The average person breathes indoor air 75% or more of the day. Yet existing regulations are based solely on outdoor concentrations. Indoor levels of many contaminants are typically higher than outdoors, and common household items such as gas stoves, paint, cigarettes, bath towels, fireplaces, cleaning chemicals—even glued furniture joints and the walls themselves—can produce significant amounts of regulated substances. Efforts are now under way to create a total-exposure air quality model that will improve epidemiologic studies of human health.

Air Quality in the Home

Security and snugness. Nothing beats the image of the family home on a winter night, windows and doors tightly closed against wind and snow outside, a crackling fire for warmth and comfort inside. Of course, there must be family members: father with his pipe and slippers, mother with her sewing, children playing on the carpet and occasionally patting the shaggy head of their faithful dog.

The unexpected fact about this carefully constructed image is that it could represent worse air quality than the downwind side of an industrial city or one of its downtown street corners at rush hour. In an environment-conscious society, there goes security.

Or does it? This startling contradiction makes a point about the indoor environments where most of us spend most of our time. It also introduces important qualifications that stand in the way of tempting but premature conclusions.

How much exposure to what?

The point is that homes, offices, cars, and factories are the source of some air constituents that are not found outdoors; they are also the site of higher concentrations of other constituents. For example, as you briskly dry after a shower, your fluffy towel sheds enough lint to bring the particulate loading of the bathroom air to a much higher level than that present in the outdoor ambient air.

Of course, this high concentration of lint is only momentary. When you hang up your towel and leave the room, normal air exchange with the rest of the house and with the outdoors begins to dilute the concentration, substantially limiting your exposure. Still, the example brings out an important caveat that must be considered in comparing indoor and outdoor air quality: towel lint and many other constituents of indoor air, although acknowledged to be foreign matter, are not generally thought to be dangerous at the concentrations we normally encounter. Concentration levels are key to indoor air quality, whether the constituent is the aerosol from a spray deodorant or the dust from a floor mop.

Establishing a substance's health effects involves a great deal of careful research and testing. With the notable exception of cigarette smoke, indoor contaminants have not been evaluated extensively. For this reason, professionals today are cautious in discussions of indoor air quality. The intent is to deal only with what the air constituents are and in what concentrations they occur. Whether the substance is actually a health hazard is generally not dealt with at this stage.

Of course, air quality is subject to value judgment on esthetic grounds—appearance, visibility, odor—before any constituent concentration is high enough to be harmful rather than just unpleasant. *Pollution* and *contamination* are long-established descriptions for perceptible outdoor hazes and odors of any kind. And when the wind brings industrial smells into our neighborhoods, the terms are bound to be used in talking of indoor air quality. However, few airborne species are known pathogens, and still fewer appear in our usual living and working spaces.

The most significant fact is that indoor air is our prevailing environment—probably 90% of the time, according to an interagency federal research group, and even more for sensitive population fractions such as babies, the very old, and people who are sick or in institutions. Does all this mean that we have been barking up the wrong tree by regulating outdoor air quality, with maximum permissible ambient concentrations and emission rates for particulate matter, a number of gases, and several trace elements? Not necessarily, because air quality has relevance for many ecologic systems (forests, agriculture, rivers, and lakes among them). But the major concern is human health, and it is well established that human activities are churning out increasing quantities of an ever larger variety of particles and gases. It is time to learn what follows us indoors (or originates there), whether the concentrations are different, and if so, why.

Indoor levels, outdoor pollutants

Ralph Perhac has headed EPRI's Environmental Assessment Department since 1980. Research in the programs under his direction may deal with any environment, most obviously those of land, air, and water and the systems of plant and animal life and enterprise they support. EPRI is most interested in the influences of environmental agents and factors introduced by the generation and transmission of electricity (and to some extent the supply of utility fuels and materials and the end use of the electricity). But it is sometimes necessary to look beyond the phenomena and products of utility operations, especially when natural processes in the biosphere produce some of the same effects but to an unknown degree. This is especially true in the matter of air constituents.

