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EXCLUSION LIST METHODOLOGY FOR WEATHERIZATION PROGRAM IN THE PACIFIC NORTHWEST



Author
Nero, A.V.

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## ENERGY & ENVIRONMENT DIVISION

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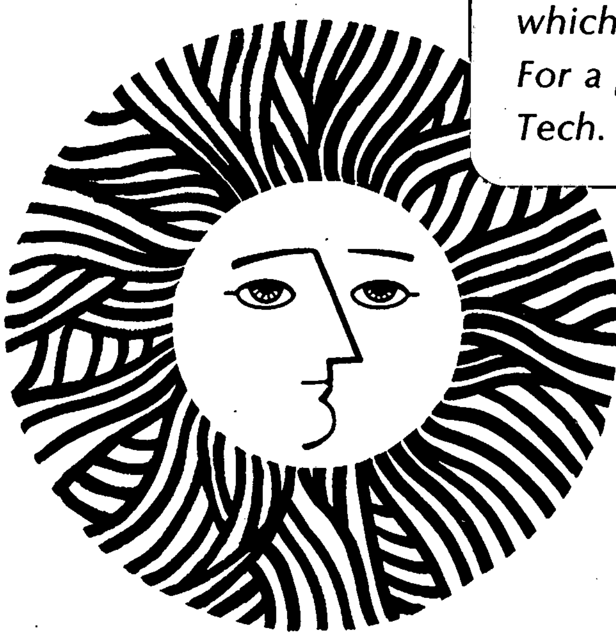

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# EXCLUSION LIST METHODOLOGY FOR WEATHERIZATION PROGRAM IN THE PACIFIC NORTHWEST

A.V. Nero, I. Turiel, W.J. Fisk, J.R. Girman, and C.W. Traynor

Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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## EXECUTIVE SUMMARY

### Background

During 1981 the Bonneville Power Administration (BPA) began its Regional Weatherization Program, offering financial incentives that encourage measures to reduce electricity use in homes. Because significant concentrations of airborne pollutants are often present in residential buildings, BPA considered explicitly the impacts on occupants' health that could arise from weatherization measures that reduce air infiltration rates and thereby raise levels of indoor-generated pollutants. As discussed in an Environmental Assessment as revised in September 1981 and in an addendum prepared for this document, the Program was designed to permit the full array of weatherization measures only in houses meeting criteria indicating that "major sources of indoor air pollutants are minimized". Infiltration-reducing measures would not be offered to homes failing these criteria, thereby avoiding potential increases in indoor pollutant levels and assuring that the Program has no significant adverse effects on the quality of the human environment.

Several classes of pollutants are known to reach potentially harmful levels in some residences: radon and its daughters, arising from the ground, building materials, or household water; combustion products, from unvented or wood-burning appliances; and formaldehyde and other organics, from building materials or furnishings. Radon concentrations vary over a factor of a thousand in U.S. homes, with a similar range in the BPA area. Continued exposure to radon (and its daughters) is presumed to cause an added risk of lung cancer that is proportional to the concentration, and the higher concentrations pose a substantial risk to occupants. Relatively few unvented appliances are present in the homes offered the program, but many of the homes contain wood-burning heating appliances, from which a wide array of pollutants are emitted, often causing airborne concentrations comparable to outdoor air quality standards. Among formaldehyde-emitting materials, urea-formaldehyde (UF) foam insulation is the most notable since -- if the material is improperly installed -- indoor formaldehyde concentrations can become high enough to cause acute distress to occupants. Ordinary infiltration-reducing measures, such as those offered in the Regional Weatherization Program, can be expected to increase indoor pollutant concentrations by about 30% on the average, a significant change if levels are already high.

The five criteria set forth in the Environmental Assessment assure that infiltration-reducing measures are offered only for houses with features that minimize the sources just mentioned: radon sources are minimized by use of ventilated crawlspaces, wood-frame construction (with little interior masonry), and municipal water supplies; combustion products are minimized by the absence of unvented combustion appliances or wood-burning stoves; and formaldehyde is minimized by the absence of UF foam insulation. Although the alternative of offering infiltration-reducing measures in conjunction with measures for mitigating potentially adverse effects on air quality was considered, the adequacy of such measures was not thought to be assured.

Since infiltration-reducing measures are among the more effective ways of reducing residential energy use, BPA continues to be interested in reducing the number of houses from which these measures are withheld. This document sets forth a strategy for offering these measures to more homes without significantly affecting the quality of the human environment. At a later date, an Environmental Impact Statement will be completed, assessing the impacts of a program containing infiltration-reducing measures. In addition, BPA and other entities are supporting research on indoor air pollutants, including monitoring and control techniques, as well as strategies for applying them.

## Methodology for Altering the Exclusion List

The list of housing classes from which infiltration-reducing measures are excluded could be altered on the basis of several different considerations: (1) Present knowledge of indoor pollutant sources and concentrations and of infiltration-reduction may indicate that the exclusion list could be altered, in certain respects, with no significant impact. Related to this is the possibility (2) that the weatherization program could include new elements that are adequate to assure no significant impact. (3) The weatherization program may be followed by programs or determinations that have the same effect as such elements. These approaches contain three essential aspects: (1) development of better information on sources and concentrations in various housing classes; (2) adoption of criteria on "significant" changes in individual or average indoor exposures to pollutants; and (3) implementation of mitigation measures, either concurrently or retrospectively, in houses requiring them.

Because the objective of changing the exclusion list is to reduce the number of houses restricted from infiltration-reducing measures, emphasis is given to the radon and wood-stove exclusion classes, each of which contain as many as half of otherwise qualifying houses. Even for the first of these, an examination of the factors affecting the radon entry rate (or source "magnitude") indicates that alteration of the radon exclusion criteria to reduce the number of houses may amount to a reformulation of the criteria, rather than simple removal from the list. Moreover, in considering other possible changes to the exclusion list, indication is given, not only of classes of houses that have a potential for removal of the exclusion, but also -- for the sake of consistency -- of classes that might be added to the exclusion list on the basis of similar considerations. For example, although the general UF-foam exclusion might be removed if monitoring is performed to assure low formaldehyde levels, similar monitoring might be required in homes with substantial amounts of other formaldehyde sources.

## Radon and Wood-Stove Exclusions

Reducing the number of radon-excluded houses can be accomplished by measuring indoor radon levels or by characterizing radon sources, either of which can usefully be linked to characterization of geographic areas for their radon (source) potential. Geographic characterization is highly significant because the main radon source is usually the ground on which a house is built, and a house's radon entry rate therefore depends ultimately on the strength of this source, as well as characteristics of the house understructure, which is the factor now considered by the exclusion list. Reorienting the radon exclusions around characterization of radon sources by area, using indoor measurements or -- even better -- wide-scale aerial radiometric survey data that are already available, could provide an efficient strategy for determining where the radon exclusion should be retained, while permitting infiltration-reduction in other areas. This strategy would also have the benefit of identifying areas having houses with unusually high indoor radon concentrations, thereby permitting the targeting of mitigating measures for people subject to unacceptably high radon daughter exposures. One element in this strategy would be adoption of criteria for radon concentrations at which infiltration-reduction is recommended and criteria for implementation of mitigating measures. A second need, pertaining also to other exclusion classes, is further development and testing of mitigating measures.

Altering the wood-stove exclusion is hampered by lack of detailed information characterizing wood-stove emissions generically, combined with the difficulty and expense of monitoring the variety of pollutants in homes that might be tightened. It is known that wood stoves can cause indoor concentrations of carbon monoxide, nitrogen dioxide, and suspended particulates comparable to outdoor air quality standards. In addition, wood burning produces organic materials that are of particular concern because of their potential carcinogenicity. Because of the potential significance of these pollutants, one strategy is to perform a comprehensive array of measurements, a possibility that is not attractive, considering the substantial instrumentation and effort that would be required. An alternative possibility is to extend the research BPA is now supporting on wood-stove emissions to include more complete characterization of pollutant entry paths and rates, as well as their dependence on installation and operational factors. Such an investigation would provide a more substantial basis for identifying cases in which the wood-stove exclusion could be lifted. This information would be useful whenever it is acquired, even if after completion of an Environmental Impact Statement.

## Conclusions

Of the two major exclusion classes, that for radon has the greatest potential for reformulation in the near future to permit offering of infiltration-reducing measures to a significantly larger number of homes than at present; a comparable basis for changing the wood-stove exclusion does not yet exist. It also appears feasible to offer infiltration-reducing measures, in some cases, even if an unvented combustion appliance or UF foam insulation is present: for gas stoves, if provision of a ventilation hood is deemed adequate, and for UF foam insulation, if monitoring demonstrates low formaldehyde levels.

In the interest of significantly expanding the offering of infiltration-reducing measures, while avoiding significant adverse effects, serious consideration should therefore be given to modification of the exclusions related to radon, including provision of monitoring and characterization efforts, as well as the offering of mitigation measures where appropriate. At the same time, more complete characterization of pollutants from wood-burning appliances can proceed as a basis for any decision to alter related exclusions. Both of these efforts, as well as investigation of control techniques, will not only benefit the weatherization program during the period when the Environmental Assessment is applicable, but also provide a continuing basis for proceeding after completion of the Environmental Impact Statement.

## PART I. INFILTRATION REDUCTION, INDOOR POLLUTION, AND CONTROL MEASURES

The Bonneville Power Administration (BPA) is engaged in a weatherization program whose purpose is to make available measures for reducing electricity use in homes that use electrical heating. A number of the measures that are included in the program have the effect of reducing the ventilation rate in the structures in question, thereby not only saving energy but also increasing the potential for increased concentrations of indoor-generated airborne pollutants.

In order to avoid having a significant impact on the health of occupants, arising from increases in indoor pollutant concentration, the Environmental Assessment prepared by BPA in connection with the weatherization program provided that measures that substantially affect infiltration would not be offered to certain classes of homes. These homes were excluded on the basis of house characteristics that may serve as indicators of higher-than-average sources of indoor pollutants. An addendum to this document has been prepared by BPA, summarizing the course of events that led to withholding of infiltration-reducing measures from specific housing classes.

The purpose of this document is to examine the list of excluded classes of homes and to delineate an approach for modifying that list in order to increase the number of houses for which infiltration-reducing measures are offered. Before proceeding to the methodology for altering the exclusion list, it is useful to examine the background against which such changes may be made.

The first part of this report therefore reviews, in section 1, the nature of the weatherization program, particularly with respect to infiltration reduction, then goes on in section 2 to survey what is known about the sources and concentrations of indoor pollutants, as well as their health effects. Finally, techniques for controlling levels of indoor pollutants, whether by source control or by ventilation and air cleaning, are reviewed in section 3. This background provides a basis for identifying the main considerations relevant to changes in the exclusion list and for formulating the elements that ought to be available in conjunction with such alterations.

## 1. BPA WEATHERIZATION PROGRAM

### A. Weatherization Measures

The Bonneville Power Administration (BPA) has proposed a ten-year program to encourage the weatherization of electrically heated homes in the Pacific Northwest.[1] The purpose of this program is to reduce residential energy demand by increasing the efficient use of energy in space heating. It is expected that 312,000 electrically heated residences (790,000 occupants) in the States of Washington, Oregon, Idaho, and western Montana will be weatherized.

The weatherization measures can be divided into two groups. The first group, to be offered to owners of all houses eligible for weatherization consists of the following measures:

(1) ceiling and attic insulation
(2) floor insulation
(3) insulation of unfinished walls
(4) vapor barriers
(5) insulation and sealing of air ducts
(6) water pipe insulation
(7) dehumidifier
(8) clock thermostat

Except for measures (4) and (5), the above measures do not alter infiltration rate, i.e., the rate at which inside air is replaced by outside air by movement through the building envelope. They therefore do not affect existing contaminant levels, in any direct way, by reduction of ventilation rates. In contrast, sealing of air ducts that are located in non-space-conditioned areas, in accordance with measure 5, can reduce the amount of outside air reaching living areas of a residence. And installation of a vapor barrier in the floor of a residence (measure 4) may also reduce infiltration. (In addition, measure (7) may affect the emission rate of formaldehyde from building materials and insulation containing urea-formaldehyde.)

If certain criteria (to be discussed in Part II, on the exclusion methodology) are met, the following measures will also be offered:

(1) caulking
(2) weatherstripping
(3) storm windows and doors
(4) outlet and switchbox gaskets.

These measures may decrease the amount of air infiltrating into the residence and thus may increase the concentrations of contaminants generated within the residence. The effects on infiltration rate of these four measures and the consequent effect on indoor air quality will be discussed in the context of specific characteristics of the Pacific Northwest housing stock. (Furthermore, thermal panes would be offered only in homes meeting the exclusion criteria, the intention being to avoid creating an incentive for adoption of this measure as an alternative to less expensive storm windows.)

## B. Housing Characteristics

During the last quarter of 1979 the Pacific Northwest Residential Energy Survey was carried out for BPA.[2] This survey contains useful information on characteristics of residential buildings throughout the BPA area. Table 1 illustrates those characteristics that will affect the expected reduction in infiltration rate from weatherization measures and that may be related to specific sources of indoor air contaminants. We can see that only 1.0% of electrically heated residences use either natural or bottled gas for cooking, and only 1.5% use natural gas or kerosene for heating hot water. A secondary heating source is used by 42% of electrically heated houses. 37% of all electrically heated residences use wood as a secondary heating fuel and 0.5% use fuel oil, gas or coal. Of those electrically heated residences using wood as a secondary heating fuel, 85% employ fireplaces and 15% employ wood burning stoves.* Turning to other fuels, only a very small number (less than 0.5%) of electrically-heated residences use non-portable room heaters as secondary heating equipment. One third of these heaters, which use oil, kerosene or natural gas, have no flue or vent to take combustion products outdoors.

Other factors that might affect indoor air pollutant source strength are shown in the second group of characteristics in Table 1. The first three affect radon source strength while the next two affect formaldehyde source strength. The only significant information available concerns foundation type; 42% of electrically heated homes have full crawl spaces, 25% are built on concrete slabs, 12% have full basements and 10% have partial crawl spaces.** Those houses with ventilated crawl spaces may have lower radon levels (all other factors being equal) in their living spaces than houses without crawl spaces. The last group of characteristics concerns factors that affect infiltration rate. These are discussed next.

## C. Infiltration Rate Reduction from Weatherization

A key factor in determining the potential effect of the weatherization program on indoor air quality is the ability to determine the reduction in infiltration rate achieved by weatherization. The measures listed below are the ones expected to reduce infiltration rates in residential buildings:

(1) caulking
(2) weatherstripping
(3) installing storm windows and doors
(4) installing outlet and switchbox gaskets

---

*Based on informally available information (rather than formal surveys), the proportion of houses with wood stoves is increasing rapidly. As many as half the electrically heated houses served by BPA may now have such stoves.

**Missing responses have been eliminated when frequencies are calculated.

Table 1. Selected Building Characteristics of Electrically* Heated Homes in BPA Area+

| | |
|---|---|
| **Combustion Sources** | |
| Primary Heating Systems | 64% built in unit, 27% furnace with duct 4% heat pump |
| Use of Secondary Heating Equipment | 45% yes, 55% no |
| Secondary Heating Fuel | 88% wood, 10% electricity, 1% nat. gas (N.G.) |
| Secondary Heating Equipment | 73% wood fireplace, 13% wood burning stove, 7% portable heaters, 2.5 other electric |
| Cooking Fuel | 99% electricity, 1.0% N.G.or bottled gas |
| Hot water heater fuel | 98.5% electricity, 1% N.G., 0.5 kerosene |
| **Factors Affecting Other Sources of Pollutants** | |
| Foundation Type | 42% full crawl space, 10% partial crawl space 12% full basement, 25% slab on grade |
| Vapor Barrier on Ground Under House | 51% yes, 49% no |
| Domestic Water Service | No information available*** |
| Wall Insulation - U.F. Foam** | No information available |
| Particle Board, Plywood, etc. | No information available |
| **Factors Affecting Infiltration Rate** | |
| Building Type | 12% mobile homes, 58% single family, 19% 5 or more units, 11% other |
| Air Conditioning Systems | 28% yes, 72% no |
| Weatherstripping on Windows and Doors | 38% on all, 20% on some, 36% none |
| Caulking Around Windows and Doors | 44% on all, 12% on some, 44% none |
| Storm Windows | 52% on all, 6% on some, 42% none |
| Age of Buildings | 84% pre 1978, 16% 1978 or 1979 |

*Primary heating fuel is electricity, mobile homes excluded.

** Survey did not discriminate by type of fill (i.e., UF foam, etc).

***Survey did not ask this question, however, a large percentage of homes use ground water. See Environmental Assessment, Page A-4

+All statistics are derived from the Pacific Northwest Residential Energy Survey by Elrich and Lavidge Inc. July 1980. Frequencies have been adjusted to eliminate unreported and don't know responses.

(5) sealing of leaks in air ducts
(6) floor insulation vapor barriers.

Data from the following weatherization studies have been analyzed:

(1) Medford, Oregon
(2) Midway, Washington
(3) Walnut Creek, California.

These were the only weatherization studies for which carefully documented data were available on "before" and "after" leakage areas or infiltration rates and for which the level of effort expended in the retrofit was specifically accounted for and within the range of efforts expected in the BPA program. In some cases, infiltration rates were measured directly by a tracer gas decay method, but in most cases, only air leakage measurements were performed.

The concept of effective leakage area is central to a predictive model of infiltration developed at Lawrence Berkeley Laboratory (LBL).[3,4] The procedure for determining the effective leakage area of the building envelope uses the technique of fan pressurization. In this technique, a fan is temporarily sealed into the shell of the house. The fan speed is adjusted to produce a specified pressure drop across the shell, and the flow rate through the fan is measured. The effective leakage area is determined by fitting the measured data points of flow versus pressure to the equation $Q = K(\Delta P)^n$, where Q is air flow, $\Delta P$ is the applied pressure drop, and K and n are coefficients obtained from a regression analysis. The flow is then extrapolated to the pressure regime driving natural infiltration (4 Pascal is used), and the effective leakage area, $A_{eff}$ is determined from the equation

$$A_{eff} = Q_4 \sqrt{\frac{\rho}{2\Delta P}}$$

where $\rho$ is the density of air (1.2 kg/m$^3$), $\Delta P$ is 4 Pascal, and $Q_4$ is the flow at 4 Pascal. Given the effective leakage area, local windspeed and temperature, building height, and various shielding factors, the infiltration rate can be calculated.

The results of the three weatherization studies are displayed in Table 2 which shows the reduction in infiltration rate or leakage area (as appropriate) achieved by the specified weatherization measures. The first two houses in Medford, Oregon showed average infiltration rate reductions of 20 and 30%, respectively, for measures A, B, and C which do not involve use of a blower door and caulking.[5] The infiltration rate in the first house was reduced from an average (over two weeks) of 0.62 to 0.49 ach with the addition of storm doors and windows, the replacement of two sliding glass doors, and the weatherstripping of doors. The second house's infiltration rate was reduced from 0.82 to 0.58 ach with the addition of storm doors and windows and the replacement of one sliding glass door. The doors were already weatherstripped in this house. The other seven houses in Medford showed no statistically significant reduction in leakage area (which is assumed to be proportional to infiltration rate) when measures A and C were carried out. The reason given for this result is that the ductwork, which was located in unconditioned

Table 2. Summary of Infiltration and Leakage Area Reductions from Weatherization.

| City | # Houses | Infiltration Rate Reduction | Average Leakage Area Reduction | Weatherization Measures |
|---|---|---|---|---|
| Medford, Oregon | 2 | 20%, 30% | | A + B + C |
| | 7 | | 0 | A + C |
| Midway, Washington | 6 | | 14% | A + D |
| | 6 | | 27% | F |
| | 6* | | 20% | E |
| Walnut Creek, California | 19 | | 25% | E |

*Same six houses that already received A + D weatherization measures.

A = add storm doors and windows

B = weatherstrip doors

C = replace sliding glass doors

D = Caulk around foundation sill

E = one day "house doctor" program which includes use of blower door to find and plug leaks in building shell

F = same as E but two days taken

spaces, was very leaky, so the potential for reducing air leakage was not fully realized.

In Midway, Washington, twelve relatively tight (with average infiltration rates all less than 0.5 ach for the heating season) houses were weatherized in two phases.[6] In Phase I, 6 houses had storm doors and windows added and caulking around the foundation sill. The average reduction in leakage area was 14% with a range of 0 to 43%. In Phase II, the house doctor technique was used where, in addition to weatherstripping, a blower-door, smokesticks, and an infra-red scanner were used to detect air leaks, so that they could be plugged by caulking and taping. When the procedure was carried out in the first six houses, an additional 20% reduction in leakage area was achieved for a total of a 31% reduction. In six other unweatherized houses a similar house doctor approach was used to achieve a 27% reduction in infiltration rate. In this case, twice as much time (2 person-days) was spent weatherizing the houses.

