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THE DYNAMICS OF INDOOR AIR QUALITY

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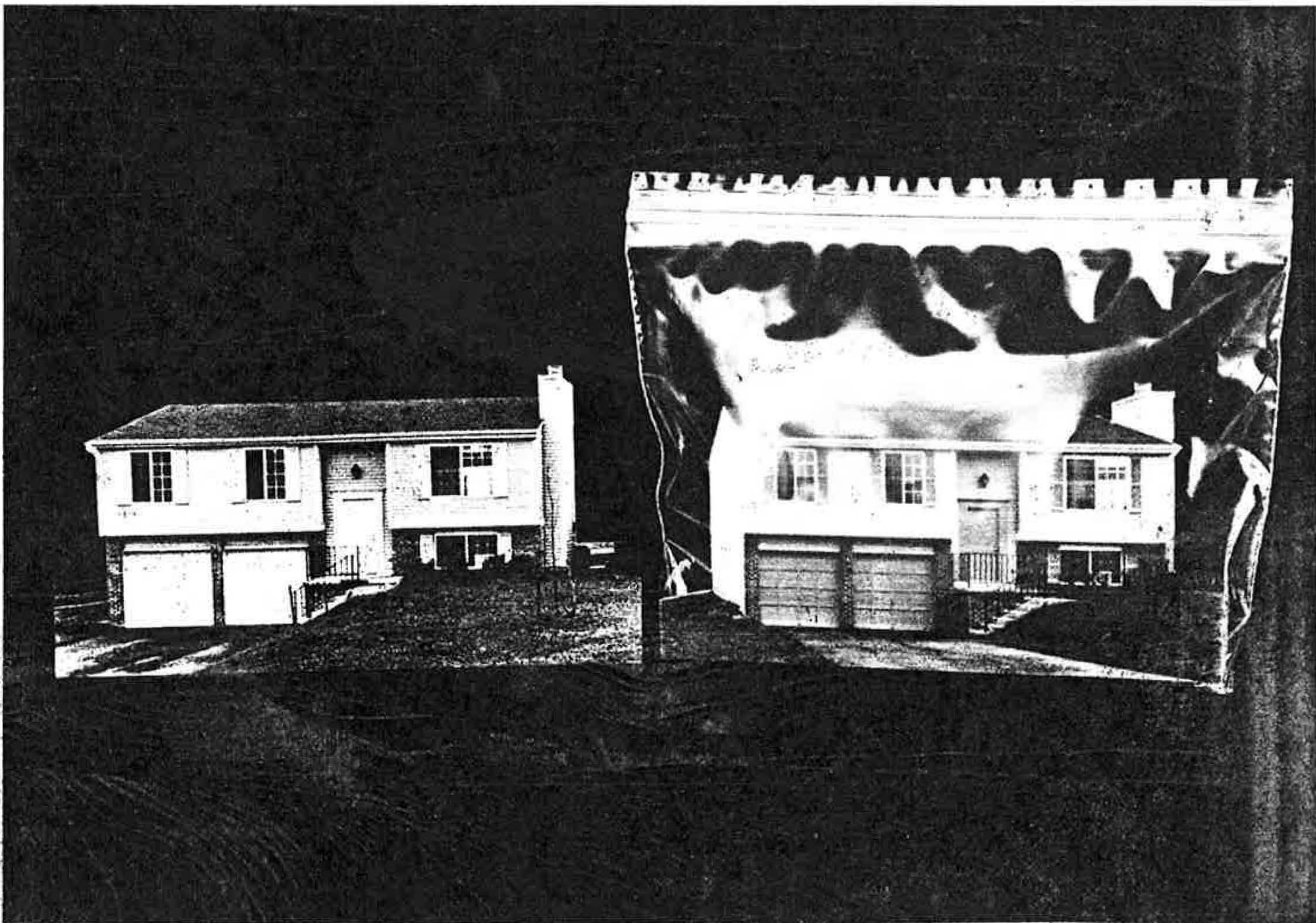
Home energy conservation measures that reduce air exchange rates have raised concerns that harmful levels of pollutants could accumulate indoors. New research suggests that tight construction and good indoor air quality are compatible goals.