When EPRI first began to investigate indoor air quality, it focused mainly on air constituents already being monitored (and many of them regulated) outdoors. The point was to compare indoor and outdoor concentrations and, where possible, define the relationships and find the reasons for differences. Because individuals spend so much time indoors, large and consistent differences would be important in the scientific study of the effects of air pollution. The information also could be useful to those involved in setting air quality standards.

The initial sponsored research dealt largely with pollutants produced in fossil fuel combustion. Sulfur dioxide, nitrogen oxides, ozone, carbon monoxide, carbon dioxide, and certain hydrocarbons were the gaseous species of interest. Particulates were sampled and analyzed to differentiate the fraction of respirable matter and quantities of trace metals and various compounds.

Geomet, Inc., conducted the measurement and analytic effort for EPRI over a two-year period, 1978–1980, during which ten single-family houses and two office buildings in and around Boston were successively instrumented and monitored for two-week periods. Gross characteristics of the houses and their occupancy were cataloged in advance. For example, four houses were all-electric, and six used natural gas for cooking and heating. Five houses had occupants who smoke, two had fireplaces, and one had a wood stove. Occupancy ranged from two to six people, and five houses had dogs or cats.

Air quality was monitored at three points indoors (typically, the kitchen, a bedroom, and the living room) and at one point outside, together with four items of weather data: temperature, humidity, wind direction, and wind speed.

Hourly rates of air turnover were also calculated. This is the volume of air exchanged between indoors and outdoors and the basis for changes in various concentrations. Air exchange was computed from measurements of building volume

and the timed decline in the concentration of a tracer gas (sulfur hexafluoride) injected into the indoor air. The relative tightness of house construction is a major influence on air exchange. Other variables are the use of windows and heating and air conditioning systems to control temperature, patterns of entry and exit, and wind intensity against specific leaks.

Air exchange in the EPRI-tested houses was found to range from as little as 0.5 to as many as 1.3 complete turnovers in one hour. The average was about 1.0.

Oxides and particulates

Findings from the study are provocative rather than conclusive. Researchers accustomed to relatively ponderous, weather-related shifts in outdoor air quality were surprised by fast and marked changes—virtual spikes—in the indoor records of constituents traceable to specific human activities, such as the use of stoves or cleaning fluids.

The maximum concentrations named in ambient air quality standards are time-averaged values, the averaging periods being as short as one hour and as long as one year. Because the EPRI-sponsored measurement program allowed only two weeks at each test site, it was not possible to draw precise comparisons with all air quality standards.

Measured outdoor concentrations of regulated pollutants seldom exceeded federal standards. And for indoor concentrations traceable only to outdoor sources of those pollutants, the same was true. In fact, sulfur dioxide and ozone levels were typically lower indoors than out, although ozone was the subject of occasional spikes exceeding the one-hour outdoor standard of 120 ppb.

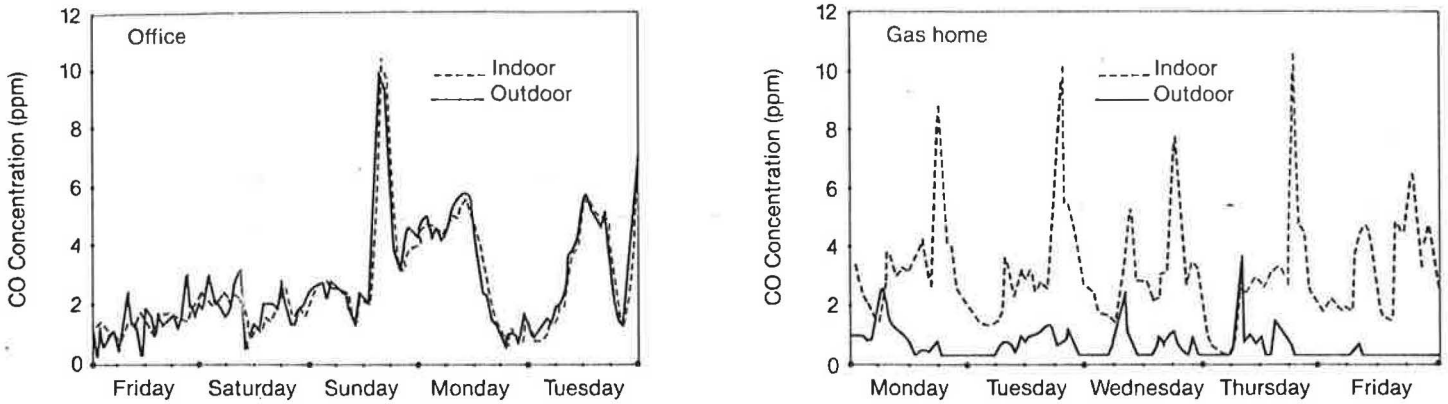
Offices and all-electric houses generally tracked the outdoor air quality, rising and falling at about the same rates and times of day. Houses with gas facilities understandably showed somewhat higher concentrations of carbon monoxide and nitrogen oxides. Values of both peaked when meals were being cooked. However, 24-hour indoor average values for nitrogen oxides were higher than outdoor averages for the same period in all-electric as well as gas houses. This suggests that indoor levels of nitrogen oxides are augmented from outdoors but do not then disperse or react so quickly to form other compounds.

