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A PROTOTYPE EXPERT SYSTEM FOR DIAGNOSING MOISTURE PROBLEMS IN HOUSES

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ABSTRACT

A knowledge based expert system is under development to assist in the identification and diagnosis of air leakage problems in residential buildings. The expert system is intended for use by home energy auditors who are familiar with house construction and building performance issues, but do not have the expertise necessary to deal effectively with the wide variety of circumstances encountered in houses. The system development is beginning with a prototype to diagnose moisture-related problems. This prototype is the first step in the development of the more comprehensive expert system that will deal with air leakage problems associated with indoor air quality, thermal comfort, and heat loss and gain.

In this paper the moisture-diagnosis prototype is described and discussed. This prototype system requires the user to describe the symptoms of the existing moisture problems and provide information on house characteristics. Based on additional information on the symptoms and the house, this interactive program produces a list of probable causes and recommendations for remedial action. In addition to describing the current prototype system, this paper also discusses the results of an evaluation of the system based on its use by human experts in the field of residential building moisture. This evaluation, along with insights obtained through the efforts of the system's developers, has led to several proposed improvements of the prototype.

INTRODUCTION

Over recent years numerous houses have been audited to determine appropriate energy conserving retrofits and to identify the causes of problems related to thermal comfort, excessive energy use, moisture, and air quality. These audits have ranged from uninstrumented visual inspections lasting about one hour to more extensive procedures that employ instrumentation to examine the building envelope and equipment in detail. The simpler type of audit necessarily considers only general attributes of the house without recognizing the complexity of building thermal characteristics, including the importance of unexpected air leakage sites and other thermal anamolies. Such audits generally involve surveys of insulation levels, condition of windows and doors, mechanical equipment type and other building features, but neglect many other important factors such as leaks in attic floors, convective loops within the insulation system, basement air leakage and other obscure air leakage sites. Based on various simplified guidelines these audits produce suggestions regarding retrofit actions, but the audits are generally not designed to diagnose the causes of many air leakage problems and the suggestions do not involve many important air leaks.

More extensive audit procedures, sometimes refered to as "house doctoring" (Diamond et al 1982, Energy Resources Center 1983, Harrje et al 1979 and 1980), provide a much more detailed evaluation of the house and its thermal performance. House doctoring is not a standardized procedure, and different individuals and organizations have developed their own approaches. In order to locate heat loss and air leakage sites, house doctors employ fan pressurization, infrared thermography and other techniques (ASTM 1986, Harrje et al 1979 and 1980, Socolow 1978). The use of these procedures enables one to locate unexpected air leakage sites and other thermal defects in the building envelope that are otherwise difficult or impossible to detect. These unanticipated defects often constitute a more significant portion of the energy loss of a home than the more mundane defects considered by "pencil-and-paper" audits. With regard to air leakage sites, obvious leaks, such as those associated with windows and doors, generally account for only a small percentage of the total leakage of a house (ASHRAE 1985). Most of the leaks are due to a variety of other less obvious, and often very elusive, sources.

House doctors have inspected thousands of houses in North America and have obtained a great deal of experience regarding the location and significance of air leakage sites, as well as other thermal defects in houses. In some cases, extremely experienced house doctors can anticipate construction defects and other leakage problems without the use of instrumentation, from knowledge of a house's age, construction style, geographic location, and other features. In addition to identifying thermal defects in the building envelope, expert house doctors have experience with, and a general understanding of, other air leakage issues such as thermal comfort, moisture, and indoor air quality. The experience of these expert house doctors and other building performance experts constitutes a valuable resource for solving air leakage problems in homes.