The last weatherization study took place in Walnut Creek, California.[7] A one-day house doctor approach was used to achieve an average 25% reduction in leakage area in 19 houses. The range of reduction was 8 to 61%. As might be expected, the 61% reduction took place in a very leaky house.

Summarizing these results, it appears that tightening measures, including "house doctor" treatment, can be expected to reduce effective leakage area on the average about 20 to 30%, with a range for individual houses of zero to 60% reduction. Since the leakage area approach does not include natural ventilation from door and window opening we should expect a somewhat smaller percentage reduction in total ventilation rate than given by the leakage area reduction.

References for Section 1 and 2 are listed after Section 2.

## 2. INDOOR AIR POLLUTANT SOURCES, CONCENTRATIONS, AND HEALTH EFFECTS

During the past several years a large amount of data has been accumulated on the levels of indoor air contaminants in residential buildings at varying infiltration rates. Less is known about the health effects arising from long-term exposure to such contaminants at the concentrations found in residential buildings.

Table 3 lists the major outdoor and indoor sources of indoor air pollution and some of the important pollutants they emit. Outdoor generated pollutants will penetrate, to varying degrees, a building's envelope. Pollutants generated indoors will remain there for a period of time largely determined by the building's ventilation rate and the chemical reactivity of each pollutant. Measurements have shown that a building's envelope acts as a screen to many outdoor pollutants, and lower concentrations of pollutants such as $SO_2$, $NO_2$, and ozone will be found indoors than outdoors (where indoor sources of these pollutants are absent)[8]. The indoor-generated pollutants that are of most concern in residential buildings are radon, formaldehyde, and combustion products such as nitrogen dioxide, carbon monoxide, carbon dioxide, and respirable particles. A review of our present knowledge of indoor air contaminants found in residential buildings follows.

### A. Radon

#### Sources and Concentrations

Radon, a radioactive inert gas, is a decay product of radium, which is found in small concentrations in rock and soil. The radon isotope of most concern, radon-222, has a half-life of 3.8 days; it decays into polonium-218, which also decays radioactively (these decay products of radon are known as radon daughters). Several members of the decay sequence (which ends in lead-206) are chemically active and may attach themselves to dust particles in the air.

There are three important ways in which radon may enter buildings: (1) by transport from soil through cracks and openings in the structure or around the foundation, (2) through emanation from earth-derived building materials such as concrete, and (3) by transport in water and natural gas. The concentration of radon in residences depends on several factors: the location of the building, the materials used to construct it, its foundation type, pathways for air transport from soil to basement, the source of its water supply, and the average ventilation rate.

The soil under a house can be expected to be the principal contributor to the indoor radon concentration in many cases of concern[9]. Measured concentrations of radon vary over three orders of magnitude (0.1-50 pCi/l)* in living spaces of homes throughout the United States,[10] and most of this variability appears to depend on how much radon enters from the soil. There is no reason to believe that the range of

*pCi/l equals $10^{-12}$ Curies per liter. $10^{-12}$ Curies is an amount of radioactive material that yields .037 decays per second.

Table 3. Summary of Sources and Types of Indoor Air Pollutants

| Source | Major Pollutants |
|---|---|
| **Outdoor** | |
| Stationary Sources | $SO_2$, CO, NO, $NO_2$, $O_3$, hydrocarbons, particles |
| Mobile Sources | CO, NO, $NO_2$, lead, particulates |
| Soil | Radon |
| **Indoor** | |
| Building Construction Materials | |
| Concrete, Stone | Radon |
| Particleboard, Plywood Household Furnishings | Formaldehyde |
| Insulation | Formaldehyde, asbestos |
| Adhesives | Organics |
| Combustion Appliances Using Gaseous Fuel | CO, NO, formaldehyde, particles |
| Gas Stoves | |
| Indoor Water Heaters | |
| Unvented Space Heaters | |
| Gas Wall Heaters | |
| Combustion Appliances Using Solid Fuels | CO, $NO_x$, hydrocarbons, aldehydes, polycyclic organic matter |
| Wood/Coal Burning Stoves | |
| Fireplaces | |
| Human Activities | |
| Smoking | CO, $NO_2$, HCN, organics, particulates, odorants |
| Aerosol Spray Devices | Fluorocarbons, vinyl chloride, $CO_2$, odorants |
| Cleaning and Cooking Products | Organics, odorants |
| Hobbies and Crafts | Organics, Odorants |
| Human Occupants | |
| Metabolic Activity | $H_2O$, $CO_2$, odorants |
| Biological Activity | Microorganisms |
| Attached Garage | CO, $NO_2$, lead, particulates |

concentrations in the BPA area is any smaller.

Although these are not the major concern in this document, there are special areas of the country where construction materials have been made out of uranium mill tailings or phosphate mining slag, both high in radium content. For example, phosphate slag has been used in the manufacture of insulation, and this insulation has been used in residences in Washington. Additionally, phosphate slag was widely used from 1962-1977 as aggregate for the concrete foundation of homes built in southeastern Idaho.[11]

Other factors that have been found to be of importance in influencing the concentration of radon and its daughters in residences are whether groundwater is used for the domestic water supply (use of groundwater may lead to relatively higher concentrations, if this water has high radon concentrations) and whether the foundation type is a vented crawl space (may lead to lower concentrations) or other type such as an unvented basement or slab on grade. Of course, the ventilation rate will also influence the concentration of radon in a residence. If the source strength is held constant, a halving of the ventilation rate will approximately double the radon concentration (assuming, as is usually the case, that the indoor radon concentration is much higher than the outdoor concentration).

## Health Effects

The main health hazard from radon and its daughters is an increased risk of lung cancer resulting from an added radiation dose to the lung tissue. As the first four radon daughters have short half-lives (30 minutes or less), if they are inhaled and deposited in the lungs, they can expose the surrounding tissue to alpha rays before being removed by the body's lung-clearance mechanisms. The health risk from radon daughters in residential buildings depends upon the time integrated exposure to radon daughters. For this reason, radon daughter concentrations are ordinarily expressed in terms of the total alpha energy emitted as a result of the decay of these daughters, a quantity that conveys some sense of the potential alpha exposure to the lungs. This "potential alpha energy concentration" is expressed in units of working level (WL)*. Radon daughter concentrations vary from 0.001 to 0.3 WL in U.S. homes. Since the risk of cancer from radiation is related to cumulative exposure, the effect of increased radon daughter concentrations must be evaluated in terms of the duration of the exposure.

Integrated exposure or, equivalently, dose may then be expressed in terms of the working level month (WLM), where exposure to 1 WL for 173 hours yields 1 WLM. These units were originally based on the exposure of uranium miners to radon and its daughters; hence the 173 working hours in one month. The annual exposure associated with a constant radon concentration

*One WL has a value of $1.3 \times 10^5$ MeV/l, the potential alpha energy per unit of volume that would be associated with air containing approximately 100 pCi/l of each of the short lived daughters.

of 1 pCi/l is approximately 0.25 WLM**. The WLM is dose for several reasons. For example, the degree to which daughters are deposited in the lungs depends on particle size and breathing rates differ between workers and the general population (they are less for the general population). Considering breathing rates alone, if uranium workers are taken to be the standard for evaluating health risks, then the public would have to be exposed to twice the number of hours as in a normal working month (173 hours) to accumulate the same exposure as a uranium miner (assuming the same WL exposure). Another complicating factor is that when the health risks to children are considered, we must take into account the facts that children have a higher respiratory rate than adults but a smaller vital capacity.

Much of our knowledge about the human health effects of radon and its daughters is based on the experience of underground uranium miners. These miners were exposed to radiation at dose rates much higher (100 times) than would ordinarily be experienced by occupants of residential buildings, and they developed lung cancer at a higher rate than the general population. Whereas an occupant of a residential building may in rare cases be exposed to radon daughter concentrations as high as 0.1 WL, uranium miners were, until recently, exposed to 1-20 WL. The cumulative exposures (in WLM) at which additional human and animal cancers have been demonstrated are generally higher by an order of magnitude or more than those characteristic of the general indoor environment. Thus, in order to predict the health effects of decreased indoor ventilation and a corresponding increase in exposure to radon daughters, it is usually necessary to extrapolate below the range of exposures for which effects are known. The generally accepted method of predicting cancer induction rates at low dose rates is to assume a linear no-threshold dose-response function. Using the linear hypothesis, and data from studies of uranium miners in the U.S. and Czechoslovakia, the number of lung cancers per unit of exposure to radon daughters ranges from 2.2 to $8 \times 10^{-6}$/year/WLM.[12] Assuming that the upper limit of this range holds, if a million people are all exposed to 1 WLM, then 8 people per year would be expected to contract lung cancer from this exposure. We are assuming here that the actual radiation dose from 1 WLM of exposure is the same for the general population and uranium miners. Our predictions of excess lung cancers due to increased radon daughter concentrations will have more than a factor of four uncertainty due merely to the uncertainties in estimating both actual doses and risk rates in miners. Applying this information to the general population increases the uncertainty even more (e.g., ref. 12a).

Table A-1 in Appendix A lists some proposed and existing standards for radiation exposures from radon and its daughters. With the exception of the Swedish guideline, present indoor standards or guidelines are generally designed to deal with specific problems rather than to set overall standards.

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*This result is obtained assuming a value of 0.5 for the equilibrium factor, which is defined to be the ratio of actual daughter potential alpha energy concentration (PAEC) to the PAEC were each daughter to have the same activity concentration as that of the radon actually present. Ventilation and plateout of daughters to walls and other surfaces reduce the ratio of daughters to their parents below one.

B. Formaldehyde

Sources and Concentrations

Formaldehyde (HCHO) is primarily an indoor-generated pollutant; its sources are building materials, furniture, carpets, combustion appliances, tobacco smoke, and consumer products. Formaldehyde is used in a wide variety of products, mainly in urea, phenolic, melamine, and acetal resins. These resins are present in insulation materials, particleboard, plywood, textiles, adhesives, etc., that are used in large quantities by the building and furniture trades. Emission rates for formaldehyde emitted in the indoor environment are generally unknown.

Urea-formaldehyde (UF) foam has been used extensively as thermal insulation in the walls of existing residential buildings. It is injected into wall cavities through holes that are subsequently sealed up. Installation involves mixing partially polymerized UF resin with a foaming agent and an acid catalyst under pressure that forces air into the mixture to create a foam. Under certain circumstances, large quantities of formaldehyde may be released into the building. Even proper formulation and mixing of UF-foam will not entirely prevent some formaldehyde release. The U.S. Consumer Products Safety Commission has recently banned the use of urea-formaldehyde foam insulation.

The superior bonding properties and low cost of formaldehyde polymers make them desirable chemicals for use in resins for the production of building materials such as plywood and particleboard. Urea-formaldehyde resin is the most common adhesive used in indoor plywood and particleboard. Plywood is composed of several thin sheets of wood glued together with UF resin. Particleboard is made by saturating small wood shavings with UF resin and pressing the resulting mixture into the final form. Particleboard can emit formaldehyde continuously for a period of years. In buildings in which these wood products are used for partition walls or furniture, formaldehyde may reach concentrations sufficient to cause eye and upper respiratory irritation.

Formaldehyde is also produced during combustion processes such as in gas cooking and heating. Chamber studies have indicated that combustion processes can contribute significant quantities of formaldehyde to the indoor environment[13].

A substantial number of residential buildings in the United States and other countries have been monitored for formaldehyde and total aldehyde concentrations. Particularly high concentrations (2.4 ppm)* have been found in mobile homes where occupants have complained about indoor air quality[14]. A tightly built (0.2 ach average) energy-efficient house in Maryland has been found to have indoor formaldehyde concentrations that exceed 120 $\mu g/m^3$**[15]. Measurements at another

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*1 ppm ≅ 1200 $\mu g/m^3$.

** 120 $\mu g/m^3$ is the promulgated standard in the Netherlands and has been proposed in other nations. See table A-2.

energy-efficient house (0.4 ach average) in California indicated that the presence of furniture plays a major role in influencing the ambient levels of formaldehyde indoors.[16] The average HCHO concentration increased from 80 to 223 $\mu g/m^3$ when furniture was added to the vacant house. A further increase was noted when the house was occupied, very likely because of such activities as cooking with gas. Formaldehyde levels were also measured in four energy-efficient houses (0.2 ach average at time of measurements) in Eugene, Oregon[17]. Outdoor levels were less than 3 ppb and the average indoor levels were 50, 55, 94, and 100 ppb for the four houses.

Twelve houses in Midway, Washington were monitored for formaldehyde levels before and after weatherization[18]. In general, because these houses were more than thirty years old (aged building materials) and had no combustion appliances, formaldehyde levels were low. However, in one home with new furniture the average level was found to be 79 ppb. When the furniture was moved to another house the formaldehyde level jumped from <5 ppb to 79 ppb, while dropping in the original house to 13 ppb. The outdoor HCHO concentrations were all below the detection limit of 5 ppb.

The emission rate of formaldehyde from building materials, insulation and furniture is known to decrease with time. The half-life of formaldehyde contained in particleboard is not known but informal estimates range from 1-4 years. It is also known that humidity levels affect formaldehyde emission rates. Higher humidity levels increase the HCHO emission rate. Decreasing infiltration rates in residential buildings may cause higher humidity levels and thus higher HCHO concentrations. This process will be discussed further in the section on measures for pollutant control.

## Health Effects

Formaldehyde is a colorless, very water soluble gas with a pungent odor that can be detected at levels well below 1 ppm by most people. Connecting specific health effects to specific concentrations of formaldehyde is difficult because people vary widely in their subjective responses and complaints. Interpretation of the health effects of formaldehyde must also consider the exposure time of subjects; short-term inhalation studies cannot accurately predict the effects of long term continuous formaldehyde exposures of building occupants. Odor irritation may be followed by tolerance after several hours of exposure and modify the response to formaldehyde.

Reactions to formaldehyde may be brought about by contact with skin and the mucous membranes of the eyes, nose and throat. Exposure to formaldehyde may cause burning of the eyes and irritation of the upper respiratory passages at concentrations of 0.05 - 0.5 ppm, depending on individual sensitivity and environmental conditions (temperature, humidity, etc.). Table 4 summarizes the reported health effects of formaldehyde at various concentrations, based on a National Research Council Committee on Aldehydes report[19]. High concentrations (>few ppm) often produce coughing, constriction in the chest, and wheezing. Studies in rats and mice have shown that concentrations of formaldehyde of a few

Table 4. Reported Health Effects of Formaldehyde at Various Concentrations[a]

| Effects | Formaldehyde Concentration, ppm |
|---|---|
| None reported | 0-0.05 |
| Neurophysiologic effects | 0.05-1.5 |
| Odor threshold | 0.05-1.0 |
| Eye irritation | 0.01-2.0[b] |
| Upper airway irritation | 0.10-25 |
| Lower airway and pulmonary effects | 5-30 |
| Pulmonary edema, inflammation, pneumonia | 50-100 |
| Death | 100+ |

[a]Derived from National Research Council (Ref. 19).

[b]The low concentration (0.01 ppm) was observed in the presence of other pollutants that may have been acting synergistically.

ppm for several months induce nasopharyngal carcinoma[20].

Table A-2 in Appendix A summarizes various recommended and promulgated indoor formaldehyde air quality standards. There is no outdoor standard for formaldehyde in the United States, but the American Industrial Hygiene Association recommends a guideline of 0.1 ppm. The Netherlands, in 1978, established an indoor standard of 0.1 ppm (120 $\mu g/m^3$) maximum permissible concentration. Denmark, Sweden, and West Germany are all considering establishing a standard at approximately the same value (0.1 ppm).

## C. Combustion Products

### Sources and Concentrations

A wide range of combustion products can be emitted by indoor sources such as combustion appliances and cigarette smoke. These include carbon monoxide (CO), carbon dioxide ($CO_2$), water vapor ($H_2O$), nitric oxide (NO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), formaldehyde (HCHO), and respirable particles. Combustion appliances that may be found in residential buildings are gas-fired stoves, indoor gas-fired water heaters, unvented gas-fired space heaters, gas-fired and oil-fired furnaces, and portable kerosene-fired space heaters. Wood-burning stoves and fireplaces and coal- or wood-burning furnaces may also contribute pollutants such as hydrocarbons and polycyclic organic matter (POM) to the indoor environment in addition to the aforementioned pollutants. Automobile exhaust from vehicles in attached garages can also be a source of combustion byproducts in buildings.

#### a. Gas Stoves

There have been many field studies that monitored the concentration of various pollutants in residential buildings with gas stoves. In almost all cases, indoor/outdoor ratios of CO, $NO_2$, and NO have been greater than one. In a number of cases, levels comparable to existing health standards (see Table A-3, Appendix A), of $NO_2$ and CO have been reported. For example, $NO_2$ and CO concentrations in a kitchen of a suburban house in Connecticut averaged approximately 0.05 and 3.5 ppm respectively, during the winter.[21] A series of indoor air quality measurements were performed at an unoccupied energy-efficient research house in California.[22] CO and $NO_2$ were measured in several rooms during a period when the infiltration rate varied between 0.33 and 0.44 ach. With a "typical" gas stove operation scenario taken from an American Gas Association study, peak one-hour average $NO_2$ levels in the kitchen and living room were 450 and 400 ppb, respectively, which exceeds the California short term standard of 250 ppb (470 $\mu g/m^3$). The outside level of $NO_2$ was 70 ppb. The one hour CO outdoor standard of 35 ppm was not exceeded anywhere in the house, although the indoor CO concentration (a peak of 25 ppm in the kitchen) was much higher than outdoors.

Controlled chamber studies have been performed to characterize the emissions from a gas stove. Studies at LBL have shown that using the oven at 350 °F in a 27-$m^3$ chamber with a ventilation rate of 1.0 ach, $NO_2$ and HCHO concentrations exceed the one-hour California $NO_2$ standard and the European HCHO standard, respectively.[23] To keep $NO_2$ and HCHO concentrations within the established air quality limits, either local ventilation or an overall kitchen ventilation rate of at least 170 $m^3/h$ (5 ach) was required. Carbon monoxide and particulate concentrations at 1 ach are higher than outdoors but lower than the relevant EPA standards. Emission rates of a large number of combustion products from gas ovens and top burners can be found in a report by Traynor _et al_.[24]

b. Unvented Space Heaters

Several studies have been performed to assess the level of air contamination from unvented gas-fired and kerosene-fired space heaters. Experiments in a 27-$m^3$ chamber with a portable, convective-type kerosene space heater show that at a ventilation rate of 1.9 ach, CO and particulate concentrations are low, but, $CO_2$ and $NO_x$ concentrations are high.[25] $CO_2$ concentrations reach 5000 ppm, the occupational standard established by the U.S. Occupational Safety and Health Administration (OSHA), after 45 minutes of operation. After 45 minutes of operation, the $NO_2$ concentration was greater than 1 ppm over background, four times the California peak one-hour outdoor standard.

Additional experiments with portable, convective and radiant kerosene heaters, in a 27 $m^3$ chamber, found that $CO_2$ levels can reach 10,000 ppm. $NO_2$ levels exceeded the California one-hour standard of 0.25 ppm -- by a factor of seven for the convective heater and by a factor of 2 for the radiant model.[26] The heaters were operated for one hour at a fuel consumption rate of approximately 8,000 BtuH, and the air exchange rate was 0.40 ach.

Emissions from unvented gas-fired space heaters are highly dependent on the size of the heater, the manufacturer, and the state of tuning of the appliance. Eight heaters, ranging in size from 12,000 to 40,000 BtuH were tested in a 27 $m^3$ chamber.[27] $NO_x$ and HCHO emission rates were found to be lower than for gas-fired stoves. CO and HCHO emission rates were found to be much more variable than those of other pollutants and very sensitive to the state of tuning for some heaters. After 30 minutes of operation, typical pollutant concentrations were 4,000 ppm of $CO_2$, 4 ppm of CO, 1 ppm of $NO_2$, and 3 ppm of NO.

c. Wood-burning Stoves, Wood-burning Furnaces, and Fireplaces

Several studies have shown that wood burning combustion sources are significant sources of CO, $NO_x$, hydrocarbons, and respirable particulates including polycyclic organic matter (POM).

Measurements show that pollutant emission rates from wood combustion can vary over a wide range. CO emissions can vary from 4 to 400 grams per kilogram (g/kg) of wood burned; particulate emissions can vary from 0.5 to 63.5 g/kg; total hydrocarbons from 0.2 to 48.5 g/kg; $NO_x$ from 0.2 to 7.3 g/kg; and POM from 0.004 to 0.37 g/kg.[28] All of these pollutants can enter the living space under certain circumstances.