Nitrogen dioxide is a constituent for which comparisons of concentrations are awkward because no short-term averages are given in the federal standard; the federal standard of 50 ppb is an annual average. The only other basis, even for academic comparison, is California's one-hour average of 275 ppb. EPRI's test program in the Boston area never exceeded one-hour average values of 196 ppb outdoors or of 241 ppb indoors. The highest 24-hour averages were 70 ppb outdoors and 102 ppb indoors, not badly out of line with the one-year federal limits.

Particulate levels indoors were found to be higher than outdoors in almost all cases, regardless of what room concentration was considered. On average, living room concentrations were about 50% higher than outdoors. (In houses with smokers, the difference was 300%.) These differences are startling, so it must be emphasized that the outdoor concentrations never exceeded either the primary federal standard (260 $\mu g/m^3$) or the secondary standard (150 $\mu g/m^3$). Also, the two office buildings in the test program must be distinguished: their particulate concentrations were always slightly lower than outdoor levels, because of their air conditioning and filtering systems.

Analysis of air samples permitted separate measurement of respirable particles, defined for this study as particles in the range of 0.5–3.5 μm in diameter. Their occurrence was about the same as for particulate matter in general, being highest in houses with smokers and on occasions when fireplaces or (to a lesser extent) woodstoves were in use. Fireplaces are incontrovertibly serious

The high air exchange rate in office environments where mechanical air-handling systems are used cuts indoor carbon monoxide (CO) concentrations to about the same levels recorded outdoors (left graph); indoor CO concentrations in all-electric residences are slightly higher, although they still track the outdoor changes very closely. In contrast, the significantly higher CO levels in a residence with gas facilities (right graph) do not closely follow changes in outdoor concentrations, being more dependent on indoor activities, such as cooking and heating. Note the regular occurrence of sharp peaks around the dinner hour.



contributors to reduced indoor air quality, just as suggested by the vignette of the family living room. When wood was burned, concentrations of particulates increased four or five times; the 150-$\mu g/m^3$ secondary standard for total suspended particulate matter in the outdoor air was always topped in the indoor air by the smaller, respirable fraction alone.

Benzo-a-pyrene (BaP) is an organic particulate derived mainly from the combustion of coal, wood, and refuse and to a lesser extent from automobile engines. It is a carcinogen, so measurements of BaP were added to the Geomet test plan. For the most part, indoor BaP concentrations were about 2–3 ng/m^3, the same as or only slightly higher than outdoors and not influenced by the different characteristics of house type or occupancy. But when wood was burned in either fireplaces or stoves, indoor BaP levels were as much as 20 times the outdoor levels. Even when averaged over 24 hours (the fire having burned for less than 3 hours), the concentration in one instance was 4.7 ng/m^3. The urban outdoor average, on an annual basis, is only 0.9 ng/m^3. BaP exposure in woodburning homes may be significant to public health.