It would be extremely beneficial if the knowledge of these experts could be used to improve the effectiveness of energy audits by nonexperts. Expert systems constitute a computer software approach employing the techniques of artificial intelligence to real-world problems (Forsyth 1984, Hayes-Roth et al 1984) that could potentially provide this knowledge regarding air leakage problems to nonexpert auditors. Expert systems are particularly applicable to the problem of identifying and diagnosing air leakage problems in residential buildings because these systems are appropriate to domains characterized by uncertain data and incomplete information. A traditional, computational approach to analyzing infiltration would calculate the quantities of interest by applying computational algorithms to a numerical model of a house. While there is sufficient physical understanding to determine infiltration rates, airflow rates into and out of specific locations, and interior contaminant concentrations, moisture levels and temperatures in this manner, the calculation of these quantities is prevented by the inability to determine all of the required inputs. One must know the location and leakage characteristics of every opening in the building envelope and in the interior partitions. In addition, wind pressure coefficients must be known over the building envelope as a function of wind direction. The determination of indoor contaminant and moisture levels also requires values of interior source strengths and outdoor concentrations as a function of time. Such detailed knowledge about a specific building is generally unobtainable without intensive instrumentation and study. Even if all of this information were available, it is not clear whether a detailed computational approach is appropriate to deal with the types of problems that are encountered in the field. Alternatively, an expert system can deal with the more realistic situation in which there is incomplete knowledge of a home's detailed infiltration characteristics, but valuable nonquantitative information is available. The ability of expert systems to deal with qualitative information makes them appropriate to the problems associated with air leakage and to use the knowledge of expert house doctors.

This paper begins with a description of a proposed expert system intended to deal with air leakage problems. This expert system has been described in general terms in a previous report (Persily 1986), and is intended to identify and diagnose air leakage problems related to heat loss and gain, thermal comfort, moisture, and indoor air quality. The current effort toward the development of this system involves a prototype concerned primarily with the diagnosis of moisture problems in homes, and a description and discussion of this prototype constitutes the bulk of this paper. The prototype is serving to explore conceptual approaches to the general problem of diagnosing and identifying air leakage problems to assist in developing the proposed system, as well as to develop a useful tool for the domain of moisture problem diagnosis.

GLOBAL SYSTEM FRAMEWORK

The term global expert system refers to the proposed expert system intended to deal with air leakage problems related to heat transfer, air quality, moisture, and thermal comfort. The development of this global system itself has not yet begun, but a conceptual framework does exist and this section describes the current conception.

The basic goal of the global system is to use the knowledge of house doctors, and other experts in the area of air leakage problems, in order to improve the effectiveness of procedures employed by less experienced auditors. The proposed expert system is intended to be used by on-site auditors who are familiar with home construction and building energy conservation, but are not experts in the field. The expert system will deal with three basic situations or questions regarding air leakage: diagnosis, identification, and retrofit planning. The diagnosis mode is intended to determine the causes of existing air leakage problems. In this situation, the house has a problem such as drafts, a cold room, lingering odors, or moisture damage. The system will determine why these symptoms are occurring and suggest corrective action. The second problem type concerns the identification of air leakage problems that are presently unknown to the occupant and auditor, but that may be potentially serious in the future. These problems might involve the potential for moisture damage, excessive heat loss, or poor indoor air quality. The final situation that the expert system will address is retrofit planning. Given that the homeowner is contemplating air leakage and/or other retrofits to the building, the system determines the most appropriate and effective retrofits and anticipates potentially adverse side effects of the proposed retrofits. The expert system is intended to explore these three questions for existing homes, but the potential exists for expanding the system to include the anticipation of air leakage problems in new buildings at the design stage.

Content of the Knowledge Base. The types of air leakage problems that the expert system will deal with concern heat loss and gain, thermal comfort, moisture, and indoor air quality, and several examples are listed in table 1. These are general problem types, as opposed to their specific causes and the symptoms that reveal their presence. For example, the cause of a cold interior surface of an outside wall may be air leaking into the wall system at a second-story overhang and flowing within the wall. The symptoms of this problem may include occupant discomfort, and perhaps condensation or mildew on that wall. To further explain the content of the knowledge base, this example is considered in relation to the three situations discussed above. In the diagnosis mode, the symptoms of the cold room will be entered, along with other house information such as the existence of an overhang, and the expert system will suggest a leak into the wall as a potential cause. The system may specify additional inspections to the auditor in order to support the diagnosis, as well as provide appropriate techniques for repairing the leak. In the identification mode the expert system will consider the fact that the house has a second floor overhang, and based on experience regarding this house style and its construction, will suggest the possibility that such a leak exists. Again, appropriate verification and repair techniques will be provided. Finally, if the user is planning to retrofit the house, including the installation of wall insulation, the expert system will identify this leakage site as an important envelope tightening retrofit and as a means of making the proposed insulation more effective.