Measurements in three suburban residences in the Boston area indicated that woodburning produced elevated levels of total suspended particulates (TSP), respirable suspended particulates (RSP), defined in this study as particulates less than 3.5 μm in size, and benzo-a-pyrene (BaP).[29] An all electric house (designated A) with a closed combustion woodburning stove in the basement and an average ventilation rate of 0.68 ach was monitored over a two week period. TSP in the living spaces of Residence A averaged 1.8 times the outdoors level on woodburning days and exceeded the secondary 24 hr TSP outdoor standard of 150 $\mu g/m^3$. RSP in residence A averaged 1.4 times the outdoor level on woodburning days. Two other residences (designated B and C) that had woodburning fireplaces exhibited much higher indoor/outdoor ratios for TSP and RSP during woodburning days. BaP concentrations were measured only in houses A and B and were found to be five and ten times the outdoor levels, respectively. Carbon monoxide was measured in residence A and found to be at a higher concentration than outside when the wood stove was used, reaching a maximum of 5.5 ppm on one day. It is important to note that, in residence A, higher contaminant levels than reported would have been found if sampling had occurred in the room where the woodstove was located.

Another study of three houses with woodburning stoves and furnaces showed elevated levels of CO, $NO_x$, and $SO_2$ during the period when these appliances were operated, although the pollutant levels observed were generally below occupational and outdoor air quality standards.[30] Particulates were not measured in this study. The average infiltration rates in these three houses -- called House A, House B, and House C -- during the measurements were 0.30, 0.08, and 0.40 ach, respectively. Both studies showed that the magnitude and mix of pollutants from woodburning stoves and furnaces can vary widely. Comparisons of indoor pollution levels from wood-burning furnaces in Houses A and C show that the magnitude of pollutant emissions from the appliances vary, for reasons not yet identified. The major component of gaseous emissions also varies; for example, the dominant pollutant from the wood-burning stove in House B was NO; from the wood-burning furnace in House A, CO; and from the wood-burning furnace in House C, $NO_2$. As mentioned earlier, Moschandreas et al. observed a peak 1-hour CO concentration of 5.5 ppm during stoking of a wood-burning stove, significantly higher than CO levels measured in Houses A and B in Traynor's study, but lower than the CO levels from one of the wood furnaces measured. At this time the data on wood-burning appliances is limited in scope.

d. Tobacco Smoke

One of every three persons between the ages of 17 and 64 smokes cigarettes regularly. Tobacco smoke is quite prevalent in residential homes; surveys in eight cities show that from 54 to 76% of homes have one or more smokers.[31, 32] In addition, people are exposed to smoke at their workplaces and at other activities. Exposure of individuals to tobacco smoke of other people is known as passive smoking.

A distinction can be made between mainstream and sidestream smoke emanating from cigarettes. Mainstream smoke is undiluted and is pulled through the tobacco into a smoker's lungs. Sidestream smoke comes directly from the burning tobacco. Depending on smoking behavior, burning temperature, and type of filter, the composition of mainstream smoke exhaled by a smoker varies substantially. Sidestream smoke is more important to the involuntary smoker. Because of the length of the burn and the burn temperature, sidestream smoke is a more important source of local air contamination for many substances such as CO, nicotine, ammonia, and aldehydes, than mainstream smoke. The passive smoker, however, does not receive nearly as large a dose of smoke as the smoker.

A number of indoor air pollutants arise from tobacco smoke; some of the more important ones are particulates, CO, BaP, acrolein, nicotine, nitrosamines, and aldehydes. Residential measurements of RSP (defined as less than 2.5 μm in size in this study) in eighty homes across six cities with and without smokers were made by Spengler et al.[33] Daily indoor RSP concentrations frequently exceeded 200 $\mu g/m^3$ in homes with cigarette smokers.* RSP levels were essentially the same (~23 $\mu g/m^3$) indoors and outdoors in the homes without smokers. The mean RSP concentrations indoors for homes with one and two smokers were 43 and 75 $\mu g/m^3$ respectively. These data, collected over a three year period, illustrate the contribution of cigarette smoking to indoor particulate concentrations.

Repace and Lowrey have conducted measurements of RSP in many building types with and without smokers present.[34] The average RSP concentration in three residences (without fan mixing) was 24 $\mu g/m^3$. One measurement was performed during a cocktail party in a house with 2 of 14 occupants smoking. The indoor RSP was 350 $\mu gm^3$. RSP concentrations measured in other buildings (restaurants, meeting halls, sports arenas, etc.) with smokers present ranged from 55 to 700 $\mu g/m^3$.

Passive smoking was shown to be an important means of exposure to RSP in a study by Spengler et al.[35] Portable monitors were carried by several people for twelve hour periods on 15 sampling days. The mean RSP concentration in samples where participants reported passive cigarette smoke exposure was 40 $\mu g/m^3$ compared to 22 $\mu g/m^3$ for the nonsmoking nonexposed participants. The outdoor concentrations averaged less than 15 $\mu g/m^3$.

Carbon monoxide levels are known to be higher in buildings with smokers. Most measurements have been performed in public buildings; for example Sebben et al. have found CO concentrations greater than 9 ppm (the 8 hour outdoor standard) in restaurants and night clubs.[36] In most cases, the CO concentration remained below 35 ppm (the one hour outdoor

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*The short term (24h) outdoor standard for total suspended particulates (TSP) is 260 $\mu g/m^3$ (see Table A-3, Appendix A). However, this standard is inappropriate for particulates emitted from cigarettes, as the range of compounds is quite different than those found in outdoor air.

standard).

## Health Effects of Combustion Products

### a. Nitrogen Dioxides

Indoor combustion can have an important effect on the indoor concentrations of nitric oxide (NO) and nitrogen dioxide ($NO_2$). Nitric oxide binds to hemoglobin to produce methemoglobin. Many of the adverse effects attributed to CO alone may be due to the combined action of COHb and methemoglobin. NO at 3 ppm is physiologically comparable with CO at 10-15 ppm. At concentrations of 0.05 ppm or greater $NO_2$ may affect sensory perception, and produce eye irritation, especially with hydrocarbons present. Nitrogen dioxide can produce transient and long-term damage to both small bronchial airways and alveolar tissue. Ten minute exposures to $NO_2$ concentrations of 0.7 to 2.0 ppm produce increased airway resistance in humans.

The evidence of health effects from long term exposure to low concentrations of $NO_2$ and NO is inconsistent. It is difficult to separate the effects of $NO_2$ and NO from those of other air pollutants and to obtain populations that are equivalent in all respects except for $NO_2$ and NO exposure levels. Two studies, one of the relationship between respiratory illness in primary school children in England and the use of gas for cooking and the other, of the relationship between lung function and respiratory illness in children and the concentration of $NO_2$ in their homes, suggest that there is a relationship between gas cooking, $NO_2$ concentration, and respiratory illness.[37, 38] However, a similar study by Keller *et al*. failed to establish any increase in respiratory disease or decrease in pulmonary functions associated with the use of gas for cooking.[39] Another study, which is still ongoing, indicates that children in homes with gas stoves had a greater history of respiratory illness before age 2 than children in homes with electric stoves.[40]

### b. Carbon Monoxide

At present, the most dangerous result of exposure to CO occurs when combustion takes place without an adequate supply of air (e.g., in closed garages). In such a situation CO levels can reach 1500 ppm, a life threatening concentration. Carbon monoxide enters the body through the respiratory system and reacts primarily with the hemoglobin of the circulating blood. The affinity of hemoglobin for CO is over 200 times that of oxygen. The absorption of CO is associated with a reduction in the oxygen-carrying capacity of blood and also with a reduction of the ease with which the blood gives up its available oxygen to the tissues. Experimental exposure of nonsmokers to 50 ppm for 90 minutes has been associated with impairment in time-interval discrimination.[41] This exposure is likely to produce a carboxyhemoglobin (COHb) level in the blood of about 2.5%. This same COHb level will occur with continuous exposure to 10-15 ppm CO for 8 or more hours.

The current EPA outdoor CO standards (8 hr - 9 ppm, 1 hr - 35 ppm) are mainly justified on the basis of adverse CO effects in patients with cardiac and peripheral vascular disease and effects of CO on oxygenation of skeletal muscles in exercising normal human subjects. There appears to be an adequate safety factor between the lowest COHb concentration that has been demonstrated to cause adverse effects and the maximal COHb concentration that can occur at 9 ppm CO for 8 hours or 35 ppm for 1 hour.[41]

c. Carbon Dioxide

The present Federal standard for carbon dioxide in the workplace is 5000 ppm of air by volume for a time weighted 8 hour daily average. Much of the research on physiological effects of $CO_2$ exposure has been done to establish safe limits for submarine crews and astronauts. The NASA limit for a 6 month exposure in spacecraft is 10,000 ppm. The Bioastronautics Data Book states "that for prolonged exposures of 40 days, concentrations of $CO_2$ in air less than 5000 ppm cause no known biochemical or other effect.[42] Concentrations between 5,000 and 30,000 ppm cause adaptive biochemical changes which may be considered a mild physiological strain; and concentrations above 30,000 ppm cause pathological changes in basic physiological functions." Schäfer in his review of submarine research states "at a 15,000 ppm exposure, performance and physiologic functioning were not adversely affected, although acid-base and electrolyte adaptation occurred as as result of continuous exposure. At levels above 30,000 ppm $CO_2$, deterioration in performance may be expected, as may alterations in basic physiologic functions, such as blood pressure, pulse rate, and metabolism."[43] Some Russian studies find respiratory effects at $CO_2$ levels as low as 1,000 ppm.[44] The amplitude of the respiratory movement was reduced and peripheral blood flow increased at this low concentration in laboratory experiments. It should be noted that occupational standards are meant to protect the adult healthy worker and may not be adequate to protect children, older people, and sick people. Thus, it is uncertain if occupational standards may be safely applied to the diverse population in residential buildings.

d. Particulates

Since the respiratory system transports gases from the atmosphere to the lungs, a wide variety of particulate matter may be inhaled. Some of the inhaled particulate matter is deposited and retained in the various parts of the respiratory system. Two important factors determining the likelihood of particle deposition are particle size and density. Large particles ($>5 \times 10^{-6}$m) have a small probability of reaching the alveoli, the air sacs in the lungs. Particulate matter may exert a toxic effect because:

(1) The particle may be intrinsically toxic due to its inherent chemical or physical characteristics (e.g., lead and asbestos).
(2) The particle may act as a carrier of an adsorbed toxic substance (e.g., radon daughters can be adsorbed by particulates emitted in cigarette smoke).
(3) The particle may interfere with one of the clearance mechanisms in the respiratory system.

Carbon particles, such as are emitted in combustion processes, are efficient adsorbers of many organic and inorganic compounds and can carry toxic gases such as $SO_2$ into the lungs. This can lead to a "potentiating" effect in the human body in which particles that contain an adsorbed toxic substance increase a person's physiological response to that toxic substance to a level above what it would be if the substance were present without the adsorbent particle.

Epidemiological studies indicate that particulates are associated with health effects of varying severity. Respiratory illness, especially from chronic diseases such as bronchitis and emphysema show the strongest positive association with levels of particulate matter.[45] Adverse health effects have been observed for annual mean levels of as low as 80 $\mu g/m^3$. However, these particulate levels are usually associated with high levels of $SO_2$ and the effects of the two have not been separated.

e. Other Combustion Products

As mentioned earlier, other combustion products may have adverse health effects on occupants of residential buildings. Some of these pollutants are: hydrocarbons, nitric oxide, benzo-a-pyrene, and nicotine; the latter two resulting from cigarette smoke. Benzo-a-pyrene is known to be carcinogenic.[46] Cigarette smoke can cause eye, nose, throat, and respiratory irritation to passive smokers. There may also be an association between long term passive exposure to cigarette smoke and an increased incidence of lung cancer in healthy nonsmoking adults.[47]

D. Other Pollutants

Sources

There are many other sources of indoor air pollutants that have not been specifically mentioned. These include the following: insulating materials containing asbestos; household products such as paints, aerosols, and cleaning fluids; cooking products such as greases, water vapor and odorants; bathroom activities that release water vapor and odorants; and humans and animals, which are sources of bacteria, viruses, fungi, odorants, and water vapor.

Health Effects

Asbestos fibers can be released from pipes insulated with asbestos plaster and, if inhaled, may remain embedded in lung tissue for very long time periods. Asbestos fiber inhalation has been associated with lung cancer, asbestosis, and mesothelioma (cancer of the membranes surrounding the lungs).[48] The assessment of the human exposure and adverse health consequences due to the storage and use of consumer products is made difficult by the irregular, sporadic, and highly variable exposures, by scarcity of measurements, and by limited knowledge about the composition of many of the products. Knowledge about the synergistic effects of many air pollutants acting together on building occupants is also lacking.

Microorganisms can produce infection, disease, or allergic reactions. Respiratory viruses and bacteria can be transmitted from person to person in buildings and confined spaces. Some fraction of the incidence of respiratory disease results from airborne transmission, but it is not clear what effect ventilation, air conditioning, or air cleaning will have on disease incidence. Several measurements have been made in public buildings to determine the effect of reduced ventilation on the numbers of colony forming particles (CFP) per unit volume of air. The Naval Bioscience Laboratory found that the number of CFP/$m^3$ did increase with reduced ventilation but remained within the range of measurements taken in a large group of buildings where ventilation changes were not made.[49]

Decreases in ventilation tend to increase the indoor relative humidity during the heating season. Excess water vapor is adsorbed or condensed onto drier or colder surfaces, causing deterioration or corrosion of building materials, furnishings, etc. Increased relative humidity may also promote the growth of molds, algae, and fungi, which can cause an increase in allergic reactions of building occupants. On the other hand, in colder climates many homes use humidifiers to increase moisture content of the air, in which cases reducing ventilation, thereby raising the humidity, is an advantage.

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## 3. INDOOR AIR QUALITY CONTROL TECHNIQUES

### A. Introduction

Indoor air quality control techniques can be divided into the following three general categories: (1) techniques that reduce or remove pollutant sources, (2) ventilation, and (3) air cleaning. This section contains an introduction to each category of control techniques followed by a discussion of techniques that may be suitable for controlling indoor levels of radon, formaldehyde, and combustion products. Control techniques that are not suitable for a weatherization program, such as exclusion of building materials, are not considered here. In addition, techniques that appear too expensive for a weatherization program, even if they may be suitable in other situations, are mentioned only briefly. Available data describing the effect of each control technique on indoor pollutant concentrations is summarized. A simple model for estimating the effect of a control technique on indoor air quality is presented in Appendix B.

### B. Source Control

The sources of indoor air pollutants can be removed from the residence, isolated from the indoor air, or modified so that the rate of pollutant emission is decreased. Removal of pollutant sources is advantageous because it is a permanent, effective measure and because no future maintenance or operating costs result; however, the sources must be identified before they can be removed. In addition a substitute for the removed item is generally required and the initial cost, operating and maintenance costs, and performance of the substitute should be considered. Some methods of isolating pollutant sources from indoor air involve ventilation and are discussed in the section on ventilation control techniques.

#### Radon Source Control

Removal of radon (Rn) sources involves the removal and replacement of concrete, masonry, or brick building materials or removal of the soil surrounding the basement, slab floor, or crawlspace. Removal of these materials is generally undertaken only when the materials have a high radium content due to contamination by mining or industrial processes. These techniques have been used successfully in a few homes with very high radon levels but appear too expensive for a weatherization program. Tap water from wells can be a significant source of radon. In such cases a switch to a water supply that is low in radon will reduce indoor radon levels. Aeration or storage of the water prior to its entry into the residence are other possible control measures.

The principal means of reducing the transport of radon to building interiors are to seal materials having significant emanation rates or, for the more common case of transport from surrounding soil, to plug cracks or holes through which air with a high Rn content (i.e., soil gas) moves. Materials may be sealed by epoxies or other coatings with up to 90 percent effectiveness.[1-4] Filling holes with impervious materials, stopping transport by installation of plastic or other barriers, or sealing surfaces has proved effective in some cases that required remedial action (see, for example, references 5 to 7), but all require integrity of the barrier for long-term transport reduction. The general applicability or effectiveness of these measures as long-term passive controls is not known. (It should be noted that confinement of radon by diffusion or convection barriers results in a buildup of radon and its daughters behind the barrier, causing an increase in gamma irradiation from building materials. This increase appears less significant than the associated decrease in airborne radon and daughters.[8])

Further study of the mechanism and location of radon entry into residences should probably precede efforts to isolate radon sources from the indoor air.

Formaldehyde Source Control

Removal and replacement of building materials that emit formaldehyde is a potential control measure but is generally expensive.

In laboratory studies[9-11], various paints, lacquers, varnishes, and vinyl papers have significantly reduced the rate of formaldehyde emission from particleboard. Some of these coatings contain substances that react with formaldehyde, thus preventing its release into the surrounding air. The effectiveness of surface coatings, when applied to the exposed surfaces of installed particleboard, is not well known.

Ammonia fumigation and dehumidification are two promising techniques for reducing the rate of formaldehyde emission from building materials. In the ammonia fumigation technique, ammonium hydroxide is placed in shallow pans in every major room of the residence. The home is sealed for at least twelve hours while fans circulate the indoor air and the indoor temperature is maintained at 27 °C or higher. Jewell[12] used this technique in twelve mobile homes and reported 45 to 90 percent initial reductions in formaldehyde levels and 39 to 81 percent reductions in fur homes monitored after a 40 to 60 week period. Further work is needed to obtain additional long term data on the effectiveness of this technique.

Dehumidification is another potentially useful technique for reducing the rate of emission of formaldehyde from building materials. Birge et al.[13] report results of recent tests in a climate-controlled chamber containing particleboard. The tests indicate a 17.5 percent decrease in formaldehyde levels for every 10 percent reduction in relative humidity. (The authors assumed a linear relation between formaldehyde level and relative humidity; however, their results are reported only for two relative humidities.) Similar experiments performed by Anderson et al.[14], but at several humidities, indicate a linear relation between formaldehyde concentration and humidity ratio (i.e., mass of water vapor/mass of air). In their studies, when the chamber temperature and air change rate were maintained at 22 °C and 0.5 air changes per hour, respectively, a decrease in relative humidity from 70 to 30 percent caused a 50 percent decrease in formaldehyde levels.

A study by Long et al.[15] indicates that the release of formaldehyde from urea-formaldehyde foam insulation is also reduced when humidity is lowered.

No studies have been performed in actual homes to determine the effect of dehumidification on indoor formaldehyde concentrations. Also, it is possible that dehumidification may slow the rate of formaldehyde emission from materials but not decrease the total amount of formaldehyde emitted. The available chamber studies indicate, however, that dehumidification may cause reductions in formaldehyde concentrations sufficient to counteract or partially counteract the moderate increases typically expected from a weatherization program. (Weatherization measures may increase indoor formaldehyde levels by decreasing infiltration and also indirectly by causing increases in indoor humidity levels). Dehumidification can be accomplished by employing residential dehumidifiers, by local ventilation near humidity sources (e.g., use of bathroom fans that exhaust to outside), or by providing ventilation with outdoor air when the outdoor air is less humid than indoor air.

While dehumidification may be a useful technique for reducing indoor formaldehyde levels, the effects of indoor humidity on human health should be considered.[16] Some studies associate an increase in respiratory illness with reduced humidity levels. On the other hand, increased humidity may promote the growth of molds, fungus, and house dust mites which cause allergic reactions in some individuals.

Combustion Product Source Control

Removal of unvented combustion appliances (e.g., gas stoves, unvented space heaters) is an obvious technique for eliminating their emission of combustion products into the indoor air. When evaluating removal of an unvented appliance, the initial, operating, and maintenance costs for the substitute appliance plus the form of energy used by the substitute appliance (e.g., natural gas or electricity) should be considered and compared to the benefits of the weatherization program. As discussed below, local ventilation may service adequately to vent products from some combustion appliances, gas stoves in particular. (The removal of unvented combustion appliances with no specific ventilation may be desirable from a health standpoint, even if no weatherization measures are implemented.) Vented combustion appliances can be a significant source of indoor pollutants if they perform improperly (e.g., if a furnace has a cracked heat exchanger) or if the vent system does not work properly. In such cases, repair or replacement of the appliance or vent system is appropriate, independently of the weatherization program.

## C. Ventilation Control Techniques

The replacement of indoor air with outdoor air (i.e. ventilation) is the most common method of reducing the levels of indoor generated air pollutants. Ventilation can be local or distributed, periodic or continuous, natural or mechanical, and with or without heat recovery. A significant advantage of ventilation is its ability to reduce levels of all indoor air pollutants if the outdoor concentrations are less than the indoor concentrations;[17, 18] however, ventilation is more effective for some pollutants than for others. A few studies have suggested that increasing the ventilation rate is only partially effective in reducing formaldehyde levels because high ventilation rates increase the rate of formaldehyde emission from building materials.[13, 14, 19] The increase in formaldehyde emission rate, however, may cause a decrease in the time period over which significant formaldehyde emissions occur. Models for indoor air quality[20] indicate that increased ventilation will cause a smaller decrease in the concentration of a reactive air pollutant than the level of a non-reactive pollutant. (Examples of reactive pollutants are nitrogen dioxide, formaldehyde, and some particulates that are removed from indoor air by interaction with indoor surfaces.) The reduction in indoor pollutant concentration due to an increase in ventilation rate can be estimated using the model presented in Appendix B. Disadvantages of ventilation as a control technique are (1) it may cause an increase in indoor levels of outdoor-generated air contaminants, (2) it generally increases heating or air conditioning loads, and (3) mechanical ventilation equipment has significant initial, operating, and maintenance costs.