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Awareness is growing that the air indoors, where most people spend 80–90% of their time, often holds more pollutants than the air outdoors. One avenue of pollutant removal from buildings is air flow—precisely the flow that weatherization measures aim to reduce. As a result, conservation programs that plug air leaks in buildings to save energy are now being questioned. The stakes are high. Air leakage accounts for perhaps one-third of the heat loss from residential buildings and wastes about 5% of the nation's total energy consumption every year. Given the potential savings, government, utilities, and homeowners have all supported home weatherization programs. Counteracting the known benefits, however, are the unknown health effects that rising indoor pollution levels might instigate.

How tight is too tight? Under what circumstances does energy-saving weatherization seriously compromise air quality? The quantitative information that utilities and others need for guidance in conducting conservation efforts is just beginning to emerge.

A benchmark study by Geomet Technologies, Inc., is developing data on the air quality effects of weatherizing a home. One effort under this study has been an experiment carefully designed to quantify the relationships between the three major variables that enter into the search for a satisfactory balance: air flow, energy use, and pollutant levels. An improved understanding of the physical processes in buildings will, in turn, point the way toward better control strategies.

The indoor setting

The air quality issue has moved indoors by stages. Outdoor standards set by the federal government in 1970 targeted the major precursors of urban smog, namely combustion products from auto exhaust and industrial stack emissions. The initial worry was that these pollutants could seep indoors. The realization soon followed that the indoors, with fuel-burning appliances and fireplaces, had combustion sources of its own. Identifying other pollutant problems that are specific to the indoor environment, such as radon, formaldehyde, and household chemicals, has been the third and most recent step.

Government response to indoor air quality problems has lagged far behind the effort outdoors. There are no overall federal standards specific to indoor air. Outdoor standards and industrial standards set by the Occupational Safety and Health Administration (OSHA) sometimes serve as a basis for guidelines in public buildings. Policing air quality in 85 million private homes is clearly not feasible, although better information could help the residents identify and manage any pollution problems that may occur.

Basic to indoor air quality research is the concept of air exchange between a building and its surrounding environment. A building's rate of air exchange is the number of times its full volume of air is replaced with outside air during a given period of time. As many as four air changes per hour (ac/h) have been measured in leaky older homes. Supertight homes can be built to achieve average rates as low as 0.1 ac/h. Rates can vary greatly from season to season, day to day, or even hour to hour, depending on weather conditions.

Air exchange occurs both intentionally and unintentionally. Deliberate air exchange, accomplished by opening windows or running exhaust fans, is termed ventilation. Uncontrolled leakage of air through cracks or other openings in a building's shell is called infiltration. The actual rate of infiltration is governed by wind pressure on the building and by temperature differences between indoor and outdoor air. Note that the terms *tightening* and *weatherization* as used here refer to measures that reduce air infiltration—caulking, weatherstripping, storm windows or doors—and not to insulation measures, which focus on reducing conductive heat loss.

Indoor pollutant concentrations depend both on source strength and on rate of removal. Because air exchange is a major means of removal, houses with significant indoor sources can experience pollutant buildup when tightening measures succeed in cutting the rate of air infiltration.

Common indoor pollutants may be classified into several types. An important health concern is radon, a naturally occurring radioactive gas that can become trapped indoors after emanating from the earth beneath the house or even from earth-derived building materials used in constructing it. Colorless and odorless, radon decays into highly unstable elements known as radon progeny, which attach readily to dust particles in the air and then deposit in the lung, where the alpha radiation they emit can cause cancer. Although exposure risks may not be adequately quantified, radon concentrations of more than a few picocuries per liter of air could be considered cause for concern. Many houses in Sweden have registered such levels, as have American homes in locations as diverse as Maine, Florida, and Montana.

Volatile chemicals make up a second class of indoor air pollutants. Formaldehyde is perhaps the best known. It occurs in synthetic building materials and in many household furnishings, including carpets and drapes. The pungent smell is a warning signal, but irritation can begin at exposure levels even below the odor threshold of 0.05–1.0 ppm. Although OSHA's eight-hour average standard for U.S. workers is 3 ppm, current recommendations target the range between 0.1 and 0.5 ppm as an upper limit for nonoccupational indoor exposure, consistent with the indoor formaldehyde standards now being established in some northern European nations.