In addition to the types of problems listed in table 1, the knowledge base of the expert system will contain other information. Table 2 presents an outline of the content of the knowledge base. There are two basic types of information that will be included in the knowledge base, factual and heuristic. The factual information consists of descriptive information regarding houses, their construction, air leakage problems, and symptoms associated with such air leakage problems. All of this factual information serves as the components for developing a useful characterization of a house within the expert system.

The second type of expert knowledge to be included in the knowledge base, referred to as heuristic, is divided into problem specific and strategic. Heuristics are generally acquired from experts and are used in solving the problems in the expert system's domain. The heuristic knowledge consists of relationships between building characteristics and air leakage problems and other building characteristics, problems, and retrofit procedures, as noted in table 2. The strategic heuristics refer to more general rules that embody the problem solving approaches of the system.

Structure of Knowledge Base. The global expert system is envisioned as an interactive program in which information provided by the auditor will be used to create an "image" of the house under consideration. This image will be a combination of characteristics, varying in degree of detail and quantification, and will include information provided by the auditor and default values supplied by the expert system. Based on the application of the rules discussed above, and additional information supplied by the user, the house image will be progressively refined and made more useful.

A session will begin with the auditor providing preliminary information on the home. Initial inputs will include which of the three situations discussed above, diagnosis, identification and retrofit planning, are relevant. In addition, information regarding the home's physical description, age, mechanical equipment, and other features may be added at this stage. The system will interact with the user/auditor as this information is being input, for instance requesting additional explanation of the inputs. At the conclusion of this initial session, the system will produce a tentative list of conclusions (i.e. problems, causes, and/or retrofits), plus a list of requests to the auditor for further information. These requests may involve physical inspections ("Go to the kitchen and determine whether the exhaust fan actually exhausts to the outside or simply recirculates"), or discussion with the building occupants ("Ask the homeowner if they experienced eye irritation before obtaining the new furniture"). The auditor will obtain the additional information and the interaction with the system will continue, entering the new information as appropriate. The system will then produce a new list of conclusions that is more detailed and building specific, and possibly additional requests for information. The appropriate number of iterations and length of a session will be explored in developing the system. The system may also suggest more involved study of the building, such as pollutant concentration measurements with passive monitors or pressurization measurements of whole building airtightness, followed by another session with the system at a later date.

As mentioned above, the information provided by the user will be used by the system to create an image of the house. This image will not be a detailed, physical model of the house for use in a calculation of infiltration, involving exact descriptions of every leakage site, the building geometry, pollutant source strengths, and outdoor pollutant concentrations. Instead it will be a descriptive characterization of the building including both quantitative information (e.g. floor area, number of occupants, year of construction) and qualitative information (e.g. existence of a basement, geographic location, construction style). The rules contained in the expert system knowledge base will be used to convert the initial set of attributes of the home to a more specific and useful set of attributes. As the system employs these rules, and as additional information is provided by the user, the working image of the house will provide useful information to the user.

At this point it is not clear what solution strategies and software approaches will be most appropriate for this expert system. The development of the moisture-diagnosis prototype will assist in making these important decisions.

Knowledge Base Resources. Several different sources have been identified for use in developing the knowledge base for the expert system. These sources include both written documents and human experts, as outlined in table 3. The written documents include both audit and retrofit manuals that have been developed for specific retrofit programs or as general guides for retrofit planning (Diamond et al 1982, Energy Resources Center 1983, Knight 1981, Marbek 1984, Marshall and Argue 1981). These documents provide both general and specific information for locating and repairing air leakage sites in houses. They will be useful for identifying specific air leakage sites in existing buildings and determining appropriate retrofit measures for their repair. Reports on specific retrofit demonstration projects and discussions of specific energy auditing techniques will be useful in identifying air leakage sites and in suggesting appropriate measures for their repair. There are also many guides to energy-efficient house construction which supply specific information for building houses with high levels of thermal integrity (Elmroth and Levin 1983, Eyre and Jennings 1983, Nisson and Dutt 1985). Many descriptions of construction details are included to enable construction of building envelopes which are extremely well-insulated and airtight. It may be assumed that these details have been redesigned with so much attention because they have been the source of problems in past construction. Therefore these energy-efficient construction guides may be sources of air leakage sites in existing buildings and, in some cases, of retrofit measures for their repair. There are also house construction guides that describe the techniques used for building more typical U.S. homes, as well as architectural guides that provide general classifications of houses and useful terminology for the expert system.