Mechanical ventilation with heat recovery, local ventilation of gas stoves using an exhaust hood (that exhausts to outside), and natural or mechanical ventilation of crawl spaces are control techniques that may be suitable for a weatherization program, and each is discussed below.

Mechanical Ventilation with Heat Recovery

Residential heating and/or cooling loads can be decreased by reducing natural infiltration and substituting mechanical ventilation with heat recovery. The most common method of residential mechanical ventilation with heat recovery is the use of a residential air-to-air heat exchanger. The heat exchanger provides a controlled amount of ventilation that counteracts the adverse effects of reduced infiltration. In addition, the heat exchanger recovers much of the energy that would be lost when ventilation occurs by air infiltration.

Field studies by Offermann *et al.*[17] have demonstrated the effectiveness of air-to-air heat exchangers in reducing indoor pollutant concentrations. In their study, air exchange rates and indoor and outdoor pollutant concentrations were measured in nine homes for a ten day period without mechanical ventilation through an air-to-air heat exchanger, followed by a ten day period with mechanical ventilation through a heat exchanger. The average increase in air exchange rate, as determined by tracer gas decay measurements, was 80% (from 0.35 to 0.63 air changes per hour). During the period of heat exchanger operation, average indoor radon concentrations decreased 50%, average indoor formaldehyde concentrations decreased 21%, and average indoor relative humidity fell from 39% to 35%. Because the houses in this study did not have significant sources of nitrogen dioxide ($NO_2$), the outdoor concentrations of $NO_2$ were higher than indoor concentrations, and operation of the heat exchangers caused a slight increase in indoor $NO_2$ levels. The increases in indoor $NO_2$ concentrations were only a few parts per billion. (However, operation of a residential heat exchanger, can sometimes cause a significant increase in the indoor concentration of an outdoor air pollutant. For instance, one homeowner in the study shut off the heat exchanger each evening because smoke, presumably from neighbor's fireplaces, was brought into the house by the heat exchanger.) Particulate concentrations were measured in two of the houses studied and decreased approximately 30% when the heat exchangers were operated. A longer term study might have indicated different reductions in indoor pollutant concentrations because the pollutant source strengths may have changed throughout this study. In addition, the degree to which pollutant concentrations are reduced depends on the amount of ventilation provided, the method of heat exchanger installation (i.e., the characteristics of the duct system used with the heat exchanger), and on the location(s) of pollutant sources.

Laboratory tests by Fisk et al.[21, 22] indicate that heat exchangers can preheat or precool ventilation air by 45 to 85 percent of the difference between indoor and outdoor temperatures and show variations in fan power consumption from 0.4 to 2.1 watts per $m^3$/hr of ventilation supplied. Fisk and Turiel[23] have evaluated the energy savings attributable to the use of heat exchangers in new homes and have also performed a cost-benefit analysis for heat exchangers based upon the point of view of the homeowner. They compared the energy consumption and energy costs for a typical house to that for a house with low infiltration and supplementary ventilation provided through a heat exchanger. Cost effectiveness was determined to be highly affected by heat exchanger performance, climate, type of heating fuel, and the amount of ventilation supplied by the heat exchanger. Discounted payback periods ranged from 5 to over 30 years and net present benefit ranged from -$1358 to $2425 if a 20 year life for the heat exchanger was assumed.

Most models of residential heat exchangers are used with a system of ductwork for air distribution; however, some models are simply installed through the wall or window of a residence much like a window air conditioner. The window- or wall-mounted units may be more suitable for use in a weatherization program because their initial and installation costs are lower and because they are designed to provide a small amount of ventilation consistent with the reductions in infiltration expected from a weatherization program. Additional studies of window- or wall-mounted heat exchangers are needed. Studies supported by the Bonneville Power Administration are currently underway at Lawrence Berkeley Laboratory to determine how effectively these units ventilate a residence. All currently available window- or wall-mounted heat exchangers are designed to transfer moisture, as well as heat, between airstreams; therefore, some contaminants may also be transferred between airstreams in these models. Before these units are employed on a large scale, a study of contaminant transfer rates should be performed. If contaminant transfer is found to be a problem, relatively simple modifications may be adequate for reducing the rate of contaminant transfer. Finally, the economics of residential heat exchangers should be evaluated for the case of a retrofit program and this evaluation (also supported by the Bonneville Power Administration) is underway at Lawrence Berkeley Laboratory.

A second method of providing mechanical ventilation with heat recovery involves the use of exhaust air heat pumps. For this technique, a fan draws outdoor air into the house and exhausts indoor air through a small heat pump. The heat pump generally transfers energy from the outgoing air to the domestic hot water supply; however, heat pumps that transfer energy to the indoor air are possible. Exhaust air heat pump systems are gaining popularity in Sweden[24] but have not yet been utilized in the United States. An advantage of exhaust heat pumps, when compared to heat exchangers, is that a system of ductwork is not required to distribute incoming air. In some cases, however, depressurization of the house, caused by operation of an exhaust ventilation system, may increase the flux of radon into the indoor air.

Exhaust Hoods for Gas Stoves

Gas stoves are a concentrated and periodic source of indoor air pollutants. The entry of these pollutants into a residence can be reduced by providing local, periodic ventilation with a range hood. Operation of a range hood caused 60 to 87 % reductions in the amount of CO, $CO_2$, and $NO_x$, that entered a research house in a study by Traynor *et al.*[20] In their study, the flow rate of air exhausted through the range hood was varied from 150 to 420 $m^3$/hr. A range hood with exhaust rates of 120 to 400 $m^3$/hr caused 40 to 50 % reductions in average incremental $NO_2$ levels in a study by Macriss and Elkens.[25] (Average incremental $NO_2$ level is the increase in average $NO_2$ level due to operation of a gas stove.) The performance of range hoods may depend on design variables and method of installation; however, available studies indicate that range hoods are effective in removing gas stove combustion products. Range hoods will not be effective if they are not used by the homeowner, so studies of usage patterns or automatic range-hood controls may be required.

Crawl Space and Basement Ventilation

Natural or mechanical ventilation of crawlspaces or basements that are isolated from the remainder of the house is a potentially suitable method for reducing the transport of radon into the indoor air. Crawlspace ventilation has been employed in some Canadian communities[7] but has not been investigated in a systematic manner.

D. Air Cleaning Control Techniques

The term "air cleaning" refers to methods for the removal of pollutants from indoor air. Air cleaning methods that may be suitable for controlling indoor pollutant levels include filtration, electronic air cleaning, ionization, absorption, adsorption, and air circulation. Each general method of air cleaning is described briefly here; however, more detailed information is available in references on air pollution control techniques.[26-30] Following each description, the suitability of each method for the control of indoor air pollutants is discussed. As a class, air cleaning techniques will generally not increase residential heating loads, although significant electrical energy may be required to operate the equipment. All energy consumed for air cleaning will generally be delivered to the residence, thus reducing loads on heating systems but increasing loads on air conditioning equipment.

## Filtration, Electronic Air Cleaning, and Ionization

### Technical Description

Air cleaning by filtration is accomplished by passing the air through a filter which is usually constructed from a woven fabric, a paper material, or a fibrous matt. Filters are designed for the removal of particulates or mists and are generally not effective in removing gaseous contaminants. The performance criteria for filters are particle collection efficiency (which varies with particle size), air flow resistance, and particulate capacity (i.e., filter lifetime). High efficiency filters can remove almost 100 percent of particles as small as 0.3 μm; however, the fibrous matt filters typically used in residential furnace systems are not effective in removing submicron size particulates, which are of primary health concern. Filter systems with a wide variety of efficiencies are commercially available. Recently, filter materials that contain fibers with a permanent electrical charge have been developed. These filters may be more suitable than conventional filters for the removal of small particulates. Filters must be periodically cleaned or replaced, and significant trade-offs exist between filter cost, collection efficiency, capacity, and air flow resistance.

Electrostatic precipitators (one type of electronic air cleaner) can be highly effective in removing even sub-micron particulates, but they are generally not effective in removing gaseous contaminants. An advantage of precipitation over filtration is that small particles can be removed without imparting a large pressure drop to the airstream. (A large pressure drop leads to a high fan power consumption.) Also, precipitator collection surfaces are generally cleanable while high efficiency filters must usually be replaced. In an electrostatic precipitator, particles are first charged by gaseous ions produced by an electrical corona. The charged particles then pass through an electric field and are attracted to and collected by an oppositely charged electrode. The collection surfaces must be cleaned periodically. Some precipitators and other types of electronic air cleaners produce a small amount of ozone and many units are supplied with replaceable charcoal filters to remove the ozone and odors. Residential sized precipitators are readily available for installation in furnace ductwork or as portable models. Collection surfaces are usually cleaned with soap and water; in some models they can be cleaned in an automatic dishwasher.

Two additional types of electronic air cleaners are available commercially. A charged-media nonionizing electronic air cleaner consists of a dielectric filtering medium (e.g., glass fiber matt or cellulose matt) that is in contact with a grid of alternately grounded and charged members. The electrostatic field created in the dielectric filter medium causes approaching particles to be polarized and attracted to the filter. The filtering medium must be replaced periodically. A similar device, the charged-media ionizing electronic air cleaner uses a corona discharge to charge the particulates (as in an electrostatic precipitator) and collects the particulates on a charged-media filter matt.

Air ionizers produce negative ions, which can attach to particulates. Ionizers generally have no collection surface; therefore, the particulates must attach to some indoor surface if they are to be removed from the air. Ionizers generally rely on natural movement of air to bring particulates near the ionization source. The performance and usefulness of ionizers is presently a controversial topic.

## Impact on Indoor Air Quality

Particulates produced by gas stoves and sidestream cigarette smoke are almost entirely sub-micron in size.[31,32] These particles can be removed by very high efficiency filters but are probably more economically removed by electrostatic precipitators or other electronic air cleaners. The quantity and size distribution of particulates that enter indoor air from fireplaces and wood stoves have not been determined. Electrostatic precipitators should be effective in removing those particulates, however, even if they are very small. Usage patterns for electronic air cleaners and filters are important because neither device will perform properly if it is not maintained.

The effect of filtration and electronic air cleaning on radon daughter levels and the associated radiation dose is complex and not fully understood.[33,34] Each device will remove radon daughters that are attached to the particulates they collect. In addition, each device may remove some of the unattached radon daughters (i.e., daughters that are not attached to particulates) through electrostatic collection or other physical or chemical processes. One would expect these devices to reduce radiation doses because they reduce radon daughter levels and, in many cases, this may indeed be true. If indoor particulate concentrations are reduced to low levels, however, the result may be an increase in the concentration of radon daughters that are not attached to particulates because of the reduced frequency of interaction between radon daughters and particulates. According to some models of radiation dose to the lungs from radon daughter inhalation, unattached daughters cause a much higher dose than attached daughters;[35] therefore, filtration or electronic air cleaning may actually be detrimental in some cases. An additional complicating factor in assessing the effect of these measures is that each measure may, to an extent that is not now known, increase the plate out (i.e., attachment) of unattached radon daughters on indoor surfaces because of the reduced particulate levels or because indoor air movement is increased.

Elevated particulate levels may be one of the most common indoor air quality problems; therefore, studies of the performance of commercially available particulate removal devices should be undertaken. Careful study is definitely needed to evaluate the impact of these devices on the levels of attached and unattached radon daughters.

## Absorption

In absorption air cleaning the objectionable gaseous contaminant is absorbed by a liquid from the air. The terms "scrubbing" and "air washing" are commonly used to describe absorption processes. Typically the contaminanted air is passed through a liquid spray or over wetted surfaces. The pollutant can be removed only if it is soluble in the liquid or if it reacts chemically with the liquid. Water is the most commonly used liquid; however, in many cases some additive to the water is utilized. Some absorption equipment is effective in removing particulates as well as gaseous contaminants.

Absorption processes have received little consideration for the control of indoor pollutant levels despite their common use for the removal of industrial air pollutants. An initial theoretical study of absorption processes for indoor air quality control is underway at Lawrence Berkeley Laboratory. Absorption by water appears most promising for the removal of formaldehyde, because formaldehyde reacts rapidly with water. Various absorption processes are used to absorb nitrogen dioxide ($NO_2$) from industrially contaminanted air.[36] However the processes are complex and generally not suitable for indoor air which has much lower concentrations of $NO_2$. Absorption of $NO_2$ into water may be possible if additives to the water are used[37], but further study is needed. Absorption processes appear least promising for radon, which is essentially non-reactive and only slightly soluble in water.

## Adsorption

In adsorption air cleaning, gaseous pollutants are adsorbed onto the surface of a solid. The exact mechanisms of adsorption are not fully understood. Gases with high molecular weights are generally adsorbed more easily than gases with low molecular weights. Materials used for adsorption typically have a very large surface area due to the existence of microscopic pores. The most commonly used adsorbents are activated carbon (activated charcoal), activated alumina, silica gel, and molecular sieves. In many cases, adsorbents are impregnated with a material that improves their adsorption of a particular pollutant. Of the four most commonly used adsorbents, only activated carbon is non-polar. Polar adsorbents preferentially adsorb polar molecules; therefore they are usually ineffective for cleaning of moist air because they become saturated with highly polar water molecules. Non-polar activated carbon is effective in moist airstreams because the water molecules are more highly attracted to each other than to the carbon surface. Adsorbents become saturated after a period of use and must then be regenerated or replaced.

The effectiveness of adsorbents in removing radon, radon daughters, and nitrogen dioxide from indoor air is not well known. Jewell[12] and the Swedish Council for Buildings Research[38] have investigated the use of Purafil (an aluminum oxide impregnated with potassium permanganate) and found it effective in adsorbing formaldehyde from air. Jewell reduced the levels of formaldehyde in a mobile home from approximately 500 ppb to 140 ppb by passing 2640 $m^3$/hr of indoor air through a 36 kg bed of Purafil. (The air circulation rate of 2640 $m^3$/hr was equivalent to 13.6 air changes per hour.) Neither Jewell nor the Swedish researchers present data on the lifetime of the Purafil; however, the Swedish researchers indicated that Purafil systems may be much more economical than ventilation through air-to-air heat exchangers.

## Air Circulation

Air circulation or air movement is not generally considered an air cleaning method; however, it may increase the rate at which some contaminants are removed by attachment to indoor surfaces. Radon daughters, reactive gasses, and particulates are most likely to be removed by this technique. Nazaroff[39] observed a substantial decrease in radon daughter levels from operation of a furnace fan. The furnace's ventilation system did include a furnace filter; therefore, operation of the furnace fan caused both air filtration and air circulation. Because nitrogen dioxide, formaldehyde, and some particulates react with building surfaces, air circulation may also cause decreases in their levels.

## E. Discussion of Control Techniques

A large number of techniques are potentially suitable for the control of indoor air pollutant levels. The cost and effectiveness of these techniques is generally not well known; therefore, further research is needed before most techniques are widely utilized. Based upon available information, the following control techniques appear most promising for use in a weatherization program:

1. Mechanical ventilation with heat recovery - for reducing the levels of all air contaminants if the outdoor levels are lower than indoor levels.

2. Ammonia fumigation and dehumidification - for reducing the rate of formaldehyde emission from building materials.

3. Removal of unvented combustion appliances.

4. Spot ventilation of gas stoves using an exhaust hood.

5. Crawlspace ventilation - for reducing the rate of radon entry into the indoor air.

6. Electronic air cleaning and filtration - for removal of particulates and perhaps radon daughters.

7. Absorption of formaldehyde into water.

8. Adsorption of formaldehyde by Purafil.

9. Air circulation - to increase the rate at which radon daughters and perhaps other contaminants attach to indoor surfaces.

A mathematical model presented in Appendix B is useful for providing a rough estimate of the impact of control techniques on indoor air quality but further experimental data is needed to increase its usefulness.

The impact of many control measures on the levels of indoor pollutants depends on the size or capacity of the control system utilized. If too large a control system is employed, initial and operating costs will be greater than necessary. In addition, the energy savings resulting from a weatherization program can be significantly compromised or even overwhelmed by energy requirements for the control measure, if too large a control system is utilized. On the other hand, the levels of indoor air pollutants will not be reduced sufficiently if too small a control system is employed. Specifying the size or capacity of the control system will be difficult unless the impact of the weatherization measures on infiltration is known. This impact could be estimated on the basis of the weatherization audit, but the actual reduction in infiltration is likely to vary significantly from house to house. Alternatively, the leakage area (a scale parameter for infiltration) of each house can be measured before and after weatherization using the fan pressurization techniques; and the results can be used to size the control system. The leakage area measurements may be accomplished during weatherization, if fan pressurization is utilized for the identification and sealing of air leakage points.

This section on indoor air quality control techniques, and the previous two sections, provide background information for Part II of this report which describes a methodology for altering the exclusion list.

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PART II - DEVELOPMENT OF A METHODOLOGY FOR ALTERING THE EXCLUSION LIST

The purpose of excluding some houses from use of the infiltration-reducing elements of the weatherization program was to assure that no significant impact would arise from increases in levels of indoor pollutants that could be caused by the modest decreases in air exchange rates caused by infiltration-reducing measures. In the absence of more complete information, this was assured by excluding tightening measures from those houses that have a substantial chance of having higher-than-average (or higher than "acceptable") indoor pollutant concentrations. The houses excluded are those that could have larger pollutant input rates because of the presence, or possible presence, of specific sources or of unfavorable characteristics with respect to pollutant transport into the interior.

The most significant excluded classes are those associated with potential radon sources (or transport features) and those having wood-burning stoves. These excluded classes have a substantial effect on the success of the weatherization program, as measured by energy savings, since (1) infiltration reduction constitutes one of the largest sources of energy savings, as well as one of the most cost effective elements of the program, and (2) most houses in the BPA area appear to be among the excluded classes.

The degree of potential energy saving is not the principal issue in this document, but the mere size of the excluded classes is important. Approximately half of the houses have an excluded understructure and half with full crawlspaces do not have the required ground cover. Moreover, it appears that as many as half the houses otherwise qualifying for the program have wood stoves. Even though there must be considerable overlap among these excluded classes, it is apparent that tightening measures are permitted in only about a quarter of houses qualifying for other parts of the weatherization program.

Because so large a portion of the housing stock is presently excluded from the infiltration-reducing elements of the weatherization program, the effectiveness of the program could be substantially enhanced by removal of some classes of houses from the exclusion list. Several different bases could be used, either alone or in combination, for removal of excluded classes: (1) Original exclusion of the class may have been overly conservative; i.e., on the basis of present information, it may be found that tightening of certain classes of houses on the exclusion list would, without other precautions, still cause no significant impact. (2) Specific elements of the weatherization program itself may be adequate to assure no significant impact, or this burden may be assumed by parts of other programs that occur concurrently with the weatherization program. (3) The weatherization program may be <u>followed</u> by programs or determinations that effectively assume the burden of proof, provided these follow-up programs effectively determine where the weatherization program can cause deleterious effects and provided remedial action can be taken early enough to prevent significant effects.

There are three essential aspects to any of these approaches, or combinations thereof: (1) development of better information on sources in housing classes or individual houses; (2) adoption of criteria on acceptable individual or average concentrations; and (3) implementation of mitigation measures (either concurrently or retrospectively) in houses (or classes of houses) that require it. (Improvements in these respects are also useful independently of changing the exclusion list.) There may, of course, be houses that are retained on the exclusion list after consideration of anticipated pollutant concentrations, potential effects, and available mitigation measures. It is also conceivable that classes on the exclusion list may be altered, decreased or increased.

Because there are a number of grounds for removal of a class from the exclusion list and - furthermore - each of these grounds may involve a number of possible elements, a methodology for removal of classes is likely to have a complex structure, with removal of various classes occurring over a period of time and dependent on successful implementation of program elements that provide a basis for their removal. Before proceeding to the formulation of a methodology, we indicate in section 4 the expected concentration distribution in housing classes on the exclusion list and the anticipated effect of infiltration reduction. In section 5 we examine in more detail the generic considerations for a methodology, specifically the conditions that permit removal from the list (or indicate additions) and the context in which these changes may occur. Finally, in section 6 we delineate the framework in which housing classes may be removed from (or, in principle, added to) the exclusion list with no significant impact on the populations living in these structures.