Other compounds and trace metals

Of the air pollutants generated in houses, particulates come first to mind because they are associated with the traditional fires of heating, cooking, and tobacco smoking. But other agents are reckoned in assessments of air quality today, and they were monitored in the EPRI project.

Nonmethane hydrocarbons (NMHC) are subject to regulation if ozone concentrations exceed statutory limits; the guidance NMHC concentration is then 0.25 ppm, as averaged over the three-hour period from 6:00 to 9:00 a.m. The standard is so defined because NMHC is a photochemical reactant in the formation of ozone and smog. In EPRI's Boston area investigation, three-hour outdoor NMHC levels topped the guidance standard by an order of magnitude (7.4 versus 0.25 ppm), and indoor levels topped the standard by two orders (24.2 versus 0.25 ppm). One-hour indoor concentrations were even higher, traceable to such activities as the use of paints and cleaning agents. Two other categories of potential pollutants were monitored: two compounds that evolve in part from the sulfur and nitrogen oxides of combustion emissions and six metals that may occur in trace amounts.

Sulfate concentrations ranged from 2.0 to 10.0 $\mu g/m^3$ indoors and outdoors, typically a little lower indoors. The exception (paralleling observations in other studies) was found in houses where matches were frequently used by smokers and in lighting stoves. Nitrates result from the combination of nitrogen oxides and water vapor, inevitable in the kitchens of houses with gas stoves. Maximum 24-hour averaged concentrations in such cases were 1.5–2.0 times the outdoor levels; in all-electric homes the indoor levels were generally less than found outdoors.

Manganese levels, though monitored for only two weeks, compared favorably with three-month nationwide figures compiled six years ago. Lead and vanadium concentrations were mostly lower indoors than outdoors; there were no significant indoor sources, not even paint and plumbing. Indoor levels of arsenic, cadmium, and iron were likewise lower, except in houses occupied by smokers. Elevated iron concentrations are not explained, but arsenic and cadmium are known to be in cigarettes, the arsenic believed to be a residue from insecticides used on tobacco plants. The levels noted were considered typical; the arsenic and cadmium measurements,

respectively, were three and five orders of magnitude below occupational safety levels.

New air quality model needed

EPRI's Boston project findings are points at the end of a trend line, confirming prior knowledge and adding to it. On the one hand, if outdoor ambient air standards are the benchmark, few indoor levels of regulated pollutants were found to be often or consistently excessive. On the other hand, using outdoor measurements as the benchmark, several pollutants commonly occurred in higher concentrations indoors: carbon monoxide, nitrogen oxides, NMHC, and particulate matter, including BaP where wood fires burn.

At least as important as the specific data is the fact that indoor and outdoor air quality are often so different. This raises other issues that need to be probed.

- Better definition of proportionate exposure to indoor and outdoor environments could aid the development of more accurate models to assess the consequences of air pollution on health in various population groups.

- Lengthy indoor exposure calls attention to the factors that cause indoor concentrations to become and to remain higher than outdoor levels. The most obvious is the air exchange rate, always influenced by human traffic in and out of buildings but increasingly affected by actions being taken today to insulate and weatherize for energy conservation. New houses, in particular, are designed on a buttoned-up basis with features that collect solar energy for heat and minimize air exchange so as to conserve that heat.

- Indoor exposure time also raises a point about the identities and sources of air pollutants. Because of its utility industry auspices, the EPRI project concentrated on indoor manifestations of outdoor pollutants, the ones associated with industrial combustion. But reviewing the measurements, not to mention following the daily news for any period of just a few months, shows the presence and occasionally troublesome effects of substances previously unsuspected of being air pollutants. If utilities are in good conscience to encourage the energy and money savings of conservation—acknowledged to be the cheapest energy "source"—the effort needs to be paralleled by new understanding of the implications for indoor air quality and health.

Recognizing indoor exposures

Outdoor ambient air quality standards have always been subject to question on many bases, especially the precision and realism of specific values—for example, the maximum concentration levels and exposure times set to protect human health. Questions have also been raised about the relative importance of the agents defined as air pollutants.

