The Effect of Retrofit Conservation Measures on Air Quality in Existing Homes

David Grimsrud, Ph.D.
Lawrence Berkeley Laboratory

Yesterday we talked at some length about particular indoor air quality problems that concern researchers. This morning Dr. Meyer has begun to discuss issues involving standards in regulation; public policy issues which I think interest many people here in the room. I want to talk at some length about the issues or about particular policy decisions made collectively by utilities or other organizations that are related to weatherization of houses.

The typical weatherization program should modify the building shell in such a way that energy is used more efficiently. In so doing it will have some effect on the air quality in the structure as well. At least that is what we believe and we want to look in some detail at the question this morning. The change in air quality happens for two different reasons. Presumably there will be changes made in the characteristics of the pollutant sources. There will also be changes made in removal processes. In steady state, for non-reactive pollutants in a well mixed situation, we can write down an approximate relationship between concentration, source emission rate, and removal rate. This relationship says simply that the ratio between the source emission rate and the removal rate is equal to the concentration. That is the issue we are talking about today.

To affect the source term we may change the insulation level in the house, therefore reducing the need for energy to condition the volume. If we have a combustion furnace that has some problems with venting or if we have some other source of space heat that is not perfectly clean, then that can have an effect on the pollutant concentration within the space. If we insulate with urea-formaldehyde foam insulation to improve the energy efficiency of the shell, then that again can change one of the source terms that enters the equation for pollutant concentrations of the building. If we do the renovation or the weatherization, we will likely affect the ventilation rate (which is the dominant removal term) as well. So our charge today is to look in some detail at studies that have been done to see if the retrofits have actually changed indoor air quality and changed pollutant concentrations.

When I was in school I was in a discipline that emphasized problem solving. One of the first lessons I learned about solving problems was that one should know the answer to a problem before trying to solve it. Effectively, what the professor was saying was--guess at an answer, work out the problem, and see if the calculated answer agrees with the guess. What that does is help develop intuition. If we look at the problem that we are addressing today, we can argue that the change in indoor air quality is dominated by ventilation change. If we reduce the ventilation as part of the weatherization, then concentrations of pollutants inside the building should increase. Let us examine what happens. We began making measurements of these problems in the late 1970's when the only instrumentation available was high quality, real-time instrumentation. I do not want to say anything bad about the instrumentation. It was very good, but it was expensive and required a highly skilled technician to keep it running. It also required space. Our mobile laboratory at that time was a semi-trailer. One can imagine that such monitoring was expensive. It was a very intrusive way of monitoring so the buildings that were monitored were unoccupied typically. Today things have changed and some of the studies we will be talking about this morning use different kinds of instrumentation packages.

Passive instrumentation was developed in the early 1980's. The instrumentation package is not complete certainly, but there now exists available instrumentation to monitor radon, nitrogen dioxide, water vapor, formaldehyde, and hopefully soon, carbon monoxide.

A typical passive device is shown in Figure 1. This is a sampler developed at LBL that monitors formaldehyde.

