1986, additional funds were approved by the sponsor for expanded monitoring so the contract was amended to cover 13 houses. All systems were installed and reporting data in January 1987.

One of the initial houses could never be monitored because the exhaust air heat pump manufacturer failed to provide the promised unit. The remaining 12 houses represented a broad range of heat recovery technology. They were distributed over a broad climate range from the maritime mouth of the Columbia River to the high, cold, dry Rocky Mountains in Montana. The 12 houses are described below in terms of their heat recovery equipment:

1. Rotary wheel heat exchanger with duct heater.
2. Exhaust air heat pump, exhaust only.
3. Exhaust air heat pump, exhaust only.
4. Exhaust air heat pump, exhaust only.
5. Rotary wheel heat exchanger indirect to furnace.
6. Balanced flow exhaust air heat pump.
7. Balanced flow exhaust air heat pump.
8. Conventional heat exchanger indirect to furnace.
9. Conventional heat exchanger with duct heater.
10. Packaged heat exchanger/furnace combination.
11. Conventional heat exchanger with duct heater.
12. Rotary wheel heat exchanger direct to furnace.

All equipment used by the monitoring subcontractor was purchased "off the shelf." The data loggers were units originally developed for use in remote unmanned weather stations. They were packaged in a tamperproof box along with a modem connected to a dedicated phone line. Programming was contained in volatile memory, i.e., RAM. The program can be reloaded or modified remotely. An internal battery retains the program and data for several hours in the event of a power interruption. The units record up to 21 channels,including indoor and outdoor ambient temperatures as well as all parameters necessary to perform an energy balance for the heat recovery ventilators.

All points were queried every six seconds, and mathematical operations were performed to combine appropriate delta T's, humidities, and flow rates into heat transfer units. Data were accumulated and stored as hourly totals and running averages. At least once per week, the units were interrogated by a central computer at the subcontractor's home office and reset. Hourly data were archived by the subcontractor and transmitted by floppy disk to the managing contractor's office.

Air flow rates were sensed with hot tip air velocity transducers. These give an output proportional to the velocity of the air if it were at standard temperature and pressure. The transducer output was corrected directly to mass flow rate by a constant in the data logger program. The transducers were installed toward the downstream end of the longest straight ducting run available. To ensure accuracy, a duct traverse was done upon installation. This was necessary to find a position for the transducer probe where velocity would accurately represent mass flow. As installed, air flow was recorded within 8% accuracy.

Humidity was sensed upstream and downstream of the heat recovery units in the exhaust stream. These allow latent heat to be reckoned into the heat recovery calculation. Bulk-resistance-type relative humidity sensors were used. Accuracy was within 4% between 30% and 90%. From 90% to 99.9%, 5% accuracy applies.

Air and water temperatures were measured with RTD-type sensors to within 0.5°F(0.3°C).

Electric energy was measured with power transducers that sense voltage and current and give true power, not volt amperes, to the data logger. Accuracy was within the greater of 15W or 3%.

Water flow rate in the exhaust air heat pumps was sensed with a pulse-initiating nutating (i.e., wobble plate) meter. Accuracy was within 3% at flows above 0.2 gpm (13 mL/s).

Process

The anticipated process had to be modified and compressed because of schedule slippage. A late start had caused the loss of the first months of the heating season. In September 1988, the contract was amended, for the second time, to extend monitoring through May 1988 to ensure a full continuous heating season's data in nine houses where homeowners agreed to extended monitoring.

Certain important steps in the monitoring plan were completed before a contract was signed with the monitoring subcontractor. In preparing the RFP, the managing contractor had stated hardware selection guidelines and begun the outline of verification and quality control procedures. Specification of field monitoring data points was done by the contractor in the RFP and minor modifications were suggested by the subcontractor in the proposal. All of these were finalized and formalized in the contract.