## 4. CONCENTRATION DISTRIBUTIONS IN EXCLUDED HOUSING CLASSES AND THE EFFECT OF INFILTRATION REDUCTION

The several exclusion criteria of appendix E of the Environmental Assessment are based on the presumption that certain house characteristics may, in some circumstances, increase the "source magnitude" for corresponding pollutant classes. The houses included in the program are, according to BPA's Revised Environmental Assessment, "those residences in which major sources of indoor air pollutants are minimized."

By the "source magnitude," we mean in this context the rate at which the pollutant in question is emitted, by whatever means, into the house interior. (For practical purposes, the source magnitude is often taken to be the rate per unit house volume; e.g., for radon, the source magnitude could be given in units of pCi $h^{-1}$ $l^{-1}$, picocurie per hour per liter.) The source magnitude therefore depends both on the rate at which the substance of interest is produced from local sources and on the avenues for entry into the air inside the house. Furthermore, the source magnitude can, in principle, be reduced by controlling either the production rate or the efficiency of entry. The indoor concentration may, of course, also be controlled by ventilation or air cleaning.

Although the exclusion criteria are associated with specific source characteristics (either production or entry), they only <u>indicate a potential</u> for higher-than-average source magnitudes or, ultimately, indoor concentrations. In fact, in some cases, as indicated below, the exclusion criteria as formulated do not pertain to the <u>primary</u> factors that may cause higher-than-average source magnitudes; in such cases, the stated criteria tend only to modulate the magnitude to a secondary degree. In other cases, the criteria as stated are specifically associated with higher-than-average source magnitudes, but measures may be taken to identify that portion of the excluded class that suffers from such difficulties, after which mitigation of one kind or another may be advised.

Considering these limitations of the exclusion criteria, we turn briefly to the various excluded classes to comment on the degree to which higher-than-average source magnitudes or indoor concentrations may be expected to be associated with each class. For convenience, we group the excluded classes by pollutant of interest, treating first the classes associated with potentially high radon source magnitudes (i.e., foundation design, household water source, and interior masonry) then turning to combustion appliances, primarily wood stoves, and to use of urea-formaldehyde foam insulation.

### A. <u>Radon Exclusion Classes</u>

The three radon-related criteria are associated, roughly in the order given, with what are thought to be the major sources of radon indoors. In the United States, radon entering the house from under and around the foundation is thought to be the most important contributor to indoor radon. In some cases, however, radon from household water that is drawn with little holdup from groundwater - e.g., via a private well - can contribute substantially to indoor radon concentrations. Finally, in some circumstances, building materials that have unusually large radium concentrations can contribute significantly to indoor radon levels, ordinarily only in the unusual case that radium-bearing industrial waste products are used in the manufacture of building materials.

For the more usual case of building materials (such as concrete aggregate or rock) drawn from local sources, the material underlying the house (if it has radium content similar to the building materials) will ordinarily constitute a more important radon source, at least in houses with concentrations exceeding 1 pCi/l or so, largely independently of whether or not the house has a ventilated crawlspace. That is, the major factor affecting the radon source magnitude is the radium concentration in the ground and rocks in the area; this concentration affects the degree to which underlying soil, household water, and local building materials contribute to indoor concentrations.

If local sources have low radon emanation rates, then the radon source magnitude for houses is small, and the presence or absence of one of the exclusion factors is of little importance, since the indoor concentration will be low in any case. (This fact will be critically important in section 6 for framing an approach to removing classes from the exclusion list.) On the other hand, if radon concentrations, and hence source magnitudes, are high, this is likely to occur because local sources have high emanation rates, affecting virtually all houses in the area (albeit to a degree that depends on the particular house).

In the United States, the full range of radon concentrations observed indoors exceeds a factor of 100, and is probably closer to a factor of 1000, i.e., $< 0.1$ pCi/l to something above 50 pCi/l, even excluding the cases where special materials are used in the structure. Based on what is known now about the BPA area (e.g., measurements in Eugene, Oregon and Butte, Montana) a similarly large range occurs in this widely-varying region.

Because the exclusion criteria as now framed do not relate directly to the question of whether local sources are high in radium content, the distribution of concentrations in houses excluded on the basis of these criteria is likely to have the same general appearance as the distribution for houses not excluded. Both groups must be expected to have houses with radon concentrations ranging from less than 1 pCi/l to greater than 10 pCi/l. The concentration distribution for the excluded group will almost certainly have somewhat higher levels than the distribution for permitted houses. But differences of factors of three or so that are obtained by selecting on the basis of present criteria are small compared with the 1000-fold range in indoor concentrations. (On the other hand, requirement of such criteria, which make selections on the basis of factors of two or three, is a relatively strong response to the 20-30% change expected from infiltration reduction.) As discussed below, improved understanding of source magnitude distributions may provide a basis for more appropriate selection criteria.

Fundamentally, three major factors affect the indoor radon concentration: local source strengths, radon entry efficiency, and the ventilation rate. To the extent that these can be considered to be independent of each other, each factor has equal weight in affecting the indoor concentration, that is to say, a factor of two variation in any of these changes the radon concentration in first order by a factor of two. The 1000-fold variability actually observed is probably attributable to these factors in roughly the same degree, although there is some indication that the local source strength may vary somewhat more widely than the others, that the next highly varying is the efficiency of transmission into the house, and that the least highly varying is the ventilation rate (this variation is still quite substantial and probably comparable to that for transmission efficiency). Speaking only approximately, about a ten-fold variability must be expected in each of these factors, merely to include more than 90% of houses, and the range probably varies somewhat among the three factors. The exclusion criteria, as now formulated, are based, in one way or another, solely on transmission efficiency (i.e., radon entry characteristics).

Turning to each excluded class individually, it is not known how heavily radon entry rates depend on design of the house understructure. It can, however, be safely presumed that, a ventilated crawlspace with (or without) vapor barriers somewhat reduces ingress of radon from the soil under (or surrounding) the house, as compared with a house with a closed basement. How much reduction is effected is highly uncertain, depending not only on the structure itself, but also on such matters as local wind conditions. Moreover, the effectiveness of vapor barriers in inhibiting radon entry in these circumstances is not known. Because of such factors, it is likely that great variability occurs in the factor by which radon entry is reduced for permitted houses relative to unrestricted entry, i.e., the case where most of the radon that would come from "free" (uncovered) soil actually enters the house. Factors from approximately 1 (i.e., almost no reduction) to 10 or more (tenfold reduction) must be expected in the full range of possibilities.

Assuming a constant type of permitted structure (ventilated crawlspace with vapor barriers), the relative reduction (compared with an excluded alternative structure) will depend on the particulars of the excluded class. Although these relative reduction factors are not actually known either experimentally or theoretically, it is useful to indicate their probable range, purely as a basis for considering in what circumstances classes might be removed from the exclusion list. At one extreme, that of a closed full basement, the relative reduction factor for a permitted structure may typically be in the range of 2 to 4 (but with rare cases in the vicinity of either 1 or 10 or more). At the other extreme, the ventilated crawlspace may offer little more barrier than a well-constructed concrete slab, particularly a slab system that incorporates a barrier of some kind. Hence, we might assign a relative reduction factor of 1 to 3 for this kind of system, and similarly for a crawlspace that does not meet the vapor-barrier requirements or that is not adequately ventilated. As an example, the difference between a permitted structure and one having a crawlspace without vapor barriers is taken to be a factor of 1 to 3 (a mean of 2), but this may be too great (or even too little). Moreover, aside from the intrinsic or potential value of any particular measure, its actual effect will depend substantially on construction details and other factors that are very poorly defined.

Nonetheless, the view that radon reduction factors (relative to free entry) are largely in the range of 1 to 10, with most houses between 2 and something less than 10, is consistent with the picture suggested above, that variability in radon entry contributes about one of the three orders of magnitude range in observed radon concentrations. Viewed from a different perspective, changes from one understructure type to another may cause changes of roughly a factor of 2 or 3 (on the average) in radon entry rate: small compared with the wide range in radon distribution (range of 1000) and large compared with changes in ventilation rate due to tightening (20 to 30%).

Thus, if the full range of radon concentrations is of the order of 1000, the excluded group of houses will have a range in concentrations of roughly 300 to 500, as will the permitted class, assuming a factor of two or three difference between the two. Assuming a factor of three would mean, for example, that if the full range were 0.05 to 50 pCi/l, the excluded houses would have 0.15 to 50 pCi/l and the permitted houses would have 0.05 to 17 pCi/l. Tightening these two classes by 20% would yield ranges of 0.18 to 60 pCi/l and 0.06 to 20 pCi/l, respectively. The two classes have similar ranges, each with some high levels, and are similarly affected by infiltration reduction. (However, the upper end of each range may not change as much as indicated, since being at the high end of the range probably implies a ventilation rate that is already lower than average and hence not as susceptible to tightening; the lower end may not change much because of the relatively large influence - at such low levels - of radon in outdoor air.)

These nominal ranges and changes are highly conjectural and neglect the differences in the excluded classes (noted below). They do, however, illustrate the key point, i.e., that the range must be expected to be very large in both permitted and excluded classes, the main difference being a small relative shift of the two distributions. Further, as discussed at greater length in succeeding sections, the key to reducing the average exposure is to identify cases or areas with high local sources, and not only to avoid measures that raise concentrations in these areas but to take steps to reduce them. This would be the equivalent of altering the formulation of the exclusion criteria to have a more fundamental basis. Such alteration can be accomplished only on the basis of improved information, specifically the identification of the portion of the housing stock with large source magnitudes. At the same time, presently excluded homes with low source magnitudes could be offered infiltration-reducing measures.

We turn again to the various classes excluded on the basis of differences in house understructures: those with basements, non-qualifying crawlspaces (partial basement/slab, unventilated, no vapor barriers), or concrete slabs. A typical distinction between excluded and permitted concentration ranges and changes has been given above. Depending on the excluded class(es) in question, the distinction will be slightly greater or less, but not qualitatively different. The parameter of ultimate interest is, of course, exposure to radon daughters, a schematic representation of which is given in figure 4-1. Because the distributional argument just made for concentrations extends equally well to exposures, it can be expected that, for each of the excluded

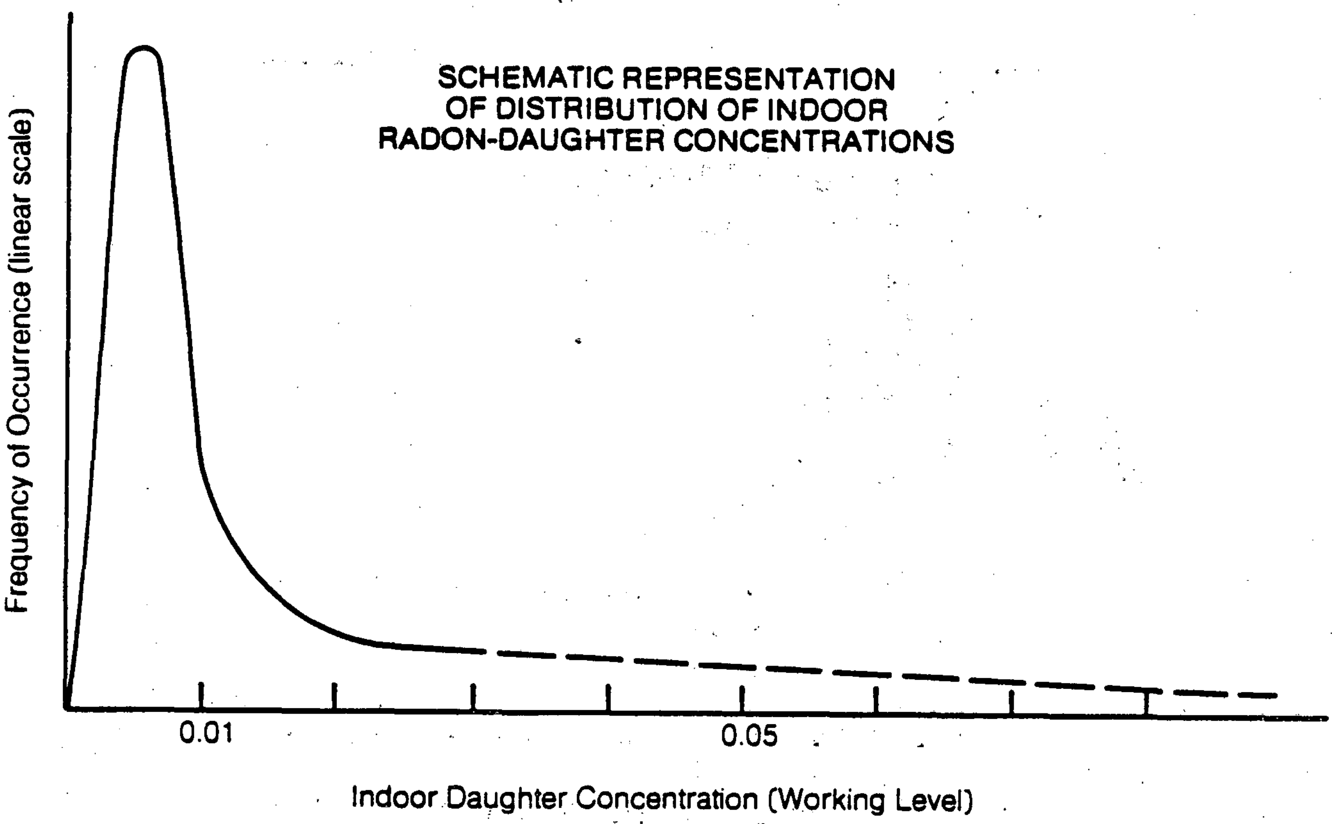


Figure 4-1. Schematic representation of the distribution of indoor radon-daughter concentrations. Most of the population is in the peak at low concentrations, and hence exposure rates. However, a significant number experience much high exposure rates, so that they suffer unusually large individual risks and, moreover, so that a substantial portion of the total exposure (and hence aggregate risk) occurs among a small number of the population. See also Figure 4-2.

Figure 4-2 (following page). Survey of radon-222 concentrations and implications for associated risk of lung cancer. The upper part of the figure shows the number of houses found to have radon concentrations in four ranges: 0 to 1, 1 to 5, 5 to 10, and 10 to 30 pCi/l. (These results are taken from: A. V. Nero et al., "Radon Concentrations and Infiltration Rates Measured in Conventional and Energy-Efficient Houses," Lawrence Berkeley Laboratory report LBL-13415, September 1981, submitted to Health Physics.) The lower part of the figure gives estimate of the corresponding U.S. lung cancer rates attributable to exposure to radon daughters indoors, assuming the housing sampled is typical of the U.S. housing stock, that annual-average radon concentrations are half those given in the upper part of the figure, and that the equilibrium factor is 0.5. Note that half of the aggregate risk can be attributed to the 15% of the houses having concentrations in the two upper ranges. Even higher concentrations than those given here have been found in the BPA area. (Because radon was measured with all windows and doors closed, the resulting concentrations cannot be taken as annual-averages in the houses monitored in this survey. Moreover, this sample was accumulated in a manner that probably gives too great a representation to houses that are "tighter" than average or that are located in "high radon" areas.)

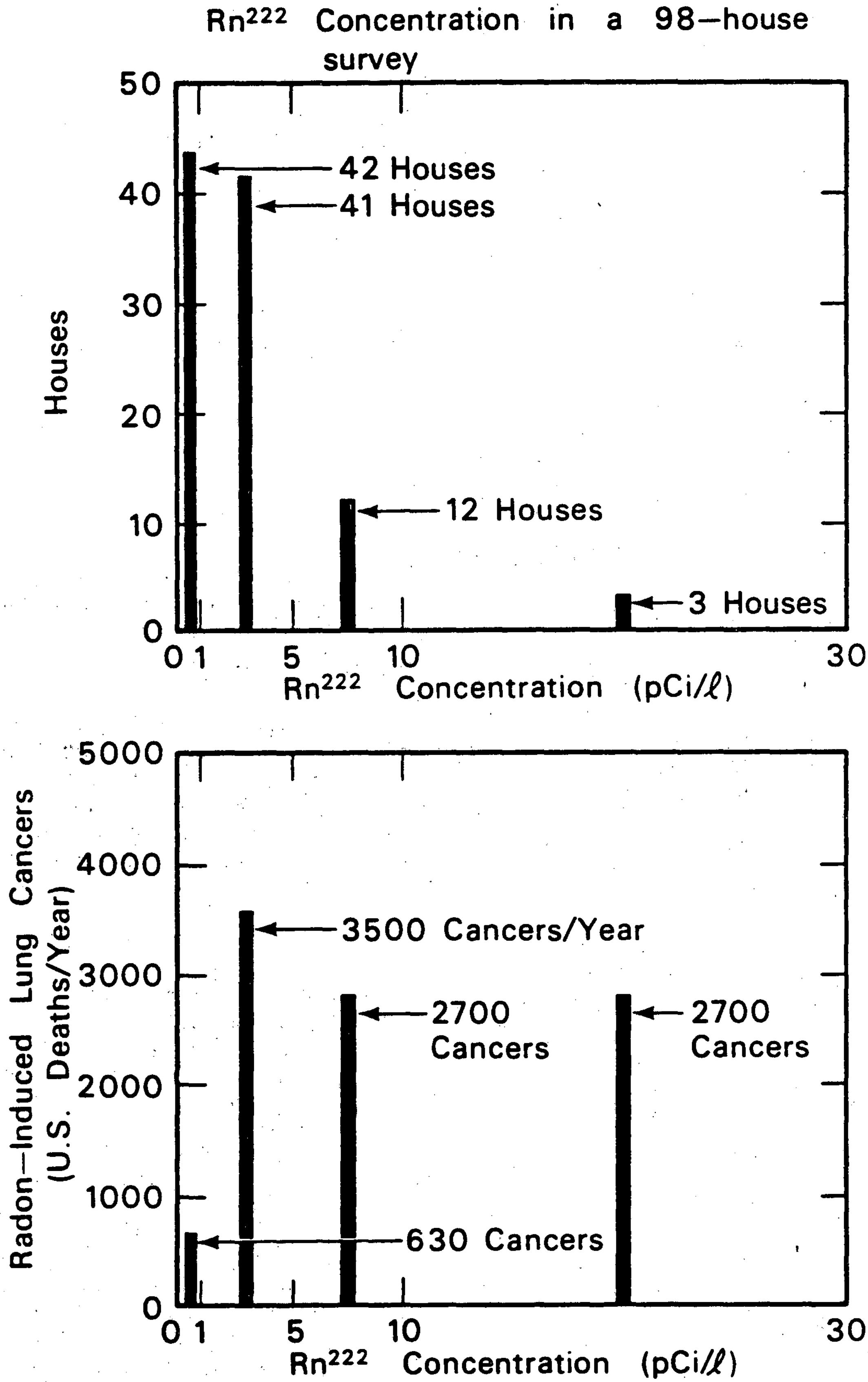


Figure 4-2 (caption on previous page).

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classes, the bulk of the population occurs in the peak at low exposure rates.

The foregoing discussion of radon has dealt only with the influence of understructure and other factors on indoor concentrations of radon entering from surrounding soil and rock. Except for the issue of the efficiency of radon entry, much of this discussion is pertinent to the two other radon exclusion classes, which are based on water source and building materials.

Based on experience in the United States, household water is the second most important means by which radon enters houses. As indicated by the exclusion as formulated, this occurs primarily with water from private wells. In areas with unusually high radium concentrations, significant amounts of radon may thereby enter houses. For typical water usage, a radon concentration of 10,000 pCi per liter of water sustains an airborne radon concentration on the order of 1 pCi/l. Concentrations of this size or greater have been found in several parts of the country. Although detailed evidence is not yet available, it can be expected that high concentrations in household water will correlate roughly with areas with high emanation of radon from soils and entry of such radon into houses. A possible exception occurs when ground water travels long distances, but the impact of such transfer tends to be mitigated by decay of radon during transit and by mixing with local waters.

Because radon content of household water from wells can vary from on the order of 10 pCi/l to in excess of 100,000 pCi/l, the contribution to airborne radon concentrations can vary from about 0.001 pCi/l to 10 pCi/l or more. As a rule of thumb, water may therefore contribute, on the average, about an order of magnitude less radon to indoor air than radon from beneath the structure, although there are known to be exceptions. Furthermore, the relatively high contributions should ordinarily occur in the areas where, because of geologic factors, relatively large amounts of radon are also available for direct entry via house understructures or for indirect entry via building materials (discussed just below). As for the effect of infiltration reduction, a range of precisely 0.001-10 pCi/l (contribution from water) would be altered, by a 20% infiltration reduction, to a range of 0.0012-12 pCi/l.