There are a variety of human experts available for developing the knowledge base of the expert system, as listed in table 3. House doctors and other expert auditors are sources of both the factual information and heuristics. These auditors have a great deal of experience in inspecting and retrofitting houses. They know of many air leakage sites, their causes and effects, and appropriate retrofit measures for their repair. They also have observed many relationships between housing style and construction, and the existence of specific air leakage sites, which will be used in developing the problem solving heuristics listed in table 2. The approaches that they use in conducting their audits will be used in developing the strategic heuristics. Energy-efficient housing designers and builders are sources of general knowledge on how to build houses properly, thereby avoiding the problems that are the domain of this system. Another source of human expertise are home inspectors that are used by prospective purchasers of houses to determine the condition of the house in question. These inspectors are familiar with many aspects of construction and the types of defects that occur in houses. Their experience, and the approaches they use to inspect houses, may also be useful in developing the knowledge base of the expert system.

MOISTURE-DIAGNOSIS PROTOTYPE SYSTEM

In developing an expert system, it is generally suggested that one produce a prototype system that deals with a limited aspect of one's problem domain. This process assists in choosing an appropriate software approach for the problem area of concern and in providing the system developer with experience that is useful in planning beyond the prototype system. Based on this recommended starting point, a prototype system is being developed in anticipation of producing the air leakage expert system discussed above. This prototype is restricted to the diagnosis of moisture related problems in houses and is called AIRDEX. The development of AIRDEX has employed several useful documents on moisture problems in buildings that contain discussions of general issues as well as case studies (Bales and Trechsel 1984, Eakes 1982, NCAT 1983, NRCC 1984, Woods and Lovatt 1986). The development of this prototype has been an evolutionary process with modifications being made continuously. The description of AIRDEX that follows therefore presents only its basic structure with several examples of its detailed content. Roughly one-half of a person-year has been expended in the development of AIRDEX.

Rather than putting a great deal of effort at this early stage into software development that might turn out to be inappropriate to this problem domain, AIRDEX is being written in a commercially available, microcomputer-based expert system shell. Such a shell allows one to enter the rules constituting one's knowledge base and quickly get a working system on line. The shell being employed is a goal-driven, backward-chaining system in which the expert system developer enters a goal or goals and a series of "if-then" rules, in the form of a text file. This file is then "compiled" with the shell. When the expert system is run, the shell attempts to prove as true or false those rules that contain the system goals as their "then" statements or consequents. The shell does this by examining the "if" portions, or antecedents, of these same rules, and attempting to prove as true or false the rules that have these goal antecedents as their consequents. The shell backtracks in this manner until it requires antecedents that are not concluded by any rules. The expert system user is then prompted to provide information regarding these antecedents in an appropriate form such as numeric quantities, true or false responses to assertions, or selections among lists of responses. In addition to proving or disproving the final goal, much important information is contained in the intermediate conclusions that are proven or disproven in the attempt to prove the final goal.

The expert system shell used for AIRDEX allows one to associate a confidence level, from 0 to 100, with user inputs or with the conclusions of rules. Several different rules may have the same conclusion but different confidence levels, depending on the strength of the supporting facts. The use of confidence levels allows one to distinguish between lines of reasoning with different degrees of certainty.