One of the modifications to hardware selection guidelines involved accounting for latent heat. It was originally intended to measure latent heat by measuring condensate instead of relative humidity. Another modification involved sensor cables. More sensor cables were necessary because some sensors required four wires. This necessitated another revision to the prewiring/preplumbing specification.

Numerous criteria were balanced in the selection of houses. It was attempted to distribute them equitably among the states and climate zones with all three innovations represented at each location and all major brands of equipment represented. It was also attempted to cluster them near major highways and airports to control personnel travel costs. Importantly, engineers foresaw that problems would occur and had an ample surplus of houses prewired. This proved to be very important and relatively cheap insurance. Houses dropped out because builders did not finish on schedule or innovation equipment manufacturers failed to deliver. Some were finished but the new home buyers wanted no part of the monitoring project. Some had hopelessly botched prewiring. Some houses had such unusual architecture or heating/ventilating systems that they were judged not sufficiently representative of the general housing stock to warrant monitoring.

The contractor's engineers hoped to obtain prewiring and preplumbing of sufficient quality that the monitoring subcontractor would not have to visit the sites prior to installation. This was not achieved; indeed the goal was probably unrealistic. One problem was the power transducers. The contractor was not confident in information received from builders regarding the capacity and location of space heat and other power circuits to be monitored. There were mixed and confusing reports regarding what equipment was on which circuit. Power transducers had to be provided with the lowest possible current range in order to meet accuracy requirements at the low end of the range. It was decided that the subcontractor would make a scoping visit of all sites to be sure they were ready and that all the right equipment was present at the time of installation.

DISCUSSION

Planning Experience

Most of the planning activities now under discussion by the ASHRAE TC 9.6 Subcommittee on Building Monitoring were accomplished during design of this field monitoring project. However, some were done rather informally, and the sequence was closer to the reverse of that suggested by the subcommittee.

No goals, objectives, or research questions were formalized until near the end of the monitoring project. These were finally prepared by the managing contractor after the sponsor indicated that a proposal from the contractor to perform analysis would be considered. The subcommittee has suggested that this be the first activity, and it is logical that it should be. It was easier to slip past this critical activity than today's lucid hindsight would suggest. The data logger project was an offshoot of a much larger overall demonstration and research project. It gradually came to life as a solution to the problem of measuring heat recovery. Understanding of the problem and the complexity of its solution came about gradually. Engineers and program personnel developed a notion of objectives and questions but did not formalize it. Perhaps there was some reluctance to do so since heat recovery from AAHXs was driving the need for real-time data loggers, and the official innovations were not the AAHXs themselves, but the adjuncts. Finally, there is the locked box problem most apparent in basic research. It is hard to anticipate what can be learned, or what its value will be, until the exploration is under way.

Other activities were done in a sequence seemingly contrary to common sense. However, given the late conception of the project, there were no other practical choices. For example, it was impossible to specify all the building characteristics data before hardware selection guidelines. Every house was unique, subject to attrition for various reasons, and experiencing the invariable stream of design changes during construction.

A Catch-22 was that the monitoring subcontractor would have the greatest expertise to accomplish several critical planning activities, but much of this planning had to be done prior to subcontractor selection in order to define the RFP's statement of work and budget ceiling. The contractor tried to handle this gingerly. Several prospective bidders were contacted and asked for assistance in defining the project. They were cautioned of the rigorous controls regulating state and federal contractor selection processes, and warned that another firm might be selected to implement their ideas. This important input was used mostly for prewiring specification development; cost estimating, which ultimately affected the scope of the statement of work; and for specification of field monitoring data points. A specification of data points and a budget ceiling were included in the RFP. The former was modified slightly for technical reasons during contract negotiations, and the latter was modified by amendment later when the sponsor approved additional funds to do more houses.

The biggest breach of sound-monitoring protocol was not planning analysis before data collection and not doing it during data collection. This is important because early analysis serves to verify proper operation of equipment and identify flaws or unanticipated opportunities in data acquisition early enough for a proper response. It was not even known whether the sponsor, the managing contractor, or others would do the analysis until monitoring was nearly completed.