Other chemical contaminants are also hard to avoid. The average American home harbors a number of aerosol cans containing chemical propellants, as well as paints, cleansers, insecticides, or other potential air pollutants. A recently completed five-year study by the Environmental Protection Agency (EPA) found that levels of some 20 volatile organic chemicals are typically much higher indoors than outdoors, sometimes 100 times higher.

Combustion products are the indoor pollutants that have been investigated most extensively because they were the first to be recognized. Measuring indoor levels from fuel-burning appliances and tobacco smoke is the current focus.

These common airborne pollutants, along with the pollutants shed by people and their pets, are the main types thought to be influenced by house-tightening measures. Asbestos and other mineral fibers are a special case that must be addressed separately because their concentrations and control are less dependent on air exchange.

Given the complex variables that operate simultaneously on indoor air, how do researchers get a grasp on air quality dynamics? One strategy is the mass balance approach, which considers a pollutant in terms of its sources and its sinks.

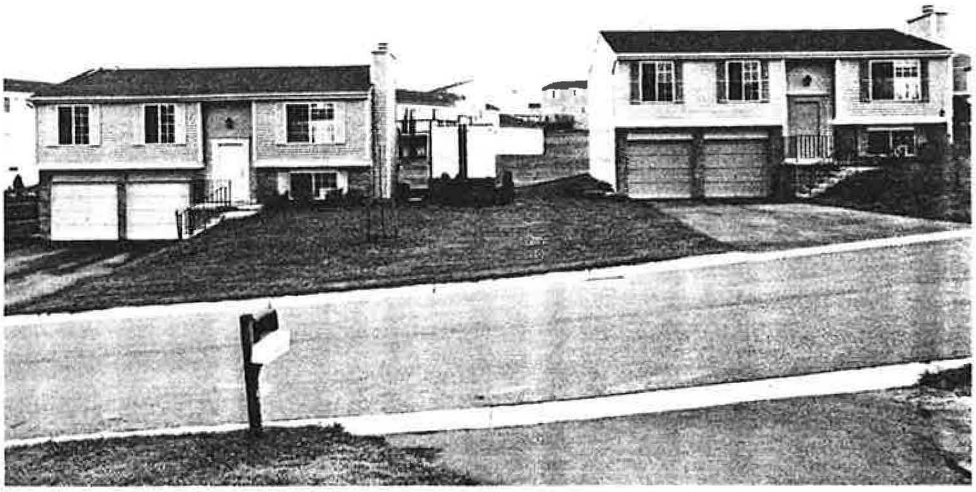
Four questions provide a framework. How much pollutant is coming in from outdoors? How much is going outdoors? How much is being generated indoors? And how much is being removed indoors, say, by filters, as opposed to being removed by expulsion to the air outside? The answers provide an estimated pollutant concentration for a specific time period. This mass balance approach is being used increasingly in current research, including the Geomet study that breaks new ground in quantifying the complex interactions that occur.