In AIRDEX the final goal is to determine the so-called "Problem" that is causing the "Symptom" of the moisture problem(s). There may be more than one such Problem that is proven to be true, and a sample list of Problems includes:

1. Interior relative humidity too high from excessive moisture sources
2. Interior relative humidity too high from insufficent ventilation
3. Cold exterior envelope surfaces
4. Excessive airflow from living space to attic
5. Insufficient attic ventilation
6. Wind-driven moisture penetration into walls
7. Excessive basement moisture
8. Plumbing or roof leak

Several different rules will conclude that the Problem is one of the above, but they are all of the basic form:

IF Symptom is _________
AND The house characteristics are known
AND The Moisture Problem is _________
THEN The Problem is _________

Examination of the form of the above rule indicates how the system runs. The goal of the system is to prove or disprove rules with a consequent of the form "Problem is _________." Proving the validity of these consequents requires three separate antecedents to be true. These antecedents concern "Symptoms", house characteristics and "Moisture Problems," and they are investigated in the order listed. The system first tries to prove as true that the "Symptom" of the moisture related problem is that one given in the rule being investigated. In practice this means the system has the user specify what the symptom(s) is (are). There are many possible Symptoms that the user can choose from and they include:

1. Window condensation
2. Wall mold
3. Basement moisture (puddles, efflorescence,...)
4. Attic misture (mold, ice, wet insulation,...)
5. Exterior siding damage
6. Wet surfaces (walls, floors, ceilings)

The system therefore begins by asking the user to choose from among these general symptom types, and more than one symptom can be selected if appropriate.

After the Symptoms are selected, the next antecendent in the rule is "The house characteristics are known." This statement is the conclusion of a series of rules that has the system request from the user some basic information regarding the house. This information includes the number of occupants, floor area, year of construction, whether the house airtightness has been measured, and whether there is a basement, attic or crawl space. Once this information has been gathered, the system concludes as true that "The house characteristics are known," and the system proceeds to the next antecedent in the rule.

Finally, conclusion of a "Problem" being true requires the conclusion of a so-called "Moisture Problem." These Moisture Problems are really just more specific descriptions of the problems causing the house's existing moisture symptoms. In the most current version of the AIRDEX prototype, these Moisture Problems include:

1. Excessive moisture sources
2. Insufficient ventilation
3. Uninsulated walls
4. Poorly insulated walls
5. Thermal bridges
6. Cold rooms
7. Basement wall water leakage
8. Exposed crawl space
9. Poor rainwater runoff
10. Poor foundation drainage
11. Bath exhaust fan exhausting into attic
12. Air leakage at attic floor
13. Undersized attic vents

Many of these Moisture Problems are similar to the final Problems, and this occurs in order to maintain a parallel among the many paths to the final Problems. Proving of the Moisture Problems as true or false constitutes the substance of the AIRDEX system. The investigation of each Moisture Problem requires more specific information on the particular symptom(s) that is(are) occuring and house characteristics.

In the current version of AIRDEX, the Moisture Problems of excessive moisture sources and insufficient ventilation are investigated in the most detail, while some of the Moisture Problems do not yet serve as the conclusions of any rules within the system. The means of determining whether "excessive moisture sources" and "insufficient ventilation" are Moisture Problems is described below. Regarding the determination of whether the Moisture Problem is excessive moisture sources, AIRDEX considers several sources of moisture and associates a weighting factor with each. For example, the weighting factor associated with a clothes dryer venting into the basement or living space is equal to ten times the number of occupants. Unvented space heaters are weighted at two times the number of hours operated per week. The other sources include whole house and local humidifiers, plants, firewood stored indoors, indoor pools, hot tubs and saunas, basement water leakage, crawl space moisture, and the fact that the house was recently constructed. The user is asked to identify which sources exist within the house and to provide any additional information required to determine the weighting factor associated with each source. After the weighting factor of each source is established, all of the individual weighting factors are added together. An arbitrary cutoff between the existence of an excessive source problem and the lack of such a problem is a total weighting factor of one hundred. A total of greater than two hundred is labelled as a serious problem, and a total between fifty and one hundred is labelled as marginal. The values of these weighting factors and these cutoffs are based on the judgement of the system's developers. These weighting factors are used in order to avoid physical units for fear that they may then be associated with a higher degree of physical significance than appropriate. One problem with these weighting factors is that if the background information (e.g. hours per week of unvented heater use) is not available, the corresponding weight can not be determined. In addition, this scheme has the shortcoming of judging the sources' excessiveness without any reference to house volume or airtightness.