Fortunately the project was spared the worst potential consequences of this. This can be credited to good guidance provided by bidders, the national experts on the subcontractor review panel, and ultimately the subcontractor. It led to a specification of field monitoring data points and real-time data processing algorithms that preserved flexibility for future analysis planning. A paramount consideration in bid review was reputation and experience with similar remote data collection projects. The monitoring contract contained a monetary penalty provision for lost data, and the contract required submittal of a written site data verification plan. Not surprisingly, data problems were quickly detected and repaired.

Implementation Experience

Prewiring an ample surplus of houses proved very beneficial. Attrition was high. It was difficult to track evolving house plans in four different states. Often changes were made, by builders, that complicated monitoring, e.g., changing from an electric furnace to a heat pump, or adding a sunspace with a hot tub. In retrospect, closer surveillance of house plans and change orders could have avoided prewiring some of the latter. In theory, anticipating problems and adding more restrictions to the prewiring specifications would have helped, but builders were already overwhelmed by the necessary detail of the specifications.

Throughout the monitoring subcontractor selection process, the contractor attended to the prewiring of houses and had revised the specifications. The revisions annoyed some builders who were well along or finished with the monitoring accommodations. However, most changes could be retrofitted by the builders or were not absolutely essential for the monitoring.

Certain problems were caused by inexperience of the contractor and/or the inadequate lead time built into the project. The most serious problem with the specifications was semantic. Cable runs were referred to as "wire runs." Since two-conductor cable was specified, some builders counted each cable as two wires and ran half as many cables as required. Other prewiring problems occurred as a result of builder, inspector, and program personnel inexperience with this type of technology.

The managing contractor initially specified one instrumentation cable. The builders or their electricians were to obtain this cable themselves. The cable manufacturer and several suppliers in all the states were contacted; they assured the contractor that their stocks were large. The contractor thought any potential availability and distribution problems had been avoided. This turned out to be almost totally false. When builders called for the cable (often only the day before installation), most suppliers were out of stock but only too happy to order more, with availability in only a few weeks. Most builders called the contractor in panic. Others blissfully substituted any other available cable, even unshielded phone wire, without notification of the contractor or their own state's program personnel. Following many frantic phone calls to suppliers and builders and identification of two alternative cable types, the problem was brought under control.

Because houses were spread over four states, engineers could not oversee the wiring of them all. State personnel and the inspectors under contract for the project helped with oversight. However, the prewiring/preplumbing specifications were necessarily long and totally different from conventional house wiring and plumbing. Inspecting data logger prewiring and preplumbing was only one of many tasks that local personnel had to perform. There was inspection of the envelope construction and energy features themselves. There was prewiring for electronic temperature recorders and extra kilowatt-hour meters, which all 200 targeted houses were to receive. Only a few houses in each state were to receive data loggers, so there was little opportunity to become experienced. The result was that a lot of problems slipped by some very good personnel.

The contract carefully bound the subcontractor to maintain the system secure against tampering by pets or occupants, and to protect it against power line irregularities and electromagnetic interference (EMI). The managing contractor had learned that voltage surges from lightning take a heavy toll on monitoring equipment, so language was carefully chosen to hold the subcontractor liable for loss of data from storms or "acts of God" unless such events did direct damage to the home. Unfortunately, the managing contractor overlooked the possibility that the monitoring equipment could harm the home. In several homes, it was discovered that the data logger caused television interference. The same problem was experienced in another related monitoring subproject using entirely different equipment provided by a different manufacturer and subcontractor. In both cases it was found that the interference persisted when all sensor leads and power cords were removed from the data loggers and they were energized only by their internal backup batteries. Both had all-metal enclosures. The problem persisted in spite of numerous attempts at filtering and shielding, and was never eliminated. It was finally necessary to compensate the occupants for the loss of reception.