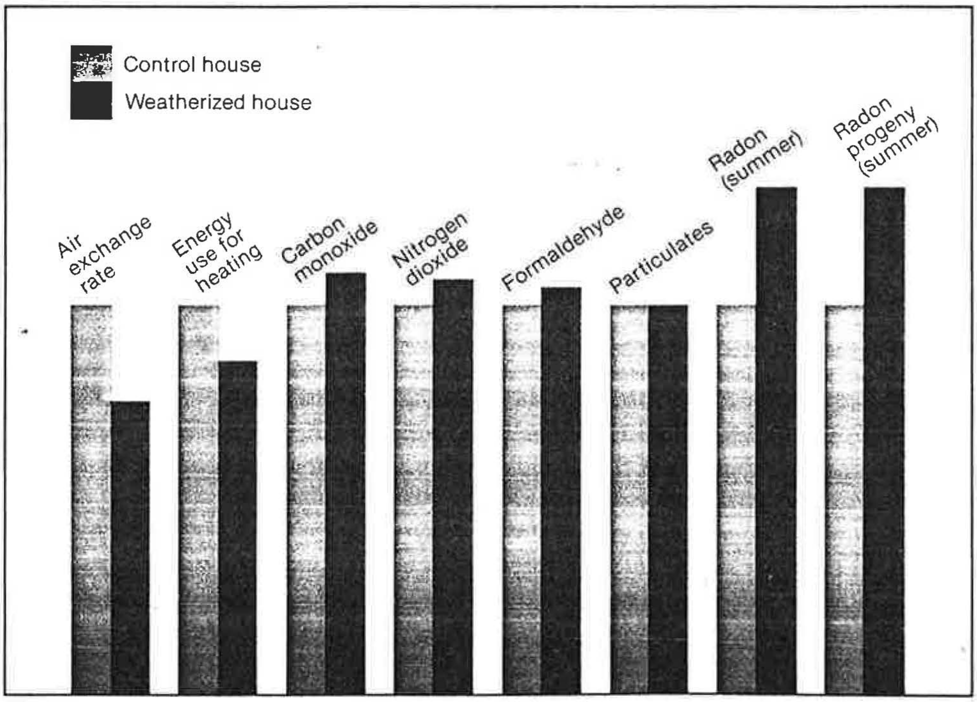
Quantifying the problem

The Geomet study used two identical, newly built houses to provide the data for this rigorously controlled experiment. Located side by side in a Maryland housing development, both were monitored for several weeks to establish baseline levels of energy use and air quality. One was weatherized and equipped with an air-to-air heat exchanger, whereas the other was not. Comparing the experi-

A Tale of Two Houses

EPRI and its contractor, Geomet Technologies, Inc., used two adjacent houses of identical design and construction to study the relationships between building tightness, energy consumption, and indoor air quality. One building was weatherized for tightness and equipped with an air-to-air heat exchanger, while the control house was kept in its original state of construction. Both houses were monitored over a six-month period (from summer to winter) for air exchange rates, electric energy use for space conditioning, indoor and outdoor air pollutant concentrations, indoor temperatures, and weather conditions.





Monitoring Results

Monitoring showed that uncontrolled air exchange rates were about 25% lower in the weatherized house, which also used 10-15% less electric energy for space heating. The most surprising results involved the air pollutant levels, all of which, with the exception of radon gas levels, grew by less than 10% as a result of tightening the house. Radon and the elements it decays to (progeny) were 25-35% higher in the weatherized house than in the control house during the summer (without the heat exchanger or other ventilation fans operating). In the winter, however, total radon levels fell dramatically, and the difference between the two houses became negligible. Radon gas and its progeny are of concern because in sufficiently high concentrations they are thought to cause lung cancer.

mental and the control houses allowed the research team to determine the extent to which the weatherization retrofit saved energy, on the one hand, and changed air quality, on the other.

The houses were unoccupied, although certain activities, such as periodic use of a gas range, were simulated for both. The investigation focused especially on those pollutants that depend on the geology of the site and the materials used to construct the building. "We chose to keep the houses unoccupied in order to sharpen our understanding of physical processes," explains Niren Nagda of Geomet, adding that occupant activities at this stage of the research could have confounded the results. Measurements were taken of air exchange rates, energy use, pollutant levels indoors and outdoors, temperatures indoors and outdoors, and other weather variables. Parallel monitoring of the two houses took place in the summer, fall, and winter to examine seasonal effects.

Weatherizing the experimental house made it 40% tighter than the control house when tested with high-pressure blowers. Under natural conditions, tracer gas experiments showed that the weatherization reduced actual air infiltration by 24%. Average air infiltration rates were 0.33 ac/h for the control house and 0.25 ac/h for the house with the weatherization retrofit.

Greater and more unexpected than the effect of tightening was the impact of seasonal change. Differences between the summer and winter infiltration rates were substantially greater than the difference caused by the weatherization itself. The average hourly air exchange rate for mild summer weather doubled in the fall, and more than doubled again with the advent of winter. The full range covered nearly a 20-fold variation: from 0.05 to 0.96 ac/h for the control house, and from 0.03 to 0.75 ac/h for the house with retrofit weatherization.

As for energy use, the weatherization did indeed provide savings. Cooling benefits were negligible, less than 3%. Heating energy use, however, declined by about 15%. The effect of weatherization on indoor air quality varied considerably, depending on the pollutant in question. For radon, the increase was marked. The retrofit boosted radon gas levels by 30–50% in the summer and fall. Radon progeny concentrations also rose during those seasons, by 20–35%, although winter measurements showed no increase.