Finally, building materials can constitute - in unusual cases - a significant source of radon. For materials derived locally and used in single-family dwellings, the contribution is usually small. For example, a typical full concrete slab in a single-story residence can ordinarily be expected to contribute less than 0.1 pCi/l to the indoor air, assuming no sealant. Smaller amounts of interior masonry with similar emanation rates would contribute correspondingly less, so that - ordinarily - radon from interior concrete or masonry can be expected to be substantially less than that from the ground under and around the house. Looking at this in a simple way, there is much more radon-emanating material around than in the house. Characterizing areas with respect to soil as a radon source will also aid in characterizing local building materials. The principal exception is materials derived from industrial processes that concentrate radium or that use non-local materials (or mined materials whose origin correlates geochemically with that of radium). Specific attention should be given to such special cases (as led to current studies being undertaken in Butte), thereby avoiding the tendency to ascribe such difficulties to ordinary building materials.

## B. Wood Stoves and Unvented Combustion Appliances

Of the two exclusions in this category, that with wood stoves is the larger, constituting as much as half of BPA-served, electrically heated homes. It should be noted that houses with fireplaces are not excluded in appendix E. Unvented combustion appliances (whether gas stoves or heaters) are present in only a few percent of the BPA houses in question.

The contribution of wood stoves to contaminants in indoor air is not well characterized and depends greatly on the specific system in question and on the manner in which it is operated. Even the few data available (see section 2) suggest that average and peak concentrations for specific pollutants can vary from a small fraction of to noticeably greater than standards applicable to outdoor exposures to these pollutants.

Based on the limited indoor wood stove data in the literature, it might be expected that average total suspended particulate (TSP) levels in homes with wood stoves during "heavy" use could range from essentially outdoor levels to over 300 $\mu g/m^3$. Comparable respirable suspended particulates (RSP) concentrations might have a slightly reduced but similar range.

Polycyclic organic matter (POM) -- also called PAH or PNA -- levels can range from 0.2 to 4% of the particulate levels resulting from wood stove use. Benzo-a-pyrene (BaP) -- part of the POM class of pollutants -- levels would obviously be less.

Indoor measurements of gaseous pollutant levels from wood appliances are limited. Whole house peak NO levels have ranged from less than 3 to 225 ppb. And peak $NO_2$ levels have ranged from 3 to 320 ppb. In the case of both indoor gaseous and indoor particulate concentrations from wood stove use, the variation from house to house far exceeds any variation expected from a residential air-tightening program.

The significance of emissions is likely to depend, not only on pollutant type and emission rate, but also on the use factor: the fraction of time the system is in operation, or the number of times it is started, stoked, or reloaded. There is evidence that fireplaces can also pollute indoor environments. Low use factors or the untested assumption that in practice fireplace flues remove all pollutants are presumably the basis upon which fireplaces were not excluded from initial participation in the tightening aspects of the program.

Finally, the question of pollutant emission rates over time has not been addressed. Since creosote builds up in the flue of any wood or coal appliance, it must, if not cleaned, eventually reduce the flue efficiency over time and increase the wood stove's potential for polluting indoor environments unless the flue is cleaned regularly. This might imply that some advice on regular flue maintenance be given to the homeowners if air tightening measures are performed.

Use of unvented combustion appliances, such as gas stoves or heaters, can contribute substantial indoor concentrations of oxides of carbon and nitrogen, formaldehyde, and particulates. Available data (section 2 and 3) indicate that concentrations of one pollutant or another can reach levels above outdoor air quality standards depending on the circumstances. Venting, of course, avoids most such emissions, assuming integrity of the flue system. Even local ventilation - such as a hood operating over a gas stove - is relatively effective in preventing entry of these emissions into the general indoor space. Assuming no venting, reduction of infiltration rates by 20 or 30% will raise indoor concentrations, whatever they may be, by a corresponding amount.

C. Urea-Formaldehyde Insulation and Other Formaldehyde Sources

Formaldehyde-emitting materials that are used in the house structure or furnishings can contribute substantial concentrations of formaldehyde to indoor air. The most notable such source has been urea-formaldehyde foam insulation. Concentrations above 1.0 ppm, well above proposed limits and sufficient to cause acute distress in a significant portion of the population, have been found in houses with such insulation. Although the distribution of concentrations in these houses is not well defined, it is known that, depending on how well the insulation is installed, substantially lower concentrations are the norm, reaching the range that might be considered acceptable. However, a significant enough portion of houses with such insulation have concentrations at or even well above proposed guidelines for the general public that it does not appear prudent to reduce ventilation rates, however slightly, in such houses without identifying those homes with elevated formaldehyde concentrations. (This identification could be accomplished by performing a measurement to determine concentrations in the houses in question.)

It is also known that other sources of formaldehyde can lead to high airborne concentrations indoors, specifically materials that are used in finishing house interiors (such as plywood, particleboard, carpet adhesives) and in furnishing them (furniture using similar material). The presence of such materials are known to lead to airborne concentrations in the range of 100 to a few hundred ppb in a significant portion of cases, at least soon after installation. Even use of gas stoves (without use of a ventilation hood) can contribute concentrations in the range of 100 ppb at normal ventilation rates. At very low ventilation rates (such as commonly occur in mobile homes or in unusually tight frame structures), the concentrations can even extend above 1.0 ppm. The latter cases are not directly pertinent to the weatherization program, since ordinary tightening would presumably have negligible effect, but even concentrations in the 100 to few hundred ppb range have to be considered carefully, considering that some proposed standards place limits (rather than averages) as low as 100 ppb for the general public. On the other hand, there is reason to think that houses that initially have concentrations in this vicinity will, eventually, have considerably lower concentrations as the source materials outgas and the emission rates decline. Thus a ventilation reduction that initially raises 100 ppb to 125 ppb would, as an example, later be responsible for raising a 40 ppb concentration to 50 ppb.

## 5. GENERIC CONSIDERATIONS IN ALTERING THE EXCLUSION LIST

### A. Requirements for Removing Classes from Exclusion List

Removal of a class from the exclusion list entails one or both of two elements: development of improved information on sources, concentration, or controls; and implementation of strategies to assure that tightening of houses in the class in question will not cause a significant impact on occupants. Formulation of criteria for judging such impacts are also important. Development of information or mitigating strategies, as well as criteria, can take place either as part of the weatherization program or as part of other efforts, either for BPA or otherwise. It is useful to consider these possibilities explicitly before proceeding to the methodology itself.

The first basis on which the exclusion list might be altered is that, based on presently available information, certain classes as previously defined may designate factors that are not themselves the origin of potentially significant impacts or that are inappropriate exclusion criteria on other grounds. As an example, it is conceivable that the criterion on interior masonry might be removed on the premise that this source in virtually no case contributes the bulk of the radon entering a house, so that any significant impact on radon levels from infiltration reduction would arise primarily from other sources associated with the house. Another example would be removal of the exclusion against gas stoves, provided that an operable ventilation hood was in place. On the other hand, reconsideration could also suggest <u>addition</u> of classes to the exclusion list if reevaluation indicated a significant enough potential impact from housing characteristics other than those initially on the exclusion list. (See section B, below.)

A second basis for removal of classes from the exclusion list is that the weatherization program provide a mechanism for information development and, if needed, mitigation. As an example, indoor monitoring or detailed source characterization would be a reasonable basis for deciding that certain houses could be tightened without significant impact or for deciding which houses required mitigation as a condition of tightening. Such mitigation, in some cases, could even occur a significant time after tightening, for those cases where acute effects are not likely to result and where cumulative effects could be avoided. A significant portion of the section on methodology will entail development of information and use of mitigation measures as part of the weatherization program.

The third basis for removal from the exclusion list is similar to the last, except that the development of information or mitigating strategies need not be part of the weatherization program per se. As above, this development could occur concurrently with or after weatherization itself. There are several important possibilities of this type:

1. Parallel or subsequent characterization of indoor air quality with respect to housing characteristics in the BPA area may better distinguish those classes or subclasses of houses that require mitigation in connection with tightening measures. For example, the

regional indoor air quality field survey described by GEOMET (and proposed in a different form by LBL) could give explicit information on the dependence of indoor pollutant concentrations on housing classes, information that would be useful in deciding which houses on the exclusion list might be removed and which require more detailed investigation. As a similar, perhaps more far-reaching possibility, successful geographic characterization of radon sources could provide a firm basis for permitting tightening of most of the houses now excluded on the basis of radon criteria. Such characterization could occur from use of presently available data that map radon daughters on the basis of aerial measurements or from performance of new measurements oriented directly toward radon source and entry characteristics; as a practical matter, effective and inexpensive mapping may require a combination of these two approaches.

2. Studies performed for entities other than BPA could provide information directly relevant to use during or after weatherization. For example, new monitoring techniques might ease the problem of measurement in all or a sample of houses weatherized. New information on the effect of aging on formaldehyde emissions could affect mitigation strategies. As another example, testing of measures to reduce radon transport cheaply could directly affect the suitability of tightening certain houses (or of living in them regardless of tightening measures).

3. The fact that BPA is developing an environmental impact statement on the weatherization program could retrospectively alter the basis on which weatherization can occur. It may also mean that houses that are tightened on the premise that mitigation will take place later, if needed, may find the need for mitigation removed on an administrative basis. The prospect of a substantive examination of benefits and costs associated with the weatherization program could therefore be an important element in a methodology for removal of classes from the exclusion list. No longer would "no significant impact," whether individual or aggregate, be strictly required.

The next section discusses circumstances in which it might be desirable to add classes to the exclusion list, an action that might even be required in connection with removing classes. Such a linkage is clearly possible if the radon exclusion criteria are reformulated. For example, identification of areas with unusually high radon sources might then permit tightening of houses elsewhere (low radon sources) regardless of understructure type, but it might - at least initially - also require withholding of tightening measures from any houses (even with "permitted" understructures) in the high-radon areas. On the whole, though, this reorientation of the exclusion criteria would probably lead to a much smaller excluded class. Information required for such alteration of the exclusion list is discussed in the radon part of the next section.

## B. Adding Classes to the Exclusion List

A substantial question to be considered and that will necessarily arise is whether other classes ought to be added, on one basis or another. Before proceeding to alterations that are nominally additions to the exclusion list itself, we consider another possibility that is effectively such as addition, but that is actually a redesignation of what measures result in tightening of the building envelop.

As noted in section 1, weatherization measures are divided at this time into two classes: those that do not cause infiltration reduction and those that do. However, two of the measures that are now regarded as not significantly affecting infiltration rates actually could affect infiltration or ventilation rates. The first is "vapor barriers", which may include those introduced along with insulation. These barriers, although not causing gross infiltration reduction (such as might be associated with continuous plastic sheeting incorporated in the building envelope), can cause a modest reduction in rates. Secondly, the sealing of air ducts can cause a substantial reduction in ventilation rates, because - as often installed - ducts are leaky enough that, when the HVAC system in operating, ventilation rates are raised by forcing air through the leaks, at least when the ducts pass through unconditioned space (such as the crawlspace or attic). This leakage can be substantial enough that sealing ducts can have as great an effect on ventilation rates as all the nominally tightening measures taken together. A possible basis for treating this measure as was done in the Environmental Assessment is to take the point of view that the ducted heating system is not intended to provide ventilation via leaks, so that operating a leaky system results in a "looser" house than is intended or reasonable.

Even more significant, it appears, is the possibility of altering or adding to the classes already on the exclusion list itself. Such possible changes apply to every exclusion type that we have considered: radon, combustion products, and formaldehyde.

### Radon

As noted in the discussion of section 4, a more fundamental exclusion class for radon would be oriented around the extent to which local radium-bearing source actually emit radon. Identification of situations with large radon sources can be undertaken using a number of different approaches. It is possible, in fact, that tentative high-radon geographic areas could be chosen merely by analysis of the aerial uranium-survey data (NURE: National Uranium Resource Evaluation) accumulated over the last decade; this survey actually measured radon daughters, a significant indicator of radon sources. Undoubtedly, the results of such analysis would have to be verified by local measurements, but the effort required for such an approach could be small compared with an effort that did not use this information. Some of the local measurements that would be required are of the same kind as has been suggested to BPA by LBL researchers. (This question is treated at greater length in section 6.) An alternative approach is to design a geographic characterization program that is dependent on other programs (such as the regional IAQ field program) or that is independent (such as the reconnaissance type of survey suggested by GEOMET). Regardless of the basis, if radon sources or concentrations can be localized geographically, houses could be excluded on this basis, rather than using the criteria on the present exclusion list.

It is important to note that such a reorientation of exclusion criteria could result in the actual addition to the exclusion list of houses that are not presently on it. This is not a necessary outcome, but it is possible if - as suggested in section 4 - relatively high radon concentrations can occur independently of the present exclusion criteria. An alternative outcome, of course, is that only in geographic areas found to have high radon sources would the present exclusions be retained.

An alternative to source characterization as a means of finding high radon areas is simply to measure indoor concentrations as part of a widespread program, such as weatherization. Such measurements alone could actually form a basis, not only for decisions on particular houses, but for classification of high-radon areas. Such a measurement program could be a relatively inexpensive means of classifying areas, particularly if used together with successful classification based on the NURE data (since that, too, would be relatively inexpensive).

Combustion Products

The examples given here would be additional exclusions based on other combustion sources than now set forth in the exclusion criteria. We understand that the explicit purpose of this document is not to suggest such additions, but set out considerations pertinent to fireplaces and smoking for consistency and completeness.

Presently one of the largest excluded classes is that containing wood stoves. However, houses with fireplaces might also be excluded on the same basis. In many circumstances, fireplaces can contribute significantly to indoor concentrations of combustion products, including not only oxides of carbon and nitrogen, but also organics, often on airborne particulates. Indoor emissions from fireplaces may even exceed those from wood stoves.

One basis for permitting tightening of houses with fireplaces is that they may not be operated a substantial fraction of the time, so that their average effect on indoor air quality is not great. However, it does not appear that the Environmental Assessment explicitly considered fireplaces as potential sources of combustion products indoors.

The choice of whether or not to exclude houses with fireplaces must be made considering in some detail the various emissions that arise from their use, as well as the use patterns that are associated with fireplaces. A complicating issue is the extent to which infiltration reduction affects fireplace operation by reducing the manner in which the chimney draws (or by reducing the need for other heat sources) and, on the other hand, the extent to which operation increases the ventilation rate in the house.

A second combustion source that might have been considered for the the exclusion list is tobacco smokers. Smoking produces significant average concentrations and unusually high peak concentrations of a number of pollutants. Fortunately, the peak concentrations are not ordinarily affected as strongly by reductions in infiltration rate, because the peak concentration builds up too quickly to be affected by the exchange of indoor and outdoor air. This, however, is not the case for average concentrations or the rate at which peak concentrations decrease, both of which are strongly affected by the ventilation rate.

Smoking is, of course, not a house characteristic and, considering the general awareness of the adverse health effects of smoking, indicates explicitly a voluntary acceptance of increased risk. Moreover, exposure to smoke by children usually occurs as a result of someone else's choice, i.e., their parents. Moreover, even though it can be argued that the increase in this "voluntary" risk (due to infiltration reduction) is modest, subsequent owners of the house would have had no choice in, and may not be aware of, the tightening. This question is complicated even more by the issue of individual versus aggregate risk, because - even with tightening of the kind provided in the weatherization program - the house will very likely have an infiltration rate within the normal range. Hence a subsequent owner can as easily have bought an "unweatherized" house with similar air exchange characteristics. On the other hand, the aggregate effect of the program will have been to increase the <u>average</u> (as opposed to the individual) risk slightly by shifting the housing distribution in the direction of lower infiltration rates. The questions of individual versus average risk and of occupant responsibility are discussed in the next subsection.

<u>Formaldehyde</u>

As suggested in section 4, even houses other than those with urea-formaldehyde insulation can have significant airborne concentrations of formaldehyde. The most common source (aside from unvented combustion appliances) is use of plywood, particleboard, or certain carpet adhesives, as well as the introduction of new furniture. On the presumption that it is the building materials that constitute the most significant source, an exclusion could be based in principle on building age or on inspection (although it can be difficult to identify potential formaldehyde sources visually). An alternative to a source-oriented exclusion is to perform an integrated formaldehyde measurement, much as is also possible for radon. These two distinct approaches could be combined, e.g., by performing measurements in relatively new structures only.

C. <u>Risk, Standards, and Responsibility</u>

In examining how to avoid significant impacts on the population, several broad questions arise in the area of how such choices are made. The first obvious difficulty in this area is that specific criteria do not exist for determination of when indoor pollutant levels are excessive. In fact, even if specific standards existed for the general population in their homes, it is not clear that this in itself would remove the onus of responsibility for health effects among that portion of the population that is more sensitive than average to particular pollutants and hence is not adequately protected by any particular numerical guideline. In such situations, it often is necessary, as a practical matter, that the burden shift directly to the individual to make choices necessary to protect his or her own health. Moreover, even in cases where numerical guidelines exist, the response to exposure to the pollutant in question cannot be assumed to involve a threshold; in many cases, the associated risk simply decreases with dose, so that at some level the individual risk is deemed acceptable. However, this judgment must be made in the context of a particular option and, in any case, does not remove the responsibility for considering the aggregate risk that may accrue as the result of a program involving many people.

It is useful to consider the question of individual versus aggregate risk in another context, i.e., in deciding when a program has "no significant impact". The existence of any applicable concentration limit (whether a guideline or a standard with regulatory force) for a particular pollutant gives some indication of the extent to which individuals ought to be protected, assuming that the limit was developed for protection of individuals and not to control average exposures. Unfortunately, this distinction is often not drawn: occupational standards are usually designed for protection of individuals from excessive risk, but standards for the general population often make no distinction between individual limits and average limits, an obvious exception being radiation standards. Nonetheless, for cases (such as radiation doses) where the risk can be taken to be proportional to the dose, a simple approach is to take measures to assure that individuals are not caused excessive risk and, at the same time, to assure that the aggregate (or average) risk does not increase unduly. To assure "no significant impact", it may be necessary to assure that the average risk does not increase at all (while, of course, avoiding excessive individual risk). This perspective will be important in fashioning an approach to altering the exclusion criteria based on radon exposures. Whether it can be extended to other pollutants is not clear.

A final question, related to much of the discussion in section 5, is the extent to which, in ambiguous cases, the occupants may be relied on to make their own judgments of what is acceptable, as well as to take actions that will limit their own exposures, to the degree they wish. Several examples are obvious:

1. Use of a ventilation hood is known to have a substantial effect in reducing the spread of gas stove emissions into the general living space (and even the kitchen). The exclusion against gas stoves could, in principle, be removed on this basis.

2. Smoking is a significant indoor pollutant but has a clearly voluntary component. Moreover, subsequent house occupants may have different smoking habits than those when infiltration reduction measures are implemented. The fact that households with smokers are not on the exclusion list can only be based on the "voluntary" nature of this practice.

3. The question of how other combustion sources contribute to indoor pollutant levels also depends highly on practices of the occupants. Certainly emissions from wood stoves can depend on stoking procedures. The same is also true of fireplaces. Moreover, in either of these cases, the amount of contaminants actually produced depends on how often the stove or fireplace is employed, clearly a matter of choice (although the use factor might be lower and the variation higher for fireplaces than for wood stoves).

## 6. METHODOLOGY FOR ALTERING THE EXCLUSION LIST

This section outlines the essential elements that might be associated with alteration of the list of housing classes excluded from the infiltration-reducing elements of the weatherization program. The outline emphasizes grounds for removal or reduction of the presently excluded classes. In a number of cases, we also indicate, consistent with the discussion of the last section, possible additions or expansions of housing classes on the list, sometimes as a part of reformulations to reduce the total number of excluded houses.

The three essential aspects of alterations of the list are: development of better information characterizing sources or concentrations; adoption of criteria for judgement of acceptability; and - where appropriate - selection of mitigating measures. Few of these elements are now available for most of the classes now, or potentially, excluded.

In spite of this, it is important to realize that tentative choices and strategic plans can be adopted sooner than full development of information, criteria, or mitigating measures, provided that the plan provides an adequate course of action to be associated with the results of such development. As a result, the question of sequence and timing is an important component in the delineation of a methodology for alteration of the exclusion list.

### A. Radon Exclusions

The potential for reorientation of the radon exclusions is treated substantially in sections 4 and 5. This section indicates the specific actions that might be associated with such alteration of the radon exclusion criteria.

#### Information Development

Two related approaches are possible in removing houses or housing classes from the radon portion of the exclusion list. One is based on acquiring information on individual houses, the other on houses by group or area. The measurements required may be oriented toward indoor monitoring or source monitoring.

Indoor monitoring - individual houses can be monitored using commercially-available integrating radon detectors. These should be used as basis for deciding whether to tighten or, if tightening has already been performed, whether to introduce mitigating measures. As such monitoring proceeds, the accumulated data could also be used for characterizing areas in respect to high-radon potential, to the extent such characterization is possible. Use of indoor monitoring for such purposes can therefore connect with area studies, below.

Source monitoring - in principle, individual sites could be monitored to determine source strengths, particularly for radon from soil. This approach would be more expensive than indoor monitoring as a basis for decisions on individual houses, even assuming adequate methods are available. On the other hand, used less extensively, i.e., at only a selection of sites, such data could constitute a basis for geographic characterization of radon source strengths, particularly if used together with other data, as discussed below. Finally, some effort could be made to sample water and building materials to assess the potential importance of these sources in the BPA area.