The existence of the Moisture Problem of insufficient ventilation is based on a comparison of the house's estimated ventilation rate and the desired ventilation rate based on ventilation requirements. The estimated ventilation rate is derived from the house airtightness as determined by a whole house pressurization test. The pressurization test result in units of air changes per hour at 50 Pa is simply divided by twenty to obtain a crude estimate of the current ventilation rate. The desired ventilation rate is set equal to the larger of two calculated ventilation rates, one based on the number of rooms and the other based on the number of occupants. The room-based ventilation rate is simply the number of rooms multiplied by 5 l/s and divided by the house volume to obtain air changes per hour. The people-based ventilation rate is equal to the number of occupants multiplied by 2.5 l/s and divided by the house volume. The current and the desired ventilation rates are then compared to determine if the house has sufficient ventilation. If the current ventilation rate is less than or equal to 80% of the desired rate, then insufficient ventilation is a problem. If the current rate is between 80% and 95% of the desired rate, then insufficient ventilation is only a possible problem. If the current rate is within 5% of the desired rate, the house's ventilation is probably adequate. Current ventilation rates that are between 5% and 20% above the desired level are more likely to be sufficient, and current rates more than 20% above the desired level are definitely adequate. This determination of the sufficiency of ventilation is simplistic and can not be used if the house has not been pressure tested. It does not consider other methods of determining the actual ventilation rate such as actual measurement or more physical prediction methods, nor does it employ any default values. Finally, the sufficiency of the ventilation rate is not based at all on the moisture generation rate within the house.

SYSTEM EVALUATION AND CURRENT EFFORTS

There are two important reasons for beginning the development of an expert system with a prototype such as AIRDEX. First, having a working system enables experts in the problem domain to evaluate the system by running it on sample problems and examining its responses. Also, since the knowledge base is explicitly visible in the system rules, these experts can examine its content and the system's organization. The second benefit of developing a prototype is that through the process of forming the knowledge base rules the system's developers obtain insights that can result in improvements to the system. The development of AIRDEX and its examination by several experts in residential moisture has been a valuable process and has led to several proposed improvements. In addition, further examination of the relevant literature by the system's developers has revealed other improvements that can be made in the system.

The evaluation of AIRDEX involved several experts in residential moisture issues who applied sample problems to the system, examined the rules contained in the system listing, and discussed moisture problem diagnosis issues with the system developers. The results of the moisture experts' evaluation, as well as the system's developers insights, concern three basic areas: the predominant moisture problems that occur in houses, the quantification of moisture source strengths, and the information that is often contained in the symptoms of the problems.

Predominant Moisture Problems. While there is less hard data than anecdotal experience, the predominant cause of living space moisture problems appears to be excessive sources of moisture. If this is indeed true, then the system should first investigate the existence of unusually strong sources, rather than beginning with equal expectations that the problem is due to excessive sources, insufficient ventilation, or cold surfaces. Similarly, the predominant causes of attic moisture problems are airflow into the attic from the living space, inadequate attic ventilation, and reduced attic temperatures due to recent insulation work. Thus, in attempting to diagnose the cause of attic moisture problems, one can assume these factors probably exist and concentrate on details of airflow paths in the attic floor, attic venting and recent attic insulation work. The other predominant moisture problems appear to be wind-driven rain penetration of the building envelope, leaky pipes and roofs, and poor rainwater runoff and foundation drainage. The fact that these common causative factors exist suggests that the system concentrate on these issues first, rather than using the open-ended approach of the current version. The approach that has been taken in developing AIRDEX is to employ a thorough investigation of the characteristics of the house, occupants and symptoms and draw conclusions based on this information. Continuing to develop AIRDEX in this manner would ultimately result in a very large system, and in a time-consuming and seemingly undirected interaction with the user. The ability to begin with reasonable expectations of the causes of residential moisture problems will be used to make future versions of AIRDEX more direct in its investigations.