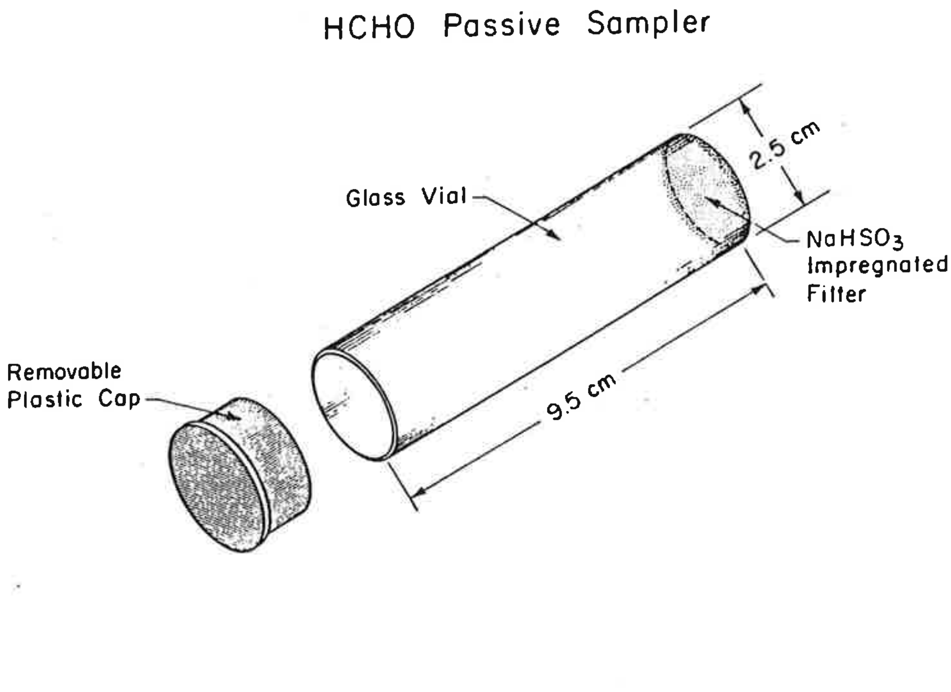

Figure 1

I must emphasize what this instrumentation does. It changes the scale of the number of measurements that can be made in any situation. It does not give real time measurements, but rather integrated measurements over time periods that range from a week for formaldehyde to a year for radon. This instrumentation has made the measurements below economically practical.

One of the first studies that was done was done at the Midway site in the state of Washington, about 50 miles from the Tri-Cities. It is a sub-station owned by the Bonneville Power Administration. It contains 18 homes, 12 of which were retrofitted using the best available technology at the time of the study, 1981. The retrofits were made using a technique that is referred to as the house doctor technique. A blower door is used while retrofitting is done to make sure that reduction in leakage is done as efficiently as possible. It is a very efficient use of time to have some kind of forced pressurization or depressurization in the building shell when one is attempting to seal leaks. The construction dates of the homes vary from the early 40's to 1968. They had single paned, double-hung windows, but most of the windows were painted closed so they were very