Geographic characterization - areas could begin to be classified as far as radon sources or indoor concentrations, either on the basis of accumulated measurements that are otherwise intended to characterize individual houses or on the basis of area studies specifically designed for this purpose. Furthermore, the individual indoor or source measurements can be used to support and validate classifications based on the area studies. These studies could be actual monitoring programs (such as the regional IAQ field program or systematic geologic studies) or analyses of presently available, but unutilized, geologic or radiometric data. Of particular importance in the last category are the data resulting from the National Uranium Resource Evaluation (NURE), which performed aerial surveys of the United States, using sodium iodide detectors to measure gamma rays from various radionuclides, including radon daughters. Only a minimal effort would be required to examine the success with which the NURE data can be used for geographic characterization of radon source strengths. If success appears likely, such classification could proceed rapidly, supported by modest validation efforts using data from other programs (e.g., the regional IAQ study and data accumulated in the course of the weatherization program) and a small amount of newly-accumulated source data. An alternative type of area study is the search and reconnaissance approach proposed by GEOMET. However, it appears that use of the NURE data would be much more efficient in terms of time and money.

To summarize information development, a useful near-term approach will be to begin indoor monitoring of excluded houses, while devoting modest efforts to soil source characterization and a minor (but rapid) corresponding effort to examination of the suitability of the NURE data for geographic characterization. A sampling of water and building materials could also be made to see whether these excluded classes can be removed on this basis, considering that geographic characterization should also cover these classes in large part. (Note: in any area in which indoor monitoring of excluded houses is performed, it would also be extremely valuable to monitor a smaller number of permitted houses in order to determine directly the effect of differences in understructure.)

As noted, the timing of removal from the exclusion list can vary greatly, as can development of information, criteria, or mitigation. There are two key choices in respect to information: first whether individual monitoring takes place before or after tightening (and at what time mitigation takes place) and, secondly, how this helps in the development of geographic classifications. Although other possibilities exist, the most advantageous approach appears to be to begin tightening and monitoring in parallel, with a commitment to retrospective mitigation as necessary, and to begin accumulation of a data base both from these results and from modest source and area studies, leading to geographic classification. The monitoring techniques necessary for this approach are, for the most part, available, the one exception being the need for testing of some source monitoring techniques. A more critical need is the adoption of criteria for judgement of when tightening and/or mitigation is appropriate.

## Criteria

The principal objective of the exclusion criteria is to assure that "no significant impact" arises from tightening. Removal of the exclusions depend on assurance of no significant impact, to individuals or to the affected group in aggregate. Criteria developed for this assurance could be modified subsequently on the basis of subsequent environmental impact assessment, particularly the expected Environmental Impact Statement.

No significant individual impact - in a number of special circumstances in the United States and Canada, suggested limits on individual houses have been placed in the vicinity of 0.015-0.02 WL, the equivalent of 2 to 10 pCi/l, depending on the equilibrium factor, or 3-4 pCi/l, assuming a factor of 0.5. These guidelines were developed for communities in mining areas, presumably subject to higher than average concentrations, but it is now known that apparently ordinary areas throughout the United States can have significant numbers of houses with concentrations exceeding 3 or 4 pCi/l. Moreover, these guidelines were usually developed without making a distinction between individual and average concentration guidelines. As suggested above, a more carefully considered approach should make this distinction. It is therefore suggested that average concentrations in "ordinary" areas be expected to be maintained well below 3-4 pCi/l (see below) but that some portion of houses be expected to be above this limit. It is thought that several to ten percent or more of U.S. houses exceed this limit, so that a range of 5 to 10% exceeding 3 pCi/l might be taken to be acceptable. On the other hand, substantially fewer should be expected to exceed, say, 6 pCi/l and - at some point - the level is so high, say in the vicinity of 10 pCi/l, that mitigation would automatically be recommended, independently of the issue of tightening.

Criteria for acceptability of individual risk therefore depend on the program sequence. If a measurement is performed before tightening, houses not exceeding 3-4 pCi/l could be candidates for tightening, in the expectation that most would remain below and only the few in the immediate vicinity of 3 pCi/l would exceed this level, but they would still be less than 5-6 pCi/l. If measurements are performed after infiltration reduction, then the result might be deemed acceptable if no more than 10% exceed 3 pCi/l and up to about 1% exceed 6 pCi/l. In either case, remedial action might be offered for cases exceeding 10 pCi/l, whether or not they have been tightened (thereby helping to assure no aggregate impact, discussed below).

It should be noted that these criteria (and those following) are stated in terms of radon concentration (pCi/l) because such measurements can be performed more reliably than radon daughter measurements. The specific numerical guidelines stated are consistent both with past practice in special cases and with current knowledge of the distribution of radon concentrations in the United States. They are intended to apply to the "living space" of a house. In some cases, this designation may be ambiguous, particularly in houses with finished basements, where radon concentrations are likely to be higher than elsewhere in the house. (In such cases, it may be appropriate to average values in the basement and upstairs, with a weighting factor based on area.)

No significant aggregate impact - that average exposures do not increase as a result of tightening can be assured by performing mitigation in a sufficient number of houses with high concentrations to offset the small increases anticipated in the larger number of houses with low concentrations. The mitigating measures can be introduced after tightening or along with it. One advantage to retrospective mitigation is that sufficient data can accumulate, either in a particular area or in the entire BPA region, to form a basis for understanding what average levels are and at what level mitigation should begin. It is suggested that at some level (such as 10 pCi/l) further investigation (such as an integrating radon-daughter measurement) should be advised in any case, with the prospect that mitigation measures would always be recommended if average daughter concentrations exceed some corresponding level (say 0.05 WL). Depending on the actual distribution found, mitigation could occur at even lower levels, but probably not lower in any case than 3 pCi/l. The objective of mitigation at these relatively low levels would be to avoid increases in average concentrations, and - for areas with low concentrations - it is possible that an environmental impact statement could serve as a basis for removing a requirement for mitigation at very low levels. On the other hand, as a tradeoff for using this dual (individual-average) approach, care should be taken that in no substantial group averages are raised above an acceptable average level, say 1-2 pCi/l. Since data are most conveniently accumulated by area within the BPA region, some areas may be found that already exceed such an average concentration; in such a case, tightening measures would presumably not proceed (and, as indicated above, remedial action would be taken in houses with excessive concentrations).

Environmental impact statement - as just noted, for areas with relatively low radon concentrations, the environmental impact statement being prepared by BPA may serve as adequate grounds for removing the commitment to no increase in average concentrations, provided that this increase is small enough to be acceptable, considering other costs and benefits of tightening.

## Mitigation

A number of techniques discussed in section 3 can be used for controlling radon concentrations in houses in which mitigation is advised. These techniques fall into the three broad control categories: source control, ventilation, and air cleaning.

Source control - controlling radon from under the house is most easily accomplished when a full crawlspace exists, in which case provision of adequate ventilation (including, in extreme cases, forced ventilation) and/or installation of vapor barriers may substantially reduce entry of radon into the house itself. These techniques may be supplemented by other measures, including installation of vent pipes. (These techniques need systematic testing, both in a controllable test structure and in actual houses.) For houses built on slabs or with basements, source control depends on addition of sealants or barriers. Since entry probably occurs primarily via cracks and other openings, sealants can be most effective in principle, but identification of entry points is required. This might be accomplished using a radon "sniffer," but this technique needs to be developed further. Moreover, the effectiveness of sealants needs to be tested. Finally, radon in household water may be controlled by aeration or storage before entry into the house. Systematic testing of source identification and reduction techniques has not occurred. Two promising avenues for examination of these techniques are in conjunction with the radon entry and source monitoring studies being performed by LBL and in conjunction with possible remedial actions for high-radon houses in Butte, Montana (identified by EPA/HUD efforts).

Ventilation - use of mechanical ventilators with air-to-air heat exchangers (AAHX) is one means of providing energy-efficient ventilation. For radon control, these devices can be deployed in a number of different ways, including installation not only as part of a duct system or in room walls (now being tested at LBL), but also in basements. In this last configuration, the AAHX removes much of the radon before it can enter the rest of the house, and has the added advantage that basements are often more open than main floors, thereby increasing the effectiveness with which the entire space is ventilated.

Air cleaning - radon-daughter exposures may be subject to adequate control by filtration or other active systems that remove particulates from the air. Daughters may also be removed, to some degree, merely by circulation of air within the house. Detailed study of daughter removal mechanisms and the effectiveness of air cleaning devices is being undertaken by a number of laboratories, particularly LBL and some European laboratories.

The radon control techniques that are most promising and best understood are those based on source control and on air-to-air heat exchangers (in various configurations). However, each of these techniques requires further testing to elucidate the manner in which they should be applied in various situations.

## B. Wood Stoves and Unvented Combustion Appliances

Wood stoves and unvented combustion appliances can have adverse impacts on indoor air pollution levels. Unvented combustion appliances will not be dealt with in this section since, in general, the use of such appliances causes elevated $NO_2$ levels, exceeding long-term outdoor standards and, in some cases, short-term standards. The only major exception would be a gas range where a range hood was employed, although BPA could not insure that the range hood was used. In any case, only a small percentage of households in the BPA region have unvented gas appliances.

The two basic options for dealing with the exclusion on wood stoves are (1) to rely on current knowledge and measure several pollutant levels in each home during periods of "heavy" wood stove use ("heavy" could be occupant defined on an individual basis or could be defined by criteria that, still, depend on occupant behavior) and (2) to conduct further research to better specify which pollutants are of concern and to develop control strategies in houses with high pollution levels. The first approach does not provide for mitigation measures since such measures have not been identified. In any case, it does not appear possible, presently, to delineate a cost-effective methodology (including information, criteria, and mitigation measures) that is appropriate to removal of any portion of this class from the exclusion list. Much of the same difficulties and information needs apply to houses with fireplaces.

In proceeding on the basis of present knowledge, there are two important measurable parameters in assessing the impact of wood stoves on indoor air quality: the indoor concentrations of pollutants during heavy wood stove use and the indoor/outdoor pollution ratios. With these two parameters and the house air exchange rate, assessment could be made of whether or not the indoor pollution levels in a home are too high, as well as the role the wood stove plays in affecting these levels. With this information, a strategy to assess the impact of a particular wood stove on the indoor air quality and whether or not to exclude it from the air tightening program is relatively straightforward in theory.

The basic strategy would be to measure both the indoor and outdoor levels of key pollutants and the air exchange rate during a period of heavy wood stove use. An estimate of the contribution of indoor air pollution from the wood stove can be made by using the measured parameters as input to a simple indoor air quality model. If it is true that the indoor pollutant levels are above a prespecified level (selected to be in the vicinity of the appropriate standard) and that the wood stove contributed to these indoor levels, then no air tightening measures would be performed on the house. This would not exclude the house from being included in air tightening programs if mitigating measures were successfully implemented. This presumes, of course, that the type of measurement performed and the implied exposure corresponds properly to some applicable standard.

From a practical point of view, several questions arise, which indicates how far we are from specifying the required information, criteria, and mitigation:

1. Which pollutants are important?

2. What indoor concentration should <u>not</u> be exceeded and for what period?

3. What is the most economical method to measure the pollutants of concern?

4. What control strategies can be employed to keep the wood stove pollutants from entering the living space?

In answering the first question, data from outdoor studies can be exploited. In general, wood stoves emit a different mix of pollutants at different combustion temperatures and different levels of excess oxygen. At low combustion temperatures (fuel combustion rates below approximately 3 kg/hr), CO, total particulate, hydrocarbon, and POM emissions all increase dramatically. POM emissions drop at temperatures below 500 $^{o}C$ while $NO_x$ emissions increase with increased temperature. The ratio of CO to particulate emissions from wood stoves varies from 1 to 200. This implies that at an RSP concentration of 50 $\mu g/m^3$ the corresponding CO concentration would range from 0.04 to 9 ppm. (RSP concentrations are used since combustion aerosols are typically in the respirable range.) The POM/particulate emission mass ratios vary from approximately 0.002 to 0.04. Thus an indoor RSP concentration of 50 $\mu g/m^3$ would correspond to POM concentrations ranging from 0.1 to 2 $\mu g/m^3$. $NO_x$/particulate emission mass ratios vary from about 0.01 to 4, implying $NO_x$ concentrations between 0.2 and 100 ppb as $NO_2$ when RSP concentrations are 50 $\mu g/m^3$. Particulate (and RSP) emissions vary over two orders of magnitude -- from approximately 0.5 g/kg to over 50 g/kg.

The previous "order of magnitude" analysis shows that, in some cases, long-term outdoor standards for CO, $NO_2$, and suspended particles -- 9 ppm, 50 ppb, and 75 $\mu g/m^3$, respectively -- can probably be exceeded by each pollutant, independently of whether the other pollutants also exceed standards. POM considerations complicate the issue substantially.

Because of the potential carcinogenicity of POM, GEOMET, in a recent report to BPA, suggested a level of concern for POM (or PAH) of 0.3 $ng/m^3$, well below levels that would be expected indoors. GEOMET set its proposed level of concern merely by chosing the minimum detectable level. The implication of adopting this level would therefore be that, if any particulate sample from a house contained any measurable amount of POM, the house could not participate in BPA's house tightening program. Based on the ratios given above, if a house had a wood-stove generated particulate level of 0.5 $\mu g/m^3$, a POM level from 1.0 to 20.0 $ng/m^3$ would be expected, well above GEOMET's proposed level of concern. It does not appear possible (if only because of stoking) for a house where a wood stove is used to have wood-stove generated particulate level less than 1 $\mu g/m^3$. Measured values range from approximately 30 to

140 $\mu g/m^3$. Therefore, if GEOMET's level of concern were used, essentially no houses that use indoor wood stoves would be eligible for house tightening measures. Therefore, either a higher level of concern must be used or houses with wood stoves will remain untightened. Since no current standards apply to POM, the remainder of this discussion will ignore POM. On the other hand, if a specific POM standard is developed, POM could be treated just like CO, $NO_2$, or respirable particles, discussed in this section.

An altered wood-stove exclusion criterion based on current knowledge would consider particulate, $NO_2$, and CO levels. The critical pollutant levels, above which no action would be taken, would probably be an average concentration specified to be in the vicinity of long-term outdoor standards. The precise proportion of the outdoor standard to be taken as an action level depends on estimates of infiltration reduction from air tightening measures, accuracy of instrumentation used, and estimates of variability in pollutant concentrations.

This initial approach, depending on current knowledge only, is measurement intensive and does not include provisions for use of control measures to include houses with wood stoves that emit "too much" pollution. In fact, of the three pollutants of concern -- RSP, CO, and $NO_2$ (or $NO_x$) -- only $NO_2$ (and $NO_x$) can be measured passively and economically. Current measurement techniques for RSP and CO would almost surely prohibit large-scale measurements of these pollutants. In passing, it is important to realize that many of these same questions apply to fireplaces.

Implementation of a research program on wood stoves and fireplaces is the alternative to an immediate attempt to change the wood stove exclusions; such work would serve to answer some of the questions raised above and to evaluate the procedures necessary to implement changes in the exclusion list.

One research component would be to characterize emissions of woodstoves (and fireplaces) more fully. This would involve both laboratory studies and field work. The first is already being undertaken for BPA. The second would involve not only integrating measurements, but time-dependent studies characterizing these sources as they are actually used. A field research program using real-time air quality monitors could:

1. identify the magnitude and mix of pollutants from wood appliances in actual residences;

2. identify paths through which the pollutants enter the living space;

3. identify the effects of burn rates, stove loadings, excess air, creosote build-up, and flue drafts on indoor emissions and the mix of pollutants emitted;

4. identify and evaluate control strategies such as sealing pollutant leakage paths and increasing flue drafts.

The basic goals of these studies would be to reduce the number of pollutants that must be measured in houses with wood stoves and identify control strategies. One possible outcome of such a study might be that RSP, CO, and $NO_2$ must all be measured in homes with wood-burning appliances. This very real possibility should encourage BPA to pursue the development of inexpensive -- optimally passive -- monitors for RSP and CO concurrent with an intensive wood stove field study. Of course, another option is to ignore houses with wood stoves in any air tightening program.

Ultimately, it is hoped that characterization studies, monitor development, and mitigation testing will provide an adequate basis for developing information, criteria, and mitigating strategies appropriate, in the near term, for removal of some classes of houses with wood-burning stoves from the exclusion list and, in the long term, for developing a comprehensive approach to tightening residences with wood-burning appliances. This question is complicated by the intrinsic difficulties with wood-burning from an environmental point of view: that many substances are produced and that quantities are relatively large and highly variable, whether in the context of the weatherization program or not. The development of "indicator" pollutants and of strategies for assuring integrity of the stove-flue system over operating lifetimes are probably key elements in controlling indoor pollution from wood burning.

## C. Urea-Formaldehyde Insulation and Other Formaldehyde Sources

The main source of formaldehyde identified in the Environmental Assessment was urea-formaldehyde foam insulation. It might be desirable simply to retain this exclusion. On the other hand, it is probable that a substantial number of homes with urea-formaldehyde insulation do not have levels of formaldehyde different from other houses of the same age, largely because homes have significant formaldehyde sources other than insulation. Because, in either case, the levels may be low enough to be deemed acceptable, by some standard, this section indicates an approach to modification of the formaldehyde exclusions that is based on use of newly available and inexpensive formaldehyde monitors.

### Information

The principal elements in modification of this exclusion is the determination of which houses have excessive formaldehyde levels and which houses have "low" formaldehyde levels. This information can be obtained, on a house-by-house basis, by use of an integrating monitor, such as is now being tested by LBL. A decision will have to be made as to deployment and period of integration, but there is no barrier in principle to use of this approach for selection of (presumably the bulk of) houses that have relatively low formaldehyde concentrations. It appears that a one-week integrated measurement of formaldehyde would be adequate for this "screening" purpose. Canada has started such a program and is using one-week sampling times. Wide-scale measurements would lead to identification of houses that have very high concentrations, in which mitigating actions could then be recommended; this could be used to offset the minor increases expected in houses with low concentrations, similar to the approach suggested for the radon exclusions.

### Criteria

The choice of a criterion for selection of houses that can be tightened is ambiguous, since no standards have been formulated for general application to the indoor environment. Based on current information, it would be generally accepted that levels above 1 ppm are not acceptable for the general population. In fact standards as low as 100 ppb have been proposed or accepted in a number of cases (and is the standard used by Canada). Accepting a guideline as low as this level for houses with urea-formaldehyde insulation would carry the implication that other houses with concentrations higher than this level should also not be tightened. This will probably include many newer homes that include substantial amounts of formaldehyde-emitting building materials and furnishings. One difficulty, of course, with any specific criterion is that the emission rates from most formaldehyde source materials are expected to decrease as the material ages. Specific criteria could consider this decrease and design the decision (and perhaps information-gathering) framework to take advantage of it. For example two standards might be developed, one for new houses where formaldehyde levels are expected to decrease and one for older houses where formaldehyde levels are presumably more stable.

### Mitigation

At this time, it is not feasible to recommend specific wide-scale economical mitigating measures for formaldehyde, with the possible exception of houses that exceed a high level, e.g., several hundred ppb. For houses with exceptional levels, occupants should be advised to take mitigating measures. This could merely entail having higher-than-average levels of natural ventilation or using an air-to-air heat exchanger. However, other mitigating measures such as ammonia fumigation or dehumidification should be studied and implemented if appropriate. To some degree (or for some occupants), mitigation measures may also be appropriate in houses with intermediate formaldehyde levels (100 to several hundred ppb). A component of this program should determine the extent to which indoor concentrations decrease with time.

Thus, as part of the weatherization program, consideration should be given to the possibility of implementing a program of measurement to identify which homes with urea-formaldehyde insulation (or homes with other potentially significant formaldehyde sources) actually have high formaldehyde concentrations. It is also appropriate that such measurements be extended to newer homes, which also have a good chance of having significant formaldehyde sources. The monitors required for accomplishing this inexpensively are now becoming available.

## D. Other Excluded Homes

The principal categories excluded, in addition to those already discussed, are mobile homes and other homes that do not use frame construction. The set of weatherization measures appropriate to these homes, at least for mobile homes, are different from those considered in this report. Deciding how to remove such housing categories from the exclusion list can follow a more careful definition of the applicability of various weatherization measures to these homes.

E. General Notes

It is useful to mention two general questions that pertain directly to the elements mentioned above in the methodologies for each exclusion class. One pertains to the suitability of actual monitoring as a basis for judgment (with the related issue of how monitoring costs compare with the benefits of infiltration reduction); the other is the extent to which mitigation measures suggested or possible in connection with the various excluded classes need further development and testing.