Quantification of Moisture Source Strengths. The discussions with residential moisture experts and examinations of the literature have also led to questions regarding the appropriate manner of quantifying source strengths. As discussed above, the current version of AIRDEX employs a nonphysical weighting scheme to determine if the various moisture sources in the house constitute an excessive moisture generation rate. The experts who evaluated AIRDEX suggested a more physical and detailed approach to quantifying source strengths and to determining the existence of an excessive source problem. The suggested approach includes using physical units for moisture source strengths, and considering the house volume and ventilation rate in determining whether the source is excessive.

While the moisture generation rates associated with some of the sources are difficult to know, many of them can be quantified in physical terms (liters per day, l/d) and associated with factors related to the occupants and the structure. In addition, some generation rates can be determined with greater or lesser certainty depending on which factors are used to determine their values. The degree of certainty in the determination of a particular source strength can be reflected within the system by the value of an associated confidence level. For example, the moisture generation rate associated with a clothes dryer that is vented indoors is related to the number of loads per week and can be converted to l/d based on an assumption as to the number of liters of water associated with a load of laundry. Alternatively, one can estimate the generation rate associated with a clothes dryer with less certainty by basing it on the number of occupants and assuming a value for the number of loads per occupant. Similarly, the moisture generation rate associated with houseplants is most directly related to the amount of water used, followed by the frequency of watering, and finally the number of plants. The relation between generation rates and these various factors will not always be well-established, but a more physical and quantitative approach to their determination will be employed in future versions of AIRDEX.

The recommendation of a more physical approach to source strengths goes along with a more quantitative consideration of the ventilation rate in determining the indoor level of relative humidity, and the reason the humidity may be too high. Current versions of AIRDEX consider the question of adequate ventilation with reference to ventilation standards only, and then only associate a ventilation rate with a house if the structure has been pressure tested. Future versions will always use a numerical value for the ventilation rate in combination with the moisture source strength to determine an interior relative humidity level. The ventilation rate will be associated with varying degrees of certainty depending on the source of its value. If the ventilation rate is based on tracer gas measurements it will be associated with a high degree of certainty. Lesser degrees of certainty will be associated with ventilation rates based on pressurization test results in combination with models, estimates based on house features such as age and condition, and default values. Such a physical approach to determining interior relative humidity is superior to the current arbitrary weighting scheme that neglects the ventilation rate and the house volume.

Based on the expert evaluations and further study of the literature, future versions of AIRDEX will employ an alternative to the numerical determination of the existence of excessive source strengths discussed above. This alternative will investigate the existence of exceptional moisture sources before employing the above numerical approach. Some residential moisture experts believe that unless the house is very tight, typical moisture sources will not lead to excessive interior relative humidity. These typical sources include respiration, bathing, plants, cooking and dishwashing, clothes drying (even if vented to the interior), and indoor firewood storage. This viewpoint maintains that there must be unusual sources such as unnecessarily high levels of intentional humidification, high moisture content in building materials in a newly constructed buildings, a new building that was closed-in during a rainy period, the existence of an indoor pool or attached greenhouse, or a very large number of occupants. If these extreme sources can be determined to exist with a high degree of certainty, it may be unnecessary to go through the detailed evaluation of less important sources and ventilation rate. A less certain determination of the existence of such extreme sources will increase the need to employ the detailed evaluation discussed above.

Information from Symptoms. The last item that was learned from the interaction with the moisture experts is the ability to use information on the symptoms to learn about the cause and severity of the moisture problem. A good example of this use of symptoms is the case of window condensation and information on its timing, extent and duration. If window condensation occurs all winter long it is a sign of continuously excessive indoor relative humidity and a severe problem. On the other hand, sporadic occurences of window condensation may provide information on the source of the moisture. For example, if window condensation is associated with cooking, bathing or unvented heater use, one probably knows the source of the excessive moisture and therefore has a good indication on how to remedy the situation. The duration of sporadic occurences reveals information about the severity of the problem. If condensation occurs during showers or cooking and then dries up quickly, then there probably is not much of a problem. But if the moisture remains for many hours, then the source needs to be controlled. Similarly, the location of the condensation provides information on the severity of the problem. If the windows in all rooms exhibit condensation, then the problem is more severe than if the condensation occurs only in the bathroom or kitchen. There are other cases where information regarding the symptoms provide information on the problem's cause and severity, and these can be used to quickly get to the important causes rather than question the user about a great many house characteristics, many of which will be irrelevent to the situation.