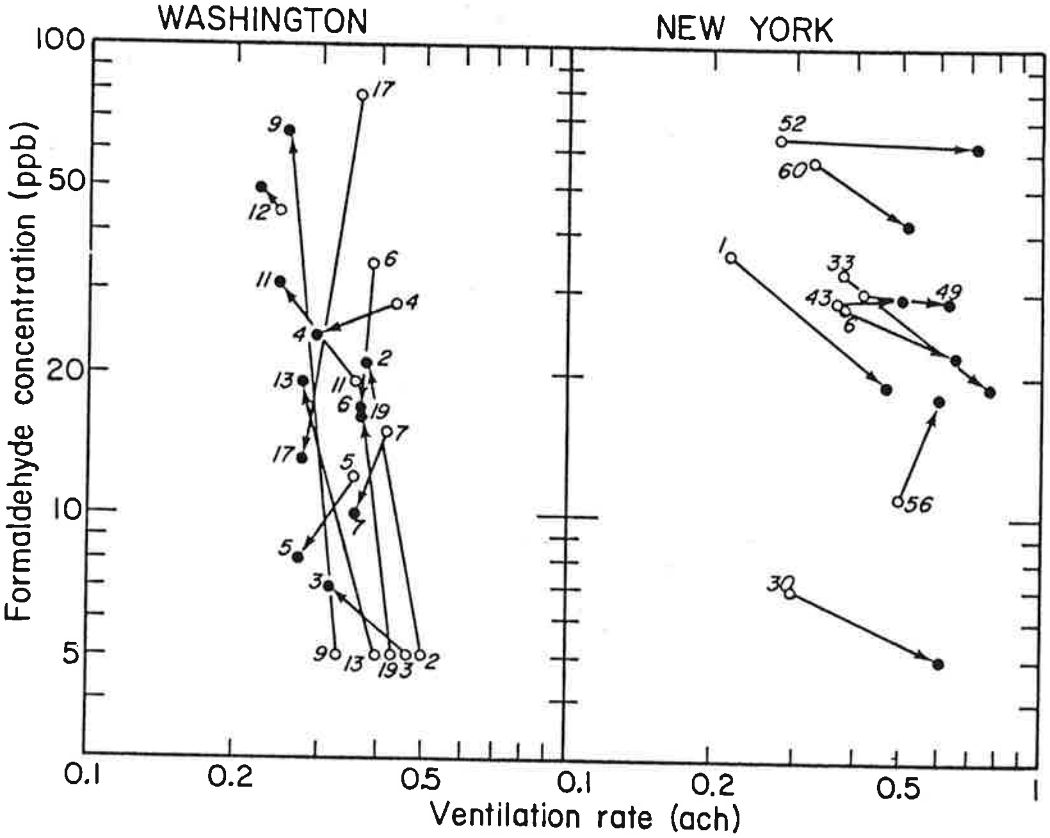

Figure 2

tight. The pollutants monitored were nitrogen dioxide, formaldehyde, and radon. At that time the formaldehyde measurements were not made using a passive sampler, but rather using a NIOSH bubbler technique. The measurements that are shown here are ten separate 12-hour measurements averaged together in each house. What the rather complicated information in Figure 2 shows is the before and after concentrations of formaldehyde in those houses plotted as a function of ventilation rate. This is a sample of old houses. There were not any new houses in this sample. Any changes that are seen in this study are dominated by changes in the furnishings of the houses. The houses were measured in November, the retrofit took place in December, and the houses were re-measured in January. One of the striking changes is that one of the homes (no. 17) in which formaldehyde concentrations were high before retrofit became tighter as the result of the retrofit. The formaldehyde concentration, however, dropped significantly. The occupant of the house moved to a different house while the retrofit was done. His house initially was high. After the retrofit his original house dropped considerably, but the concentration in his final house (no. 9) changed from a low level to a high level. The formaldehyde concentration was dominated by the source change of the personal furnishings of the homeowner. Radon changes due the retrofit were not significant statistically. In fact the numbers increased; but, given the quality of the instrumentation which was used to make the rather short term measurements of radon, one cannot say that the radon levels changed. Nitrogen dioxide levels were very low; there were no major nitrogen dioxide sources in the space.

The next study I would like to discuss briefly is a set of two homes in Medford, Oregon, and one in Cranbury, New Jersey. Three different houses were retrofitted extensively and were monitored using the equipment in the mobile trailer that I referred to above. Real time measurements were made in each of the houses for a two week period. A large number of pollutants were monitored. All the EPA criteria pollutants, carbon dioxide, radon, particles (both coarse and fine particle fractions were measured), and x-ray fluorescence was used to examine the particles collected for 28 different elemental compositions. The houses in Oregon had a problem that we find commonly on the west coast in the U.S. They had forced air heating systems where the ductwork ran through unconditioned space, in this case, the crawl space. The infiltration measurements in those two houses varied considerably depending on whether the blower was on or off. If the blower was on, the infiltration rate increased by a factor of 2. When the blower was off the infiltration was about three tenths of an air change an hour (0.3 ACH); when it was on it was about 0.6 ACH. It is not an unusual result when one looks at typical duct construction in these situations, if the ducts run through unconditioned spaces. The results of weatherization in the Medford house were a reduction of approximately 30% in the leakage. The Cranbury reduction was only about 10% of the leakage in the infiltration rate. The Cranbury house had been retrofitted to some extent by the owners prior to our measurements. In Medford the only substantial change between retrofit before and after was in the carbon dioxide level. There was some change in one of the two houses when we look at fine particle fraction. One of the occupants of that house was a smoker and if we divide the data between smoking periods and non-smoking periods, the level of particle concentrations when smoking took place increased by about 20%. In the other home the change was not significant.

Another study that I can only discuss very briefly because the results have not been published is a study that Geomet Incorporated has done in Rockville, Maryland, with support from the Electric Power Research Institute. Two identical houses built by Ryan Homes, a large home builder on the east coast, were monitored extensively over a period of a year. After initial construction and after measurement that showed the houses were indeed quite similar in terms of their physical characteristics, one of them was retrofitted extensively using the House Doctor technique. The air leakage in that house dropped about 40%. The houses continued to be monitored. Radon, formaldehyde, nitrogen dioxide, carbon monoxide, and particles were measured on a real time basis using instrumentation that is similar to the kind of instrumentation that had been used in the mobile trailer. The typical infiltration rate differences that were seen between the two houses were 25 to 30%. In this case, the houses were both two-story houses and there was a substantial difference between measurements that took place in the first floor and measurements that took place on the second floor. A one-story house physically is quite different from a two-story house and in dealing with data from the field one has to be sensitive about flow patterns within the structure. There is a significant amount of stratification in a two-story house and that shows up quite clearly in these data. The only substantial changes that were seen in pollutant concentrations were in the radon results. Radon results varied in time, but were typically of the order of the size of the change in the infiltration rate between the experimental house and the control house. The final report from this project will be released in the early part of 1985. It contains a wealth of information on things like the effect of the exchanger performance on pollutant concentrations, as well as just the effect of the retrofit. I should comment that there were not substantial sources of formaldehyde, nitrogen dioxide, carbon monoxide, or particles in the house. The only substantial pollutant that was in the house was radon. The two houses were unoccupied during this period.