Monitoring Costs and Mitigation Benefits

The two pollutants for which inexpensive integrating monitoring devices are available and for which monitoring could lead directly to removal or reduction of excluded classes are radon and formaldehyde. In each of these cases, the basic monitoring technique costs in the range of $10 to $20 per sample and the cost of each sample, including handling and program management, is likely to be two or three times this number. As a result, for $30 to $60, each of these two pollutants could be measures. Because this cost is fairly modest, it is not unreasonable to adopt a monitoring-based approach to deciding which houses (or classes of houses) may be removed from the exclusion list.

Making such a decision, however, depends on the benefits expected to accrue as a result of tightening. The benefit in terms of present value depends on many factors that are beyond the scope of this report. However, what can be said simply is that if the expected present value of tightening exceeds the cost of monitoring (e.g., $50) divided by the probability of removal from the exclusion list then it is advantageous to perform measurements in each house in question. The advantage is even greater, of course, if data accumulated in various classes serve as a basis for making decisions to remove all or portions of classes.

Estimating the present value of tightening requires knowledge of the cost of tightening, the amount of energy saved as a result, and the value placed on this energy. (Knowledge of discount rates and fuel price escalation are also required.) If, for example, the value of tightening is relatively large, particularly if tightening is accomplished relatively efficiently, and the value of energy saved is taken to be the marginal value, then monitoring costs would be considered to be unimportant. If, in contrast, tightening is relatively costly and the electrical usage avoided is assigned a relatively low value (e.g., average prices in the BPA area), then the value of tightening is relatively little, perhaps in the same range as the cost of simple monitoring.

Because the cost of performing radon and formaldehyde integrated measurements is relatively little, the methodology indicated above has included such measurements as an integral part of the development of information needed as grounds for removing houses or classes of houses from the exclusion list.

Further Development of Mitigating Measures

In connection with the various excluded classes, we have indicated mitigation techniques that might be appropriate to the pollutant of concern. In virtually every case, further testing or development of the techniques is needed to indicate in more detail how well they perform in various circumstances. It is useful to summarize those needs, indicating in addition several that were not treated explicitly above (such as the formaldehyde-mitigating techniques). In some cases, the cost-effectiveness of these measures has been examined, but in many the technical effectiveness deserves further investigation. In most cases a combination of laboratory and field studies is required. In any case, the aggregate cost of mitigation for a specific source category should be less than the aggregate energy savings from house tightening.

1. The ventilation efficiency of mechanical ventilation systems with air-to-air heat exchangers needs to be studied for cases where these devices are installed in windows. These studies are now being performed at LBL.

2. The suitability of mechanical ventilation of crawlspaces as means to reduce ingress to radon ought to be investigated. In addition, the effect of mechanical ventilation (including, as one possibility, air-to-air heat exchangers) on radon entry via basements needs study. As a basis for these investigations, study of the location and mechanism for radon entry into residences should be undertaken.

3. A choice needs to be made about depending on range hoods as mitigation for combustion emissions from gas stoves. This may involve depending on occupants to use hoods, but the other possibility - which would require study - is to install a mechanism for automatic operation of the hood.

4. Studies of the effect of dehumidification and ammonia fumigation as formaldehyde control techniques are needed.

5. Air washing techniques for removal of formaldehyde need study and development.

6. The potential use of exhaust air heat pumps as indoor pollutant control devices needs investigation.

7. Electrostatic precipitators and other particulate removal devices need testing. Parallel development of inexpensive particulate monitoring devices would be extremely useful.

8. The effect of particulate removal devices and air movement on radon daughter levels (and states of attachment) needs investigation.

These control approaches are in various stages of development. Many of them are essential to a sound basis for removal of various classes from the exclusion list, and - in any case - are required to the extent that houses with excessively high pollutant concentrations are identified as a result of the weatherization or other programs.

Acknowledgement

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# APPENDIX A - HEALTH STANDARDS AND GUIDELINES

Tables A-1 through A-4 list a number of air quality standards. Table A-1 illustrates specialized radon standards, Table A-2 recommended and promulgated formaldehyde standards, Table A-3 U.S. outdoor air quality standards and Table A-4 U.S. occupational standards.

Table A-1. Radon Standards

| Country | Average Annual Working Level | Action | Status |
|---|---|---|---|
| **Indoor:** | | | |
| United States: | | | |
| Sites contaminanted by uranium-processing | 0.015 | Cost-benefit analysis required when level is only slightly above maximum | Interim and proposed clean-up standard for buildings contaminanted by uranium-processing sites |
| Phosphate land, Florida: | | | |
| Existing housing | <0.02 | Reduce to as low as reasonably achievable | Recommendation to governor of Florida |
| | >0.02 | Action indicated | |
| New housing | Normal indoor background | -- | |
| Canada: | >0.01 | Investigate | |
| | >0.02 | Primary action criterion | Policy statement by AECB |
| | >0.15 | Prompt action | |
| Sweden: | | | |
| Max., existing buildings | 0.054[a] | -- | Proposed standard |
| Max., new buildings | 0.019[a] | -- | |
| **Occupational:** | | | |
| U.S. miners: | | | |
| Instantaneous maximum | 1 WL | -- | MSHA standard |
| Maximal cumulative dose | 4 WLM/yr[b] | | |

[a]The actual limits are given in terms of "equivalent equilibrium concentration" and are 200 $Bq/m^3$ and 70 $Bq/m^3$, respectively.

[b]Period is a calendar year. Dose for any month is defined as cumulative dose in WL-h divided by 173. Assuming 173 h worked per month (i.e., 2,076 h/yr), average annual working level is 1/3 WL.

Table A-2. Formaldehyde Standards

| | Level (0.1 ppm ≅ 120 $\mu g/m^3$) | Status | Ref. |
|---|---|---|---|
| AMBIENT AIR | | | |
| U.S. | 0.1 ppm max | Recommended by AIHA | 1 |
| INDOOR AIR | | | |
| U.S. | | | |
| California | 0.2 ppm | Proposed | 2 |
| Minnesota | 0.5 ppm | Proposed emergency standard | 3 |
| Wisconsin | 0.4 ppm | Proposed effective 05/1/80 | 4 |
| | 0.2 ppm | Proposed effective 05/1/81 | 4 |
| Denmark | 0.12 ppm max | Recommended | 5 |
| Netherlands | 0.1 ppm max | Recommended by Ministers of Housing and Health | 6 |
| Sweden | 0.1 ppm max, new buildings<br>0.4 ppm min, old buildings (a)<br>0.7 ppm max, old buildings (a) | Proposed by the National Board of Health and Welfare | 7 |
| Federal Republic of Germany | 0.1 ppm max | Recommended by the Ministry of Health | 8 |
| OCCUPATIONAL AIR | | | |
| U.S. | 3 ppm, 8 hr time-weighted average | Promulgated by OSHA | 9 |
| | 5 ppm, ceiling | Promulgated by OSHA | 9 |
| | 2 ppm, threshold limit value | Recommended by ACGIH | 10 |
| | 1 ppm, 30 minute max | Recommended by NIOSH | 11 |

References

1. American Industrial Hygiene Association, "Community Air Quality Guides, Aldehydes," Am. Ind. Hyg. Assoc. J., 29:606 (1968).

2. State of California, Assembly Bill No. 2586, as amended in Assembly April 16, 1980.

3. News release from the Minnesota Department of Health, May 22, 1980.

4. State of Wisconsin, Department of Labor and Human Relations, Safety and Buildings Division. Proposed Formaldehyde Rule, Wis. Adm. Code, November 1979. (Not enacted as of July 11, 1980).

5. I. Andersen, "Formaldehyde in the Indoor Environment - Health Implications and Setting of Standards," paper presented at the Indoor Climate Symposium, Copenhagen, Denmark, August 30-September 2, 1978.

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7. H. Wahren, "Formaldehyde Indoor Air Standards in Sweden," paper presented at the CPSC Technical Workshop on Formaldehyde, Washington, D.C., April 9-11, 1980.

8. Dr. Bernd Seifert, Institut fur Wasser-, Boden- und Lufthygiene des Bundesgesundheitsamtes, Berlin, Germany, private communication, May, 1978.

9. U.S. Occupational Safety and Health Administration, Occupational Safety and Health Standards, Hazardous Materials, 29 CFR 1910.1000, July 1, 1979.

10. "TLVs - Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1977," American Conference of Governmental Industrial Hygienists, P.O. Box 1937, Cincinnati, OH 45201 (1977).

11. National Institute for Occupational Safety and Health, Criteria for a Recommended Standard...Occupational Exposure to Formaldehyde, NIOSH Publication No. 77-126 (December, 1976).

Note

(a) 0.4 to 0.7 ppm is a border area. Levels higher than 0.7 ppm do not meet the standard. Levels lower than 0.4 ppm do meet the standard. Levels within the border area do not meet the standard if the dwellers complain. In recently built houses, 0.7 pm should be acceptable during the first six months.

Table A-3. National Primary Ambient-Air Quality Standards as Set by the U.S. Environmental Protection Agency

| Contaminant | Long Term | | Short Term | |
|---|---|---|---|---|
| | Concentration, μg$^3$ | Averaging Time | Concentration, μg/m$^3$ | Averaging Time |
| Sulfur oxides, measured as Sulfur dioxide | 80 | 1 yr | 365[a] | 24 h |
| Particulate matter | 75[b] | 1 yr | 260[a] | 24 h |
| Carbon monoxide | -- | -- | 10,000[a]<br>40,000[a] | 8 h<br>1 h |
| Ozone | -- | -- | 235[c] | 1 h |
| Hydrocarbons | -- | -- | 160 | 3 h[d] |
| Nitrogen dioxide | 100 | 1 yr | -- | -- |
| Lead | 1.5 | 3 mo[e] | -- | -- |

[a]May be exceeded only once per year.

[b]Geometric mean.

[c]Standard is attained when expected number of days per calendar year with maximal hourly average concentrations above 0.12 ppm (235 μg/m$^3$) is equal to or less than 1, as determined by Appendix H to subchapter C, 40 CFR 50.

[d]3-h period is 6 a.m. to 9 a.m.

[e]3-mo period is a calendar quarter.

Table A-4. Selected Occupational-Safety and -Health Standards as Set by U.S. Occupational Safety and Health Administration[a]

| Contaminant | Concentration,[b] ppm | Concentration,[b] $mg/m^3$ |
|---|---|---|
| Carbon dioxide | 5,000 | 9,000 |
| Carbon monoxide | 50 | 55 |
| Formaldehyde | 3 | 3.6 |
| Nitric oxide | 25 | 30 |
| Nitrogen dioxide | 5 | 9 |
| Ozone | 0.1 | 0.2 |
| Sulfur dioxide | 5 | 13 |
| Inert or nuisance dust, respirable fraction | -- | 5 |
| Asbestos | c | c |

[a]Data from 29 CFR 1910.1000, Occupational Safety and Health Administration, July, 1979.

[b]8-h time-weighted averages, except values for nitrogen dioxide, which are ceiling values.

[c]Fewer than two fibers longer than 5 μm per cubic centimeter.

## APPENDIX B - A MODEL FOR ESTIMATING THE EFFECT OF CONTROL TECHNIQUES

An equation describing the mass balance for a pollutant can sometimes be utilized to estimate the impact of control techniques on indoor pollutant levels. The mass balance equations presented below are similar to equations commonly used for indoor air quality modeling (see for example reference 20); however, the equations have been modified to incorporate the effects of indoor air quality control techniques. The equations are essentially unverified and are based upon a number of simplifying assumptions, including the assumption of perfect mixing of the indoor air. The initial equation for pollutant mass balance is:

$$\frac{dC_i}{dt} = (1 - F)\frac{S}{V} + (P_1 a_1 + P_2 a_2)C_o - (a_1 + a_2 + K + \eta Q)C_i \quad (1)$$

where:

$C_i$ = indoor pollutant concentration

t = time variable

F = correction factor for effect of control technique on pollutant source strength

S = pollutant source strength (i.e., rate at which pollutant enters the indoor air) before control measure is implemented

V = house volume

$P_1$ = fraction of outdoor pollutant that penetrates building shell
$a_1$ = air change rate for ventilation air that enters through the building envelope

$P_2$ = fraction of outdoor pollutant that penetrates mechanical ventilation system

$a_2$ = air change rate for ventilation air that enters through mechanical ventilation system

$C_o$ = outdoor pollutant concentration

K = rate of pollutant removal by interaction with indoor surfaces

$\eta$ = efficiency of air cleaning device (i.e., unity minus the outlet pollutant concentration/$C_i$)

Q = air change rate for air passing through an air cleaning device

Assuming an initial concentration $C_i(0)$ and assuming that all parameters except $C_i$ are constant over the time period of interest yields the following equation for $C_i(t)$:

$$C_i(t) = \frac{(P_1a_1 + P_2a_2)C_o + (1 - F)\,S/V}{(a_1 + a_2 + K + \eta Q)}\left[1 - e^{-(a_1 + a_2 + K + \eta Q)t}\right] + C_i(o)e^{-(a_1 + a_2 + K + \eta Q)t} \qquad (2)$$

If no indoor air quality control techniques have been employed, the indoor pollutant concentration $\dot{C}_i$ is obtained by setting $a_2$, F, and Q equal to zero with the following result:

$$\dot{C}_i(t) = \frac{P_1a_1C_o + S/V}{a_1 + K}\left[1 - e^{-(a_1 + K)t}\right] + C_i(o)e^{-(a_1 + K)t} \qquad (3)$$

The impact of a control technique could be assessed by comparing $C_i(t)$ from equation 2 and $\dot{C}_i(t)$ from equation 3, if values for all parameters in the equations were known. Little data is available to predict values for F with accuracy. Traynor *et al.*[40] present data on S, K, and $P_1$ for combustion products based upon experiments in a chamber, Nero *et al.*[33, 41] present data on S for radon (K equals zero and $P_1$ and $P_2$ equal one for radon but not for radon daughters), and some data is available for evaluation of S for formaldehyde from particleboard[13, 14]. At the present time we have only limited data on values for these parameters, however, and measurements are required to determine values for air change rate ($a_1$). In addition, operation of a mechanical ventilation system can cause a change in the infiltration rate ($a_1$) unless the mechanical ventilation system exhausts and supplies equal amounts of air. Therefore, the usefulness of equations 2 and 3 for accurately predicting pollutant concentrations and the effect of control measures is limited at this time; however, the equations do indicate the relation between variables and indicate the need for further experimental data.

If we make further simplifying assumptions, the equations become more usable but less accurate. Assuming that the indoor concentration is steady with respect to time, and also assuming the outdoor concentration is much less than the indoor concentration yields the following equation for the ratio of $C_i$ to $\dot{C}_i$.

$$\frac{C_i}{\dot{C}_i} = \frac{(1 - F)(a_1 + K)}{a_1 + a_2 + K + \eta Q} \qquad (4)$$

Equation 4 shows that mechanical ventilation will have a smaller beneficial effect if the pollutant is reactive (i.e., $K \neq 0$). If the pollutant is non reactive ($K = 0$), no air cleaning process is utilized ($Q = 0$), and if the pollutant source strength is unaffected by control measures ($F = 0$), then $C_i/\dot{C}_i = a_1/(a_1 + a_2)$ i.e., the ratio of pollutant concentrations equals the inverse of the ratio of total air exchange rates. Despite its simplicity, equation 4 should be useful for estimating the impact of a control measure in many situations.

ADDENDUM - FORMULATION OF PRESENT CRITERIA FOR INCLUSION OF INFILTRATION-REDUCTION MEASURES IN THE REGIONAL WEATHERIZATION PROGRAM

prepared by Don Wolfe, Bonneville Power Administration

When BPA began preparing its proposal for a regionwide weatherization program in early 1981, the impacts of prospective programs were evaluated in accordance with the requirements of the National Environmental Policy Act and the regulations of the Council on Environmental Quality (CEQ).

These regulations require that if the proposed action is determined to have significant impacts on the quality of the human environment, an environmental impact statement (EIS) must be prepared before the action can proceed, and if the significance of the impacts is uncertain, an environmental assessment (EA) must be prepared (40 CFR 1501.3, 1501.4). Research on the impacts of the program indicated that potentially significant impacts could result from the program due to reduced air exchange in residences, which would lead to increased concentrations of indoor air pollutants and increased impacts of those pollutants on the health of residents. This research formed the basis for an EA on the proposed program.

Significance is defined in the regulations by a number of considerations, including long-term effects (40 CFR 1508.27(a)), the degree to which the proposed action affects the public health and safety (40 CFR 1505.27(b)(2)), the degree to which the effects on the quality of the human environment are likely to be highly controversial (40 CFR 1508.27(b)(4)), the degree to which the possible effects on the human environment are highly uncertain or involve unique or unknown risks (40 CFR 1508.27(b)(5)), and whether it is reasonable to anticipate a cumulatively significant impact (40 CFR 1508.27(b)(7)).

Analysis of the program as initially proposed suggested that impacts could be significant in part because small increases in the exposure of individuals to indoor radon could contribute to long-term mortality over the population to be reached by the program due to lung cancer. Exposure to other potentially carcinogenic pollutants, specifically formaldehyde and benzo(a)pyrene, would also increase. These impacts appeared to be significant because of their long-term, cumulative effect on the public health. Their potential significance was reinforced by the growing controversy about indoor air quality, the important unknowns about source strengths and health effects, and the absence of reliable information on a number of aspects of the problem.

Analysis of the EA on the program led to the conclusion that the impacts of the proposal as initially designed were significant. According to the regulations, an EIS would have to be completed before program implementation could begin. Preparation of an EIS would have required delaying program implementation and resulting energy savings by more than a year. However, an alternative approach would permit a finding of no significant impact (FONSI) for the program so that implementation could proceed without delay for the completion of an EIS. As explained by the CEQ in the Federal Register, an agency may make a FONSI if, with mitigation, the effects of the proposal can be reduced to less than significant levels (46 FR 18038). By modifying the proposal so that significant impacts would be avoided, a FONSI for the program could be supported and the program could proceed without waiting for the completion of an EIS.

In light of the potential impacts identified, the proposal was modified to include monitoring, mitigation measures, and research on indoor air pollution to develop better information and to determine the extent of impacts and the need for mitigation. These modifications were intended to permit a FONSI on the program so that implementation could proceed without the need to prepare an EIS, and were published in the EA on the program.

In accordance with the regulations (40 CFR 1501.4(d)(2)(i)), the EA and a draft FONSI for the program were made available for public review before BPA made a final determination whether to prepare an EIS. Comments from utilities and the public in review of the EA questioned whether the document adequately supported a FONSI for the modified program. The principal concerns expressed were the following:

1. There was not sufficient evidence that the mitigation measures provided would be effective enough to avoid significant impacts from the program.

2. The program as proposed could not guarantee that mitigation measures, even if shown to be effective, would be applied so as to avoid significant impacts. For example, air-to-air heat exchangers might be disconnected if residents disliked the noise of their operation.

3. Even if mitigation measures could be assured to avoid significant impacts, their effects on program costs, cost-effectiveness, and energy savings were not known, thus it could not be demonstrated that such measures could be justified in terms of program financing.

Without considerable research, these concerns could not be answered in the EA, so the proposed program, even as modified, could not go forward based on a FONSI. However, the delay necessary for the preparation of an EIS was still not acceptable in achieving BPA's energy conservation goals, so the program was modified a second time. This time, instead of proceeding with complete weatherization and attempting to mitigate any adverse effects after the fact, the program was changed so that the potential adverse effects would not occur in the first place. This was accomplished by limiting the weatherization measures offered to those which would not reduce ventilation, except in cases where the major sources of indoor air pollutants were absent. In addition, all participants in the program were to be provided with brochures including information about indoor air pollution, the effect of weatherization on indoor air quality, and actions which homeowners can take to reduce indoor air pollution. These provisions, along with the conservativeness of the assessment of potential impacts, which would tend to overestimate rather than underestimate them, were the basis for a FONSI on the program under which implementation was permitted to proceed.

Homes in which the major sources of indoor air pollution were absent were defined by five characteristics. These were the following:

1. A full crawl space with cross ventilation (as per the Uniform Building Code), with a ground cover vapor barrier and floor insulation with a vapor barrier, which may be provided under the program;

2. No woodstoves or unvented combustion appliances, such as gas stoves or kerosene heaters;

3. A municipal water supply or surface water source for domestic supply;

4. Wood frame construction; and

5. No foam insulation.

In addition, air-infiltration-reducing measures would not be offered for mobile homes weatherized under the program. These restrictions limited the availability of complete weatherization to about 30 percent of the region's homes.

On several occasions, BPA has made assurances that the restricted measures would be offered to a greater percentage of participating homes as improved information provided assurance that no significant impacts would result. As the foregoing discussion shows, however, any changes in the availability of measures must be supported by an analysis of impacts which clearly demonstrates that no significant impacts will result.

The paper describes an approach for extending the availability of the measures restricted under the program.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720