Data Problems

The data retrieval phase of the project appears to have been quite a success. There was a only a 1.7% data loss. Early exploratory analysis has identified a small amount of additional suspect data that passed verification. Fortunately this has been either spurious but rare, or continuous but of short duration.

In general, there were few data problems. This was largely due to the verification and quality control procedures developed and implemented by the monitoring subcontractor. One data problem that managed to remain undetected until near the end of data collection was occasional spurious high water flow readings on exhaust air heat pumps. This occurred only a few times (i.e., hours) per year on each EAHP house and appears to be an endemic problem with the pulse initiating water meters. It undermines confidence in the water flow (thus water heat) data, but it appears that bad readings can be separated from legitimate high readings in analysis. By setting traps that consider the magnitude of water use with respect to water temperatures and compressor utilization in the hours immediately following high readings, all but very minor bad readings can be identified.

Data Analysis

In March 1988, research questions and a research plan were finally prepared. The research questions were posed as primary questions, each followed by considerable explanation, justification, and several secondary questions. The primary research questions were as follows:

- How does the indoor enthalpy respond dynamically to operation of systems?
- Do internal loads show significant diurnal variation?
- Are heat recovery ventilator utilization patterns consistent with expectations?
- What is the annual useful heat recovery rate from heat recovery ventilators in the case study homes?
- How is the field data acquisition system performing? Is this a sound approach to use for future cycles of this or other research?

At the time of this writing—October 1988—formal analysis had just begun. The sponsor has funded the managing contractor to perform analysis, although subsequent analysis may be performed by the sponsor or other parties. The budget includes funds to subcontract analysis support to the monitoring subcontractor.

Preliminary summary statistics have been obtained. The specification of data points appears to have been sufficient to determine heat recovered and infer whether or not it was useful in offsetting space heat. Useful space heat was inferred as follows:

- All the recovered heat was considered useful for exhaust air heat pumps that had separate refrigerant loops for space heating and heat recovery.
- Gross recovered heat was presumed to be all useful in another model of exhaust air heat pump that links supply and exhaust air by refrigerant coils in series, but this is tentative. Further analysis may reveal that some of it was applied to tempering supply air at times when no space heating was necessary. There may also be other times when some of the recovered heat may, in fact, have been recovered from supply air at a time when space cooling was not useful. With hourly indoor and outdoor temperature as well as hourly supply and exhaust air temperature, it is probable that a reasonably exact assessment of useful heat recovery can be obtained.
- Heat recovered by air-to-air heat exchangers was presumed useful if any space heat was used within two hours before to four hours after the current hour, or if the indoor temperature was below the inferred comfort temperature. Inferred comfort temperature was defined as the temperature above which the occupants would no longer desire space heating. It was inferred by looking at the mean indoor temperature, by time of day, for the months of November through February. The highest mean was assumed to represent a time of day least likely to be influenced by night (or not-at-home) setback. It usually occurred around mid-evening. The mean temperature at this time of day plus one standard deviation was taken as the inferred comfort temperature.

The monitoring subcontractor is expected to have a continuing role in data analysis and receive credit for that role. This continuing responsibility of the subcontractor is expected to be useful for explaining any ambiguous data, which might be errors, or merely unexpected behavior of monitored systems.

Lessons Learned

Ideally, monitoring protocol should be developed from a clear scientific need for certain information and the resources to obtain that information with sufficient precision. Unfortunately human organizations do not always operate with clear needs and sufficient resources. A project is more likely to be engendered by political or other circumstances. For example, there may be a certain amount of budget available to do some worthwhile project in a sphere currently enjoying the forefront of public interest. Moreover, the resources and interests may change as the project is planned. This leaves the engineer or scientist to follow the old adage of "taking the tide at its flood." He or she must become a salesperson, ready to revise the product package to meet the immediate needs and ability to pay of the client. New needs may arise, new funds may become available, or policy changes may obviate the need for data formerly needed. The need to revise the package may occur any time during the project, in the late stages of planning, or even after data collection has begun.