Another study that is close to completion, but has not been reported completely, is a study in southern Wisconsin sponsored by Wisconsin Power and Light. Fifty houses were monitored during the 1982-83 heating season. Retrofits took place during the summer of 1983. Then, during the 1983-84 heating season, measurements were made once again. The results of the first year study showed substantial levels of only nitrogen dioxide. This was observed in three buildings where there was some evidence that the heat exchangers in the gas furnaces were cracked.

Another study is a small project in Albany, Oregon, that is part of the existing home weatherization program that LBL is doing with Bonneville support. Two identical halves of a duplex were monitored during this study, which took place last spring. The monitoring was done with a mobile trailer that was a scaled-down version of the trailer that we discussed earlier. Continuous real time monitoring of criteria pollutants plus measurements of radon, formaldehyde, and particles were made during this study. This project was designed to look at both source and removal parts of the weatherization equation. Buildings were heated with an unvented propane space heater. That is an artificial situation in which we simply introduced a robust pollutant source into the house. The reason we used the propane space heater is that the emission rates of the pollutants from that heater are constant in time, based on tests on heaters like this in the lab. Two small electric heaters were used as co-heaters to attempt to quantitatively measure the average UA value of the shell. The two houses were tested for a period of time prior to retrofit to verify that they behaved in the same way. Initially, the experimental house was weatherized using an infiltration reduction scheme with a typical House Doctoring scheme to reduce leakage. The concentration of carbon dioxide, which was our test pollutant, increased in a way that was quite predictable, changing as one over the ventilation rate. Following the infiltration reduction measure we insulated the house, therefore essentially reducing the need for space heat. The carbon dioxide concentrations dropped in a predictable way (see Figure 3). Those results will be published shortly.

I do not know of other studies of the effect of retrofits on air quality in buildings. That is not a very long list. There are not many buildings in the review that I have just gone through. While there are many measurements in individual energy efficient buildings that have low leakage, the project design in the studies described above has been measurement of indoor air quality before and after weatherization. Changes that have been seen experimentally test our intuitive sense that pollutant concentrations will increase with weatherization.

There are a few other tests from the field that have examined the effects of controlled changes in ventilation on indoor air quality. I would like to show the results of two small studies, on in Rochester, New York, in which heat exchangers were installed in ten houses and pollutant concentrations were measured before and after the addition of ventilation from those heat exchangers.

Figure 4 shows the change in formaldehyde concentration in eight of the houses before and after the heat exchangers were used. The houses have sensible heat exchangers installed. A sensible heat exchanger is a heat exchanger in which the two air streams only exchange thermal energy but do not allow moisture or other pollutants to transfer between the two streams. Ventilation rates in this case went up by about 70%. We predict, therefore, that the formaldehyde would drop by about 40%; it dropped by 30%.