Many such questions stem from the wide uncertainty about how pollutants are formed and transformed in the atmosphere, how they move and disperse and recombine, and how they act on ecologic systems in general, not just on human health. The questions are important because compliance with air quality standards, especially the control of combustion emissions, is expensive for many affected companies and entire industries. (The cost flows through to consumers and is likewise expensive for them, but it is not separately evident in the cost of doing business.)

Epidemiologic studies have been conducted to defend the numerical values used in air quality standards. A principal approach has been to compile records of outdoor air quality measurements in several areas and search out correlation with epidemiologic data for respiratory disease in the same areas. The task is enormously complicated by demographic influences on the disease data. In fact, using this aggregate approach, a direct link is difficult to establish between human exposure and the presence

or absence of disease in individuals. It is becoming recognized that the sole use of stationary outdoor monitoring data is a serious shortcoming, perhaps the major one, in assessing exposures for either individuals or populations.

The professional community in air quality and environmental assessment, including EPRI's Perhac and his colleagues, sees the need to develop a new model of population exposure to air pollutants, a model that gives weight to the preponderant time spent indoors and recognizes the different identities and concentrations of pollutants typically found there. Considered as one side of an equation, such a model could be set against appropriate epidemiologic evidence for the existence of an exposure-disease relationship. If the exposure patterns and epidemiologic data are reasonably correct, it should be possible to estimate the magnitude of hazard from air pollution in a given population.

Newly modeled estimates could put into perspective the part that industrial combustion plays in the health hazards posed by today's complex air environments indoors and out. Those estimates might also be the basis for a revised regulatory approach to air quality control.

Articulating composite indoor-outdoor air quality policy would be an interesting challenge. For outdoor air quality control, the action path is well established: initiation of regulatory procedures, establishment of emission limitations, and industrial response to those limitations through use of pollution control technologies or altered patterns of plant and process function. The prospects for dealing with indoor air quality issues do not have any such precedent for measurement or control strategy. How regulation or education regarding indoor pollution hazards could be accomplished can only be conjectured.

Clearly, though, the challenge is one that crosses conventional lines of technical disciplines, industries, government jurisdictions, and geographic regions. Immediately evident is the need for self-consistent, comparable data, in turn calling for uniform instrumentation and practices in collecting and analyzing indoor air quality data.