There are other reasons why planning a monitoring project may necessarily become an iterative process. There is often not a clear line between what is absolutely essential and what is non-essential, but beneficial. Often the equipment for obtaining essential information can provide other non-essential beneficial information at only a small additional cost. This was certainly the case with the data logger project. The commitment to do real-time monitoring grew out of the need to obtain heat recovery information. Making the big commitment to real-time monitoring opened the door for other useful data to be obtained at little *additional* cost. This led to monitoring data points being tentatively identified before anyone figured out what to do with them. If a formal analysis plan had existed at the time, it would have provided a structure for evaluating the new opportunities for their ability to contribute to overall project goals.

It may be necessary to go through several cycles of deciding what is wanted and investigating what is required to get it. Often project clients have little notion of the cost or technical difficulty of obtaining field data. It is helpful if clients can confer with experts and discuss preliminary approaches and costs with prospective contractors. Knowledge of costs and methods can bring about a change in the anticipated scope of work. In the data logger project, considerable knowledge was gained by distributing the draft RFP to national experts for comment prior to its official release. A panel of these experts was convened for bid review and subcontractor interview. This was of immeasurable value. It is important to allow as much lead time for the planning process as possible and maintain flexibility to revise plans in the early stages.

A major impediment to sound monitoring project design methodology is time. Laws and regulations require government agencies and utilities to go through formal processes to select contractors without apparent or actual discrimination and to ensure the public's money is spent prudently, legally, and sparingly. These take time. Such processes can be delayed or restarted by program changes. Equipment suppliers do not always have large inventories. Sometimes many weeks of lead time are required for delivery of essential items. In new buildings construction may begin well ahead of the time that monitoring equipment is to be installed. This demands a very early design of instrument wiring and other monitoring accommodations, particularly in residential buildings that lack dropped ceilings, and wire chases for concealing wiring after construction. The result of these factors is that by the time project operators and monitoring designers are authorized to proceed, several critical dates may already be passed.

There are no perfect defenses against these problems, but certain actions can keep things from becoming worse than necessary. Keeping the prospective client informed of the need for clear goals, objectives, and research questions is essential. Likewise, the client must be frequently apprised of lead time requirements of various aspects of the project.

In the data logger project some tenets of monitoring planning protocol were seriously breached. The greatest of these was failure to formalize research questions and an analysis plan early in the project. The project's salvation was that technical personnel of the sponsor and managing contractor communicated well and had a vision of the need for information. National experts were consulted regarding specification of field monitoring data points and they participated in monitoring contractor bid review including interviews. Considerable concentration went into anticipating possible data needs and providing the system to meet them. This may translate into some unneeded data and it may still have allowed some lost opportunities. However, at this writing, it appears that the project obtained useful and appropriate data. Nonetheless, a safer approach would be to establish research questions and plans early in the project.

Monitoring objectives and research questions should be articulated and a plan of analysis developed as soon as the project is authorized. An easy pitfall is to muddle from iterative investigating into irreversible planning without ever formalizing objectives, research questions, or a plan of analysis. If circumstances never seem to gel well enough to formalize plans, a flexible plan should be developed.

Maintaining flexibility to accommodate changing or late-developing analysis plans is important. It is necessary to anticipate and provide for securing data that will be lost forever if they are not processed in "real-time," i.e., derived at scan intervals. An example is heat transfer, which is the time integral of several parameters of state and a flow parameter. Another example involves disaggregating multiple electrical loads recorded from a single power or current transducer. This can be accomplished only at scan frequency by algorithms that infer load combinations from instantaneous power or current.

