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Volume II Appendices

Final Environmental Impact Statement on New Energy-Efficient Homes Programs

Assessing Indoor Air Quality Options

BPA

U.S. Department of Energy
Bonneville Power Administration

August 1988

DOE/EIS-0127F

Volume II

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NEW ENERGY-EFFICIENT HOMES PROGRAMS
ENVIRONMENTAL IMPACT STATEMENT

VOLUME II

<u>This Volume contains</u>:

The above appendices, prepared by the Bonneville Power Administration and the Pacific Northwest Laboratory (PNL), are included in Volume II to supply key supporting information for the findings presented in Volume I of the FEIS.

APPENDICES

APPENDIX A

ESTIMATION OF TOTAL VENTILATION RATES FOR PROPOSED VENTILATION STRATEGIES IN NEW RESIDENTIAL STRUCTURES

Bonneville Power Administration

A.1 BACKGROUND

Draft Environmental Impact Statement Comments. In February 1987, the Bonneville Power Administration (BPA 1987) published the New Homes Draft Environmental Impact Statement (DEIS). This DEIS presented the health impacts and other environmental effects of various methods for constructing new energy-efficient residences. The major finding was that homes can be built with different levels of natural and mechanical ventilation and that these levels can influence directly the concentrations of indoor air pollutants. Long-term exposure to these pollutants is thought to result in an increased incidence of lung disease. The DEIS estimated this increase in disease for the various ways energy-efficient housing could be built. It was also determined that building homes with different levels of air infiltration/ventilation could affect the need for additional regional power supply and could influence the cost of providing this power supply, and the associated environmental effects.

The DEIS received public review and comment through April 1987. Numerous comments were provided to Bonneville. One particularly important comment concerned the assumptions and calculations for residential air exchange rates. Commenters questioned the technique used for establishing these rates. They suggested that since the DEIS depended on these rates to determine the incremental health impacts from indoor air pollutants for the various construction "pathways" or methods, Bonneville should use a more rigorous approach in developing total ventilation rates. Aside from the general comment that a more defensible technique was needed to calculate ventilation rates, there were other specific comments dealing with two aspects of the calculations: inclusion of effective versus actual ventilation rates and handling of uncertainty in estimated ventilation rates.

Actual versus Effective Ventilation Rates. Commenters expressed concern that the calculations should recognize the fact that concentration of indoor air pollutants is inversely proportional to the ventilation rate as shown in Equation 1 below.

$$C = S/(V*ACH) \qquad \text{(Eq. 1)}$$

where:

C = Pollutant Concentration
S = Pollutant Source Rate
V = House Volume

ACH = Ventilation Rate

Given this relationship and a series of ventilation rates over time, one can calculate an equivalent pollutant concentration for each ventilation rate period. If the source rate and house volume are constant, then it is possible to take the average pollutant concentration for the entire period and use the same equation to solve for an "effective" ventilation rate. This "effective" ventilation rate can be interpreted as the amount of ventilation that is "effective" for diluting pollutants. Using this equation, if the ventilation rate over any given time period is constant, then the "effective" ventilation rate and the average of the actual ventilation rate would be identical. However, if the ventilation rates (and by definition the air exchange rate as well) vary over the time period used for averaging, then the average actual ventilation rate and the effective ventilation rate will vary considerably. The effect is best illustrated by an example.

Suppose that for two consecutive hours the actual ventilation rate is exactly 0.9 ACH for the first hour and then drops instantly to 0.1 ACH and remains constant at that level for the entire second hour. The average actual air exchange rate for the building is:

Average Actual ACH = (0.9 + 0.1)/2 = 0.5 ACH

Using Equation 1 and assuming the pollutant source rate to volume ratio is a constant value of 1.0, then our average concentration for the same 2 hours is given as:

Concentration for Hour 1 = 1.0/0.9 = 1.11
Concentration for Hour 2 = 1.0/0.1 = 10.0

The average concentration for the 2 hours is given by:

Average concentration = (1.11 + 10.0)/2 = 5.55

Returning to Equation 1, by assuming a constant source rate to volume ratio we can calculate an "effective" average ventilation rate based on the average concentration which yields:

Average Effective ACH = 1.0/5.55 = 0.18 ACH

This example illustrates the magnitude of the potential difference between the average and effective ventilation rates when there are large sharp changes in the ventilation rate. However, the magnitude of this effect will be reduced significantly if the variations in ventilation rate are not large and vary slowly over time. The commenters argued that this very important effect must be taken into consideration to give proper credit to houses built with low natural infiltration rates and constantly operating mechanical ventilation when compared to homes relying solely on higher natural air infiltration rates.