The effect of house-tightening on other indoor pollutants was surprisingly small. Carbon monoxide levels from the operation of a standard gas range increased only about 10%. A very slight increase occurred in concentrations of nitrogen dioxide, and formaldehyde concentrations on average did not increase at all. Occasional use of a wood stove was the only indoor source of inhalable particles, and outdoor particle concentrations were low, so weatherization also produced no effect on this pollutant. Clearly, the increase in common pollutant levels, except for radon, was not proportional to the tightening effect achieved by the weatherization retrofit.

Control options

How can a homeowner control air quality problems in a tight house without throwing open the windows and wasting valuable energy? The Geomet research team tested the efficacy of an air-to-air heat exchanger as part of the experimental plan. Information on other possible methods of controlling indoor air quality, such as the use of a range exhaust fan or a central circulation fan, emerged as a by-product of the study. Overall, the results suggest that a simple solution is often the most cost-effective.

The air-to-air heat exchanger is a ventilation device that saves energy by capturing heat from the stale air being expelled and transferring it to the incoming air. Running an air-to-air heat exchanger in the experimental house at a flow setting of 100 m^3/h essentially doubled the air exchange rate. The total energy penalty from loss of indoor heat, plus the device's fan power consumption, varied according to season.

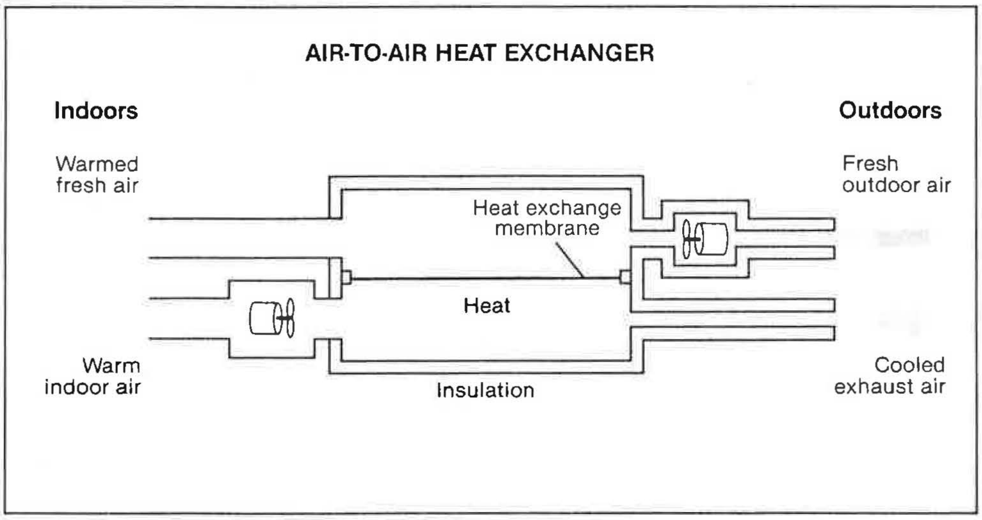
During the heating season, use of the heat exchanger reduced energy savings from 15% to about 6%. Operation of the heat exchanger during the cooling season incurred an energy penalty of 10–15%. Taking into account the heating season's greater length and other seasonal factors, the consequence is that the weatherized house and the control house would consume almost the same amount of energy on an annual basis. In addition, it is worth noting that the heat exchanger ran continuously during the monitoring periods in this study, which may have exaggerated both its energy costs and its air quality benefits for actual home use. Air quality effects of using the heat exchanger varied according to pollutant. The reduction in radon and its progeny was roughly proportional to the change in air flow; that is, doubling the air exchange rate cut radon concentrations in half. Formaldehyde levels were less affected, declining by 30%. Combustion product levels dropped unevenly. One-hour peak concentrations of carbon monoxide fell by 24%, whereas the peak for nitrogen dioxide, which is more chemically reactive with indoor surfaces and hence less dependent on air exchange for removal, was down by only 9%. The very low level of inhalable particles indoors—a level attributable to lack of indoor sources—actually increased during operation of the heat exchanger. The device brought in fresh air from outdoors, where particle concentrations were higher. Indoor concentrations of the other pollutants were able to fall because radon and formaldehyde concentrations are typically low outdoors, and concentrations of most combustion products happened to be low outdoors at the time the experiment was conducted. These results underscore the fact that the outdoors can be a source as well as a sink for indoor pollutants, an important caveat when control strategies that rely on ventilation are employed.