Many of the above conclusions based on the experts' evaluation, the developer's moisture research, and efforts in developing AIRDEX, suggest the incorporation of these heuristics into the system. The current version of this prototype system was organized with the approach of investigating almost everything, i.e. looking in detail into many characteristics of the symptoms, house and occupants. The current all-inclusive approach, if pursued, would have resulted in a large system that would ask the user for a great deal of information. It now appears that it would be better to direct the system's investigation towards those specific, dominant situations that were discussed above. These include starting the diagnostic investigation by expecting the common causes of moisture problems, and in the case of excessive generation rates looking for unusual moisture sources first. In addition, key questions regarding certain symptoms should be used to get important information quickly. Such streamlined investigative procedures are exactly the type of useful input that can be provided by domain experts to make expert systems work more quickly and effectively. Future versions of AIRDEX will be modified to employ these "short-cuts."

SUMMARY

In this paper we have presented a general description of an expert system proposed to deal with air leakage problems in houses. This system is intended to deal with the diagnosis and identification of such problems, as well as assist in the planning of energy conserving retrofits as they relate to air leakage. This effort has begun with the development of a prototype system, referred to as AIRDEX, that deals with the limited domain of the diagnosis of moisture problems in houses. Early evaluations of AIRDEX by residential moisture experts, as well as observations made by the system's developers in the process of formulating and working with the system, have revealed the need to modify AIRDEX so that it employs more of what is known about the nature of moisture problems in houses. The basic effect of these intended changes will be to alter AIRDEX's current direction of attempting to cover all possiblities with equal emphasis and to instead have it begin by pursuing its investigations along the lines suggested by common moisture problems and by existing knowledge concerning these problems.

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Table 1 Air Leakage Problems

Heat Loss/Gain:
- Excessive infiltration rates
- Air leakage decreasing the effectiveness of insulation systems

Thermal Comfort:
- Air leakage causing cold/warm interior surfaces
- Air leakage causing drafts

Moisture:
- Exfiltrating air contacting cold surfaces within the building envelope or living space and condensing (winter)
- Infiltrating air contacting cold surfaces within the building envelope or living space and condensing (summer)
- Inadequate attic ventilation
- Excessive moisture transport from the occupied space to the attic
- Excessive moisture generation and inadequate removal within the space

Indoor Air Quality:
- Excessive pollutant sources strengths
- Inadequate ventilation - whole building and/or local, and as a function of time

Table 2 Outline of the Knowledge Base

Factual Information

Generic:
- Housing styles
- Floor plans
- Roofs and foundations
- Unheated spaces - basements, attics, crawlspaces

Construction:
- Envelope systems - framing, foundations, insulation
- Details - joints, seams, interfaces
- Accessories - doors, windows, dormers, overhangs
- Mechanical equipment

Problems: See Table 1

Symptoms:
- Heat Loss/Gain - Excessive utility bills
- Comfort - Drafts
- Moisture - Condensation, Mildew, Damage
- Air Quality - Stuffiness, Lingering Odors, Chronic Respiratory Complaints

Heuristics

Problem Specific:
- Associations between building types and construction details
- Associations between building types and air leakage problems
- Associations between construction details and air leakage problems
- Associations between air leakage problems and symptoms
- Associations between air leakage problems and appropriate retrofits

Strategic:
- Problem solving approaches

Table 3 Knowledge Base Resources

Documents
- Auditing and Retrofit Manuals
- Technical Reports on Retrofit Techniques and Demonstration Projects
- Energy-Efficient Construction Guides
- Home Construction Manuals
- Architectural Guides

Human Experts
- House Doctors and Other Expert Auditors
- Energy-Efficient Housing Designers
- Energy-Efficient Housing Builders
- Home Inspectors