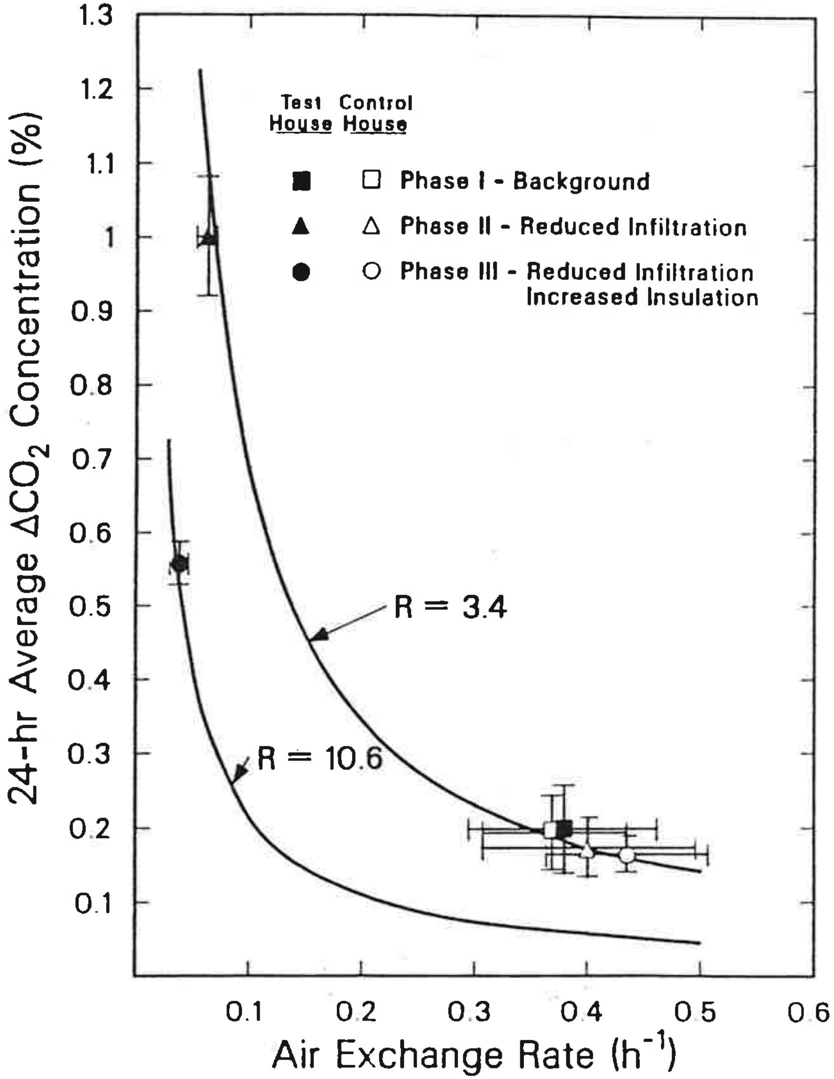

Figure 3

Exchange Rate and Formaldehyde Concentration (Rochester, N.Y.)