An alternative way to clear the air

around a gas stove is to operate an exhaust fan in the range hood. A range fan lacks the heat recovery ability of a heat exchanger, but it need only be operated when the gas range is on, so the period of any energy loss is quite limited. During these tests, the range hood fan was able to cut eight-hour average concentrations of carbon monoxide in half, just as the heat exchanger did. Being source-specific, it was also more effective in reducing carbon monoxide and nitrogen dioxide peaks by 50% and 40%, respectively, versus reductions of 25% and 10% achieved by the heat exchanger.

A third option tested was the use of a central circulation fan for radon control. A circulation fan mixes the air, redistributes the gas, and enhances the process whereby newly formed radon progeny are removed from the air by plating out on available surfaces. The results with a circulation fan (about a 40% drop in airborne levels of radon progeny) were the same as those achieved by the heat exchanger through removal of the parent gas. The upshot of this work with indoor pollutant controls is that the most efficient solutions tend to be specific to a pollutant, to a house, or even to a particular source within that house, as well as to weather and air quality conditions in the surrounding area.

An air-to-air heat exchanger can freshen the air in any house and reduce all pollutant levels to some extent, assuming that pollutant levels are low outdoors; it is particularly appropriate for tight homes in severe climates with significant indoor pollutant sources. But it is not the best solution in every situation. Geomet's work indicates that other control devices can be equally or more effective, as well as considerably less costly to purchase and install. A final aspect of the present Geomet effort is its contribution to modeling of air infiltration, energy use, and air quality in buildings. Tapping the rich store of measured data generated by this experiment, models were developed that could explain as much as 90% of the variation in hourly air infiltration rates; 90–95% of the daily variation in heating energy use during the winter; 60–90% of the hourly variations in indoor concentrations of carbon monoxide, nitrogen dioxide, and radon progeny; and nearly 90% of the daily variation in formaldehyde levels. This parallel approach of data analysis and model development provided a solid physical basis for interpretation of the study results.



Changing Air, Saving Heat

Air-to-air heat exchangers are sometimes used to ensure that adequate ventilation is maintained in tightly sealed houses. Inside the heat exchanger, warm indoor air leaving the building releases heat to colder incoming air. The Geomet study found that the heat exchanger did improve indoor air quality (reducing levels of radon and its progeny by about 50%) while maintaining the weatherized home's energy conservation advantages. A circulation fan and exhaust hood over the gas range proved similarly effective in reducing pollutant levels, but these devices do not have the energy conservation attributes of the heat exchanger.

Integrating the research

Tightening the experimental house in this study produced variable effects on the pollutants that were measured. Although it yielded a small increase in concentrations of carbon monoxide and a larger increase in radon and radon progeny, it had virtually no effect on nitrogen dioxide or formaldehyde. The effect of weatherization on inhalable particles could not be determined because of a lack of indoor sources.