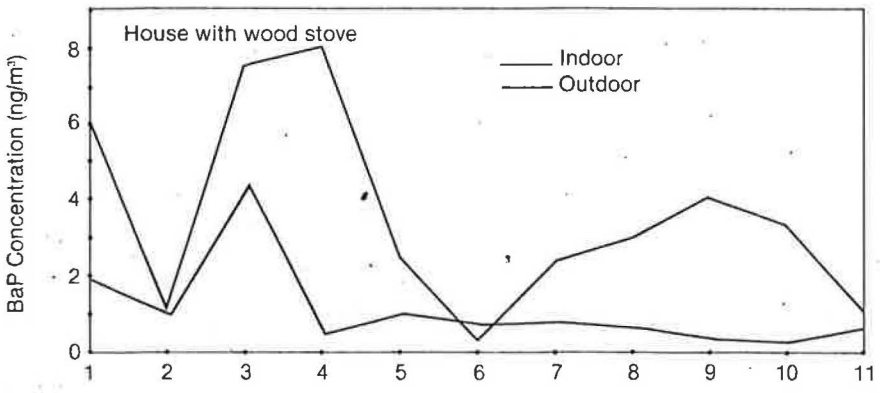
Assessing air exchange

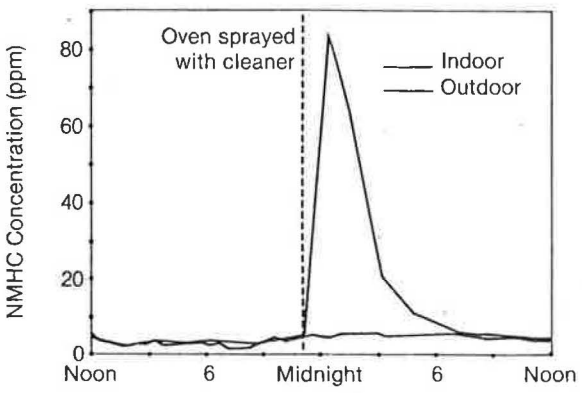
The indoor-outdoor rate of air exchange has also come to be seen for its connection with energy use. Storm windows, caulking, plastic barriers, and weather stripping—the most obvious measures to conserve heat—have led to a widening range, but especially a downward trend, in the air exchange behavior of U.S. houses. The suburban Boston residences in EPRI's project ranged from 0.5 to 1.3 exchanges per hour. But building materials are becoming available and design research is afoot that will hold the exchange rate down to as little as 0.1 or 0.2.

Perhac and other air quality researchers who observe this trend are cautious. "If ambient air quality standards are true measures of safety, then we see little need for concern where air infiltration in a house produces at least 0.5 exchange per hour." But for tighter houses, there simply are not enough data to draw firm conclusions about health effects.

This implicit conflict between energy conservation and indoor air quality is a distinct disappointment for many electric utilities. The Bonneville Power Administration is a case in point. Urged by the times and ultimately required by congressional action to invest in energy conservation where that would cost less than the installation of new generating capacity, BPA developed a regionwide program to assist its utility customers in auditing houses and providing financial

Patterns of household activity can have extreme effects on air quality in the home. In a residence with a wood stove (left), average levels of benzo-a-pyrene (BaP) were significantly higher than those outdoors except on days 2, 6, and 11, when the stove was not in use. In another case (right), a commercial oven cleaner caused levels of nonmethane hydrocarbons (NMHC) recorded in a kitchen to increase 16-fold in less than 90 minutes.





assistance for energy conservation measures that would be cost-effective. Indoor air quality questions came to be a limiting factor when BPA, in its assessment of environmental consequences, could not flatly conclude that there would be "no significant adverse impact" on indoor air quality as a result of BPA's actions.

The BPA program is for the most part restricted to electrically heated dwellings. The uncertainty about indoor air quality meant a further restriction; BPA decided it would limit its aid to insulation in those houses that contain fireplaces or wood stoves, are built of masonry, have basements, or use well water supplies—factors that relate to the origin and dispersal of pollutants. For other houses, BPA would authorize complete weatherization. The distinction is important: insulation alone is a barrier only to heat exchange; weatherization also includes the weather stripping, caulking, and storm windows and doors that impede air exchange. The effect of this distinction has been to limit the most comprehensive conservation measures to only about 30% of the targeted houses. Because one-third or more of typical residential heat loss results from infiltration, it is evident that BPA and its utility customers have had to forgo significant energy savings, at least until a formal environmental impact statement and its risk analysis can be completed and evaluated.

BPA's caution is shared by other utilities. The caution at times becomes a dilemma where state regulatory bodies not only allow but encourage or require utilities to offer technical and financial aid in customer energy conservation.

Identifying true pollutants

One of the most difficult aspects of indoor air quality is the everyday advent of new pollutants, either the new presence or the recognition of a hazard. Singular episodes appear in the news, such as in June 1981, when trichloroethylene leaked at a small furniture factory in Tennessee, evolving vapors that sent 36 workers to the hospital with temporary dizziness and breathing difficulties.

More insidious are the recurrences, frequently in office buildings, that become virtually chronic for some groups of employees. In the Denver area, annoying respiratory symptoms—congestion, headaches, breathing problems—were ultimately traced to residues from a carpet shampoo that was being used periodically and without the recommended dilution.

Control or removal of trichloroethylene or carpet shampoo is one thing. Wholesale avoidance of an established building material is something else. Yet studies show that formaldehyde outgasses for long periods from particle board, some plywoods, and some foamed insulation. These materials are extensively used throughout the construction of mobile homes. Urea-formaldehyde foam has been considered for banning by the federal Consumer Product Safety Commission, but the matter remains unresolved.