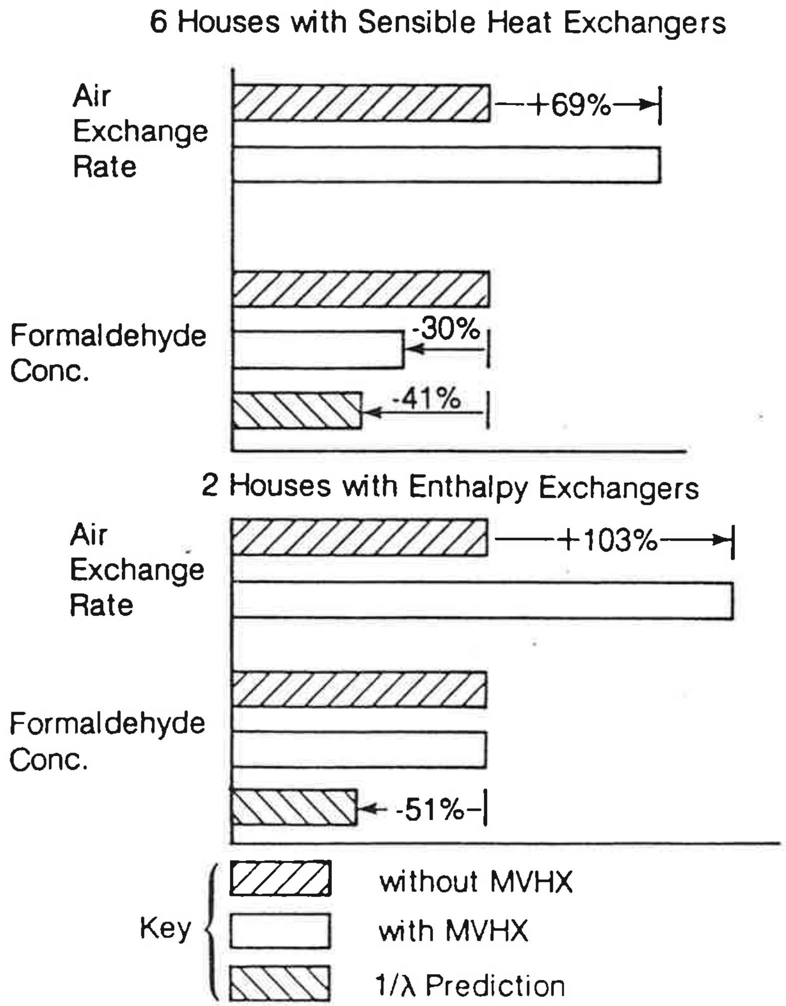

Figure 4

Those were long term averages of concentrations. Two houses had enthalpy exchangers; exchangers that also allow water vapor to transfer between the two air streams. The two houses doubled the ventilation rate with the operation of the heat exchanger, but there was no change seen in formaldehyde concentration. I should comment that that observation caused us to begin to look at the issue of whether formaldehyde is actually transmitted across the core of these water permeable heat exchangers. We have finished that study and the results we see indicate that, for the most part, the answer is negative; there may be perhaps 4% leakage of pollutant across the core of these heat exchangers. I am talking about two different brands. One was a rotating heat wheel that uses a desiccant to trap moisture and move it from one stream to another. The other is a heat exchanger that uses a porous paper surface as a heat exchanger surface. The formaldehyde transfer between streams is about 8% and of that about 4% is probably leakage, measured with tracer gas. This result eliminates the issue of whether formaldehyde transfer across the core is a serious issue in that type of heat exchanger.

The radon change (Figure 5) is roughly the amount we would expect from the change in ventilation rate. Ventilation went up by about 80% and the radon concentration dropped by about 45%, which is what we would predict. Figure 6 is another set of measurements that were made in a school in New York City in which ventilation rates were changed in a controlled way, in an occupied classroom. The top figure shows the concentrations of carbon dioxide in a classroom where the ventilation rate was nine cubic feet per minute per person (9 cfm/person). The ASHRAE standard calls for 5 cfm/person in this kind of situation. The peak in the distribution is about 1500 parts per million of carbon dioxide. The ventilation rate was dropped to about 5 cfm/person, which is the ASHRAE level, and the median concentration increased. The distribution is beginning to shift to the right toward higher concentrations. When the ventilation rate is reduced to 3 cfm per person, we again see a shift to the right and the median value is