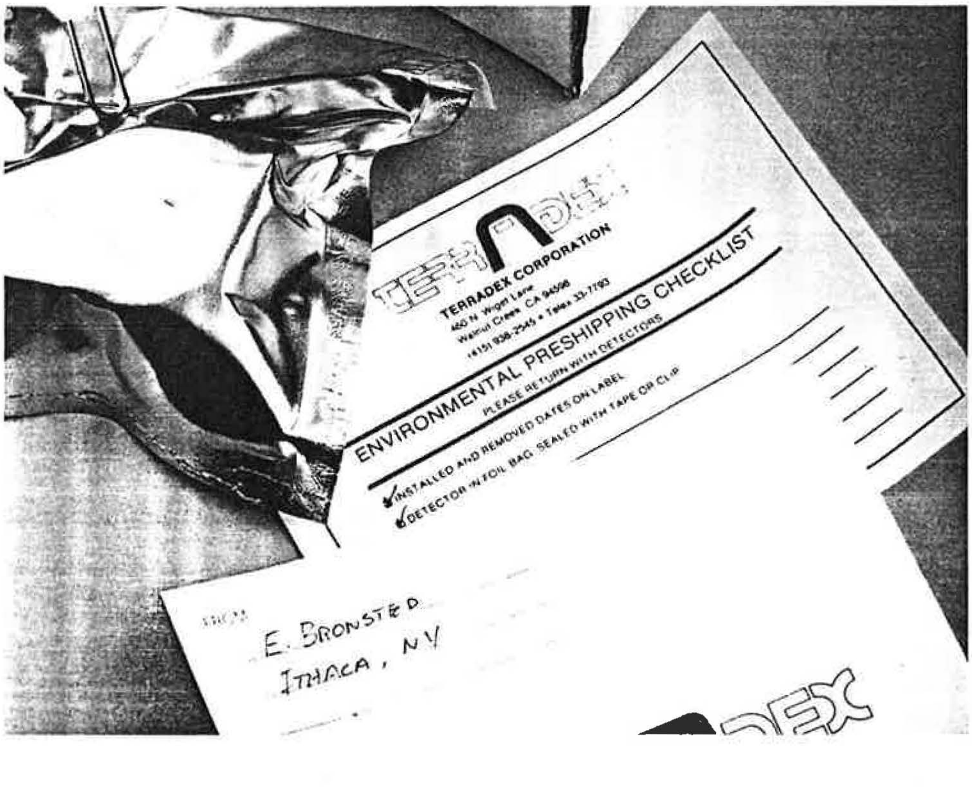
These findings suggest that the air quality consequences of basic home weatherization may be minimal unless significant indoor pollutant sources are present. But the results so far are limited to two homes in a single location, and indoor air quality varies a great deal by region. The weather that drives air infiltration rates is clearly regional in character. Less obvious but also very important are regional variations in radon sources, in the use of wood stoves and kerosene heaters, and in home construction types. Both the specific nature of air quality problems and the appropriate strategies for coping with them will probably have to be explored at a regional or even a local level.

Future EPRI-sponsored work by Geomet will consolidate utility data from homes in diverse parts of the country to see whether some of the patterns found in this study appear on a broader scale. It will also use the two test homes in Maryland for further research on control strategies for radon and radon progeny. And it will take the logical next step in quantifying indoor pollution dynamics by studying the effects of occupancy.

Yet quantifying the physical processes that occur in buildings, occupied or not, is only part of the challenge in dealing with air quality issues. The other part is quantifying the effect of indoor pollutants on human health. To know how

Detecting Indoor Pollutants

Several relatively inexpensive (under $75), easy-to-use devices are available to detect formaldehyde, radon, and nitrogen dioxide. These devices are installed in the space to be monitored for a specified period and then sent to a laboratory for analysis. Comparing the results with existing standards and with levels known to cause health problems can help determine if the building in question has an indoor pollution problem.



tight is really too tight, we have to know more about human responses to the pollutant dose that an indoor environment can deliver.

"I believe that we'll understand the physical processes in buildings long before we understand the cumulative health effects," says Gary Purcell, project manager for residential buildings research within the newly created Energy Utilization Department of the Energy Management and Utilization (EMU) Division. Cary Young, project manager working with air quality health effects for the Energy Analysis and Environment (EAE) Division, agrees. "We do know what substances to be concerned about," he adds, "but we don't know in any systematic way what levels of indoor exposure constitute health risks for various groups in the population."

Besides cooperating with EMU on research into the processes that govern indoor pollutant levels, EAE cofunds the ongoing Harvard air pollution health study, also known as the six cities study, to assess the human health effects of both outdoor and indoor pollutants. The current phase of this study is monitoring the air quality of 300 homes in each of six communities to develop pollutant exposure estimates for the people living there. Eventually, these exposure estimates will be correlated with data collected on the respiratory health of the residents to assess the effects of pollutant exposure over time.

Combining research on energy-efficient buildings with health effects studies provides an integrated approach to the questions surrounding indoor air quality. EPRI is funding about $3 million in research over five years. As the work continues, more information will emerge to support decisions that are sound in terms of both energy conservation and air quality goals. ■

This article was written by Mary Wayne, science writer. Technical background information was provided by Gary Purcell, Energy Management and Utilization Division, and Cary Young, Energy Analysis and Environment Division.