Perhaps most vexing has been the rising awareness of radon gas and its implications. Radon, a product of radium decay, in turn decays to other radioactive elements. Alpha particles given off by those elements can constitute a dangerous dose of radioactivity if the elements are inhaled in sufficient quantity.

Radon is almost omnipresent in rock and soil, from which it out-gasses constantly and is dispersed. (For this reason, radon commonly occurs in well water but not in the water of rain- and snow-fed streams.) It also emanates from rock products, such as the brick, tile, block, and concrete used in construction. Where those materials are used inside buildings, the concentration of radon may go up, and so does the potential for inhaling its radioactive decay products, which may become attached to the fine respirable particulate matter that already abounds in indoor air.

Along with weatherization that bottles up indoor atmospheres and their heat

...e of today's building design features is the concentrated use of stone and concrete as thermal mass to absorb, store, and then release solar energy for space heat. This so-called passive solar energy design is cheap and practical, but it is now being reevaluated because there is also some question about the lung cancer hazard from exposure to radon and its decay products.

Needs that point the way

Recognition of indoor air quality problems and responses to them date back only to the 1960s and probably include fewer than 100 research studies. Nationwide investigative scope began with work by EPA in 1975. Two recent efforts are truly comprehensive in consolidating the knowledge of indoor air quality and the research needed to extend that knowledge and solve the associated problems of air pollution.

Indoor Pollutants, published last year by the National Academy Press, is a National Research Council report by its Committee on Indoor Pollutants at the request of EPA. The project tallied indoor pollutant sources and characterizations, explored factors that influence exposure, discussed health and welfare effects, considered control measures, and presented recommendations on seven pollutant classes, ventilation and control strategies, education, and needed exposure studies.

The federal Interagency Research Group on Indoor Air Quality cataloged research needs late in 1980. This group brings together representatives of many federal agencies concerned with research on the indoor environment. Among the participants are the departments of Energy, Defense, and Housing and Urban Development; EPA; the Consumer Product Safety Commission; the Center for Disease Control; the National Institute for Occupational Safety and Health; the National Institute of Environmental Health Sciences; and the Occupational Safety and Health Administration.

An IRG workshop in December 1980 brought together more than 200 conferees to inventory current research efforts, review a strategy for proposed indoor air quality research, and outline specific research needs. The workshop called for a vast range of air quality monitoring and data collection, for adequate and standardized instruments and methods, for determinations of health effects, for research in control technology, and for work in risk analysis.

The National Research Council report and the IRG workshop report both constitute excellent agendas for indoor air quality research. Prospects for aggressive work under federal coordination are uncertain now, however, although one widely useful beginning has been made. Anticipating expansion of its energy conservation aid to utilities, BPA sought EPA assistance in developing a generally applicable methodology (known as a protocol) for conducting indoor air quality assessments. Geomet, Inc., under contract to EPA, has since furnished the protocol needed by BPA; and an expanded version for nationwide use is now in review before publication.

For EPRI, the next research step combines concerns with indoor air quality and with energy conservation. Ralph Perhac's Environmental Assessment Department is cooperating with Thomas Schneider's Energy Conservation and Utilization Department in a two-year experimental and analytic investigation of residential air exchange rates, energy consumption, and concentrations of key indoor air pollutants.

Correlation of air exchange and energy consumption was originally seen as an economic comparison alone; it would produce data and permit conclusions about the cost-effectiveness of various residential insulation and weatherization measures, including air-to-air heat exchangers that salvage indoor heat while permitting air exchange. Perhac saw the proposed research as an opportunity also to develop further information on the relationship of indoor air quality and air exchange rates. The work will therefore include measurements of radon, formaldehyde, respirable suspended particulate matter, carbon monoxide, nitrogen oxides, and other substances that may be designated.

It is clearly evident that there must be a balance between the value of energy saved by conservation measures (which result in reduced air exchange) and the value of indoor air quality lost by the same means. EPRI's research in the coming two years is planned to gain some better sense of where that balance point is or of how to locate it in specific situations. ■

This article was written by Ralph Whitaker. Technical background information was provided by Ralph Perhac, Energy Analysis and Environment Division.