Ample prewiring and preplumbing should be specified in new residential or other situations where after-the-fact changes would be difficult. Extra instrumentation cables, conduits for pressure tubes or electric cables, plumbing unions, extra phone droplines, etc., are cheap insurance. If thermocouples or heat flux sensors might be used, these will require special cable. Even preparing extra buildings is important insurance in situations where occupant attrition or project expansion is possible. These precautions were all taken in the data logger project. Still there were no instrumentation cables and no houses to spare.

Special care is necessary when responsibilities become fragmented among various parties. Problems can occur where parties interface. Relationships and responsibilities need to be clearly documented. If an outside contractor is used, extreme care should be taken in the selection and contract writing. Field data acquisition makes use of rapidly evolving equipment in custom applications. Serious losses of data have been commonplace in the past. It is important to choose a contractor with the financial strength to survive a design or hardware calamity. Contract language should be very precise in defining lost or faulty data and the exact penalties for it. Even a financially strong contractor may be unable or unwilling to shoulder full financial liability for lost data, but a substantial sharing of risk is appropriate and motivating.

Little technical details are often very important. Power line irregularities and electromagnetic interference (EMI) are good examples. Emitted interference can be insidious and persistent. It can shut down a project. Any monitoring contracts or equipment purchase agreements should require rigorous testing and certification of equipment to safeguard against emitted EMI. If possible, suppliers or contractors should be held liable for data lost because monitoring equipment is too obnoxious to be operated. When selecting candidate buildings, it may be prudent to avoid ones with vulnerable sensitive electronic equipment such as residences without cable TV availability or facilities with expansive computer networks.

Lightning-induced power surges took their toll on equipment in this project and, from the literature, the problem appears to be endemic to the field. Equipment suppliers and monitoring contractors will not want to accept liability for what is termed "acts of God." Purchase agreements and contracts should carefully define which of these acts are routine and which are extraordinary. Exemptions from liability should only be granted for the latter. Agreements should not exempt liability for damage from natural events unless they are severe enough to do direct damage to the building or its other appliances.

CONCLUSIONS

The greatest challenge presented by the project was coping with the multiplicity of involved parties and the size and operating constraints of the parties. It was hard to adhere to orderly sequential planning in this operating environment. To maintain the project under control, it was necessary to be especially attentive to the following interrelated factors:

- Flexibility
- Communication
- Verification

Change is inevitable during planning and implementation of such projects. The sponsor and the project management entity must devise a system for quickly responding to unforeseen problems as well as attractive opportunities. This may take the form of some sort of budget reserve or contingency line item. It may also take the form of special procedures for fast tracking changes.

A system for communication should be devised early in the planning process and adhered to. This should address the obvious need to keep the parties coordinated and focused on the objectives, but also ensure visibility to parties not immediately involved with the project. This can attract useful suggestions from other parties with related experience. It also creates a potential to enhance the project by picking up additional sponsors to expand scope and resources.

Verification plans should involve not only data acquisition personnel, but the sponsor and managing entity too. The ideal way to do this is to complete analysis plans early and implement analysis with the *beginning* of data retrieval. No matter how good the data verification procedures, they will not be able to detect many subtle anomalies until they are revealed in comprehensive analysis. Often the opportunity to repair a problem or investigate and explain unusual phenomena is lost if it is discovered months after its occurrence.

REFERENCES

Fowlkes, C.W., and Cady, F.M. 1985. "An experiment with a remote data sharing network." *Proceedings of the DOE and ORNL National Workshop on Field Data Acquisition for Building and Equipment Energy Use Monitoring*, CONF-8510218, October.

Mazzucchi, R.P. 1985. "Design of a large scale metering project." *Proceedings of the DOE and ORNL National Workshop on Field Data Acquisition for Building and Equipment Energy Use Monitoring*, CONF-8510218, October.

Misuriello, H.P. 1987. "A uniform procedure for the development and dissemination of building monitoring protocols." *ASHRAE Transactions*, Vol. 93, Part 1.

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