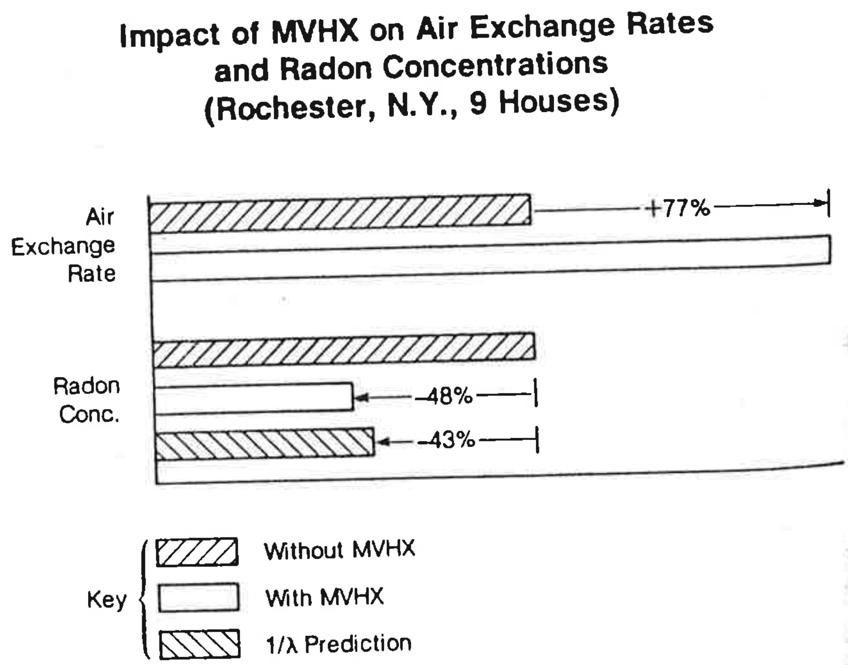

Figure 5

CO2 CONCENTRATIONS AT VARIOUS VENTILATION RATES

Room 323 - Oakland Gardens Elementary School

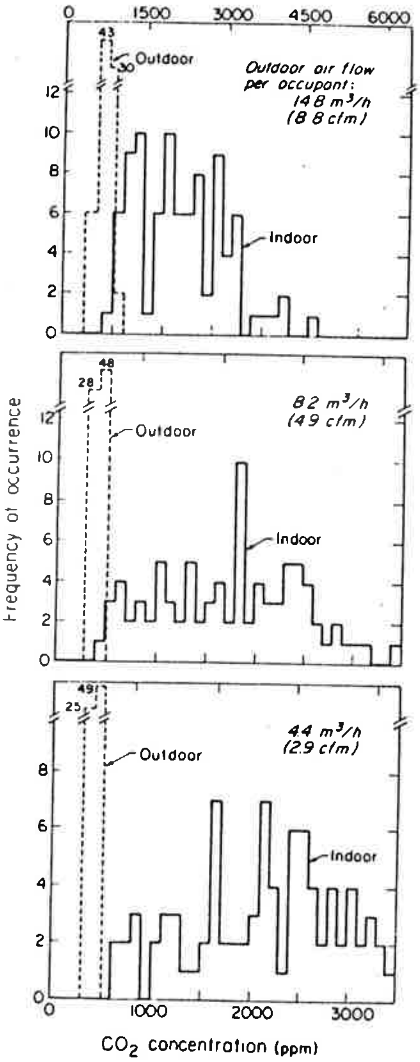

Figure 6

around 2000 ppm of carbon dioxide. Changes of carbon dioxide concentrations are discernible with changes of ventilation in these results. The minimum acceptable ventilation rate depends on our perspective of what concentration of carbon dioxide is permissible in a classroom--or what level of other pollutants would be permissible in a classroom.

The point I want to conclude with is not that we have answers, but that if we make an intuitive guess about the effect of weatherization on pollutant concentrations we may err. Field measurements of pollutant concentrations made before and after weatherization show that measurements after treatment are often statistically the same as measurements before. There is very little change seen when we actually look at the empirical evidence. I would agree that the data set is too small to make definite conclusions, but the differences that are seen are not very striking. The measurements tend to be difficult to make because we are making an assumption about source behavior. If we want to look at the effects of ventilation reduction on concentrations, the sources must remain constant during this time. Unless one is careful to control temperature and humidity, for example, when looking for formaldehyde that question cannot be tested, since the source strength will change.

I would like to discuss very briefly a study that we are doing in Vancouver, Washington, and in Spokane with the support of the Bonneville Power Administration. This study will examine pollutant concentrations in residences that will be weatherized in a controlled way. We are currently screening samples of approximately one hundred homes in the two areas. Of these one hundred homes, we will select forty (twenty at each site) and six control homes (three at each site) that will be selectively weatherized and monitored using real-time instrumentation where possible and where necessary and passive intrumentation where possible. We will be looking at formaldehyde, repirable suspended particles, carbon monoxide, water vapor, nitrogen dioxide, and radon. The houses are being selected to have initially measurable but low levels of pollutant concentrations. For example, we will selectively weatherize homes where radon concentrations fall in the band of 1 to 6 pCi/l. We will weatherize them in a controlled way after pre-measurements; this will be followed by a weatherization phase, post-measurements, in some cases a second weatherization phase, and again by post-measurements. The measurement period will be of the order of seven to ten days in each case. Weatherization will be done by local contractors who will be participants in the post-weatherization programs. After the final set of measurements we will embark on a mitigation effort in at least twenty of the houses, depending on the concentrations of pollutants that are seen. These measurements will clearly add to the data set. In these measurements, we are looking for changes of the order of 20% with 90% confidence. As a result, we may miss small changes, but I think the addition of this set of measurements and the existing set of measurements will allow us to better put a bound on the kinds of changes one would expect to see in typical weatherization programs. I should emphasize an important distinction between what might be called super house doctoring--the kind of weatherization that takes place when a group of trained people who are concerned with energy conservation go into a house for three or four days with the help of a blower door and integrated diagnostic instrumentation to do a very complete weatherization on a home--and the kind of weatherization that is likely to take place in real situations. The latter is the kind of weatherization we have to monitor to get a sense of what kind of increased risk people will experience who are living in those particular houses.

QUESTION: You mentioned two studies that haven't been released yet. How can we get information about them?

ANSWER: The person who headed the Geomet study is Niren Nagda. To get a report one should contact either Geomet, Incorporated or else the Electric Power Research Institute. The project manager for EPRI is Dr. Arvo Lannus. In the case of the Wisconsin Power and Light study, the head of the research team was Jim Quackenboss from the University of Wisconsin in Madison; he should be contacted about that particular report.

QUESTION: With the exception of the very last study, you did not investigate water vapor. To me, water vapor is the biggest problem I have. Before I can even get concerned about health problems, I have to be concerned about building integrity. Water vapor is attacking my buildings. So I'm disappointed to see so little interest in water vapor. Am I in a unique situation or is it just strictly health that you are studying?

ANSWER: I apologize to the questioner for being selective in information that I have reported this morning. In some cases relative humidity measurements were made and I didn't report them. That's a bias on my part I'll confess. I don't think of water vapor as a significant indoor pollutant from a health perspective. But I think your point is well taken and there is information in some of these studies about relative humidity before and after weatherization. I should point out that water vapor concentrations will be measured in the BPA studies using a water vapor passive sampler that measures a weekly average value.

QUESTION: What is a safe ventilation rate for residences?

ANSWER: I think one of the things that people can take away from this two-day session is that there is a lot of controversy about that. I realize when a builder constructs buildings, he has to try to design to a particular level. Let me simply try to report some recommendations groups of people adopted. The Nordic standards in Norway, Denmark, and Sweden, where tight construction is typically practiced, recommend that buildings be built to levels of natural infiltration rates of about 0.1 ACH. The buildings must have added mechanical ventilation so that the ventilation is increased up to 0.5 ACH. The ASHRAE standard 62-1981 recommends a value that is equivalent to 0.4 to 0.5 ACH, depending on the design of the house. As a researcher and someone working with indoor air quality, I don't like to make that kind of comment because I know that with that ventilation rate there may be some houses that have problems. On the other hand, from a builder's perspective, he has to build a building and I think that's an appropriate target to push for.

QUESTION: Should the mechanical ventilation system be on all the time, or can it be turned off sometimes?

ANSWER: If you're concerned about acute responses, then you have to have a continuous ventilation rate. If you're talking about average exposure, which is certainly the key to some of the pollutants, then one can certainly have variable ventilation rates. The advantage of variable ventilation rates from my perspective is not total ventilation of the structure, but is rather that variable ventilation to me means something like task ventilation; ventilation in the kitchen or the bathroom where some major sources are occurring. If ventilation is used appropriately there, it is much more effective because it controls the pollutant source, i.e. it doesn't allow the pollutants to move through the home.

QUESTION: We install ventilation in crawl spaces as well as attics. I wonder, based on what was said yesterday and today, it seems to be that radon in particular is affected favorably if you've got a crawl space and you've vented it. In homes that don't have crawl spaces, can you address the ventilation in a retrofit situation in an attic and how it may affect pollutants like radon and formaldehyde and whether or not, if the ventilation in the attic is increased, it actually works against what you want to achieve in terms of pollutants and moisture.

ANSWER: My sense is that ventilation in the attic has nothing to do with radon because the dominant source is the soil. The ventilation in the attic would have no effect on pressures in the house. I would hope that the attic and the living space are regions that are quite isolated from each other. They're on different sides of the building envelope. Therefore, attic ventilation should have little to do with ventilation in the house and pollutant concentrations in the house.

QUESTION: Are there any studies going on comparing a new code home to a superinsulated home with an air-to-air heat exchanger as far as pollutants?

ANSWER: There is a study we hope to begin rather soon. We're involved in one project that we'll begin this winter heating season where fifty matched pairs of houses in the Spokane and Portland areas will be monitored. That is, fifty homes built to the new conservation standard and fifty typical new homes matched on a fair basis. So one hundred homes will be monitored for a period of one to two weeks. Following that study, twenty-five of the homes will be selectively mitigated as pollutant concentrations are seen that are above high levels. Phil, do you have any comment?

PHIL THOR, BPA: LBL was hired by BPA to get an overall picture of how homes constructed to the proposed standard compare to conventionally built homes. Those homes are part of the Residential Standards Demonstration Program (RSDP) which in total will include nearly 1,000 homes in all four states of the BPA service area. Five hundred are going to be built to the new Model Conservation Standards (MCS) and about five hundred are going to be the current code practice. The one hundred David is taking are part of those RSDP homes. We are monitoring for energy usage, temperatures, and some relatively crude measurements of indoor air quality. We are making two radon measurements in every house; one for a three month period during the heating season, and one twelve-month reading during a single year. We are also monitoring the formaldehyde concentrations for a week during the wintertime, using the small plastic monitors you're familiar with already. The other thing we're going to do is some infiltration measurements in some number of houses. We're going to distribute about a thousand small PFT detectors from Brookhaven in houses; half in MCS houses and half in old houses. Since the number of PFT detectors per house is determined by the style of the house, we can't tell yet exactly how many homes will be monitored, but we expect around three hundred. And then there will be blower door tests as well.