Uncertainty in Estimated Ventilation Rate Calculations. Another comment that was strongly supported related to the way that the analysis treated the uncertainty of the assumptions. In the DEIS, the fact that there was considerable uncertainty about the measurements of ventilation rates was handled by the use of a multiple "baselines" i.e. different assumptions about what the "true" ventilation rate is for buildings constructed with current techniques. The DEIS included a "high" baseline, a "low" baseline, and a floating baseline that went from high to low over a period of years. Unfortunately, this choice of "multiple baselines" added more confusion than it dissipated and therefore comments indicated that a different method of handling uncertainty was needed.

Final Environmental Impact Statement Estimated Ventilation Rate Methodology. In order to address these comments, the methodology for calculating estimated ventilation rates for the Final Environmental Impact Statement (FEIS) was completely revised. After examining several alternatives, the following criteria were developed for the development of the analysis methodology. First, it was decided that it would be undesirable to depart from the basic premise in the DEIS that the analysis would be based on measured and not theoretical data wherever possible. However, this requirement meant that the available data would have to be reanalyzed to derive specific normalized construction parameters that could be applied to any building.

Second, in order to develop a more scientifically defensible estimate of the ventilation rates, it was determined that a model would need to be developed that could take the parameters derived from the data and use them directly to compute a ventilation rate for a prototypical building. The model would have to calculate both actual and effective ventilation rates for buildings with varying combinations of air leakage control packages and mechanical ventilation systems.

Third, the analysis would have to deal directly with the issue of data and model uncertainty without destroying the usefulness of the results in the policy decision making process.

The resulting methodology consisted of the following components. The data that had previously been used in the DEIS (i.e. RSDP data) would be used and supplemented where necessary to derive normalized air leakage and ventilation data. These normalized parameters would be used as inputs to two distinct ventilation rate models.

The first model would be engineering based and would incorporate the infiltration rate calculation procedures developed by Sherman and Grimsrud (1981) at Lawrence Berkeley Laboratories. This model would take the normalized specific leakage area data from the various sources of fan pressurization data available and calculate the natural component of the total ventilation rate. The model would then include a separate calculation for adding the appropriate amount of mechanically induced ventilation. By performing these calculations hourly, the effective ventilation rate could be computed by merely calculating and summing the inverse of the hourly ventilation rate and then inverting the average over the entire period.

The second model would be a statistically based regression model that uses various physical characteristics data to predict an effective ventilation rate for a prototypical building without whole house mechanical ventilation. The statistical model would only provide an estimate of the effective ventilation due to natural forces (wind and stack pressures) and normal occupancy (bath and kitchen fan intermittent use for spot ventilation needs). This statistical model would be based on an analysis of the Perfluorocarbon Tracer (PFT) gas testing on the RSDP control home sample. This effective ventilation rate would then multiplied by a series of factors derived from the engineering model to compute the effective ventilation rate of the building with the added mechanical ventilation systems and the actual ventilation rate both with and without mechanical ventilation.

After reviewing the literature, it was determined that the biases inherent in the data and the models would tend to drive the results from the two models in opposite directions. It would therefore be possible to use this bias to allow the results from the two models to "bound" the range of ventilation rates. By assigning the higher set of ventilation rates to the "upper bound" and the lower set to the "lower bound" the analysis would allow the policy makers to examine the likely "best" and worst" case outcomes from a particular policy choice and have some confidence that the actual result will fall somewhere in between.

This technique for dealing with the uncertainty in the data was ultimately preferred over a traditional error analysis where a median value would have been bounded by a range of standard deviations or a confidence interval. In the traditional technique, the policy makers usually end up looking at the data as three separate estimates, a median case, a median plus and a median minus a specified interval. Unfortunately, the additional information tends to get lost and only the median values used for policy planning. By using the upper/lower bound concept it was felt that an adequate allowance for uncertainty was insured while maintaining the usefulness of both estimates.

It is important to note that there are some combinations of parameters that result in the two models switching places between higher and lower values. Given that the values were merely being used to "bound" the ventilation rates for a given set of measures, it was determined that there was no technical reason for not placing the lower values in the lower bound and the higher values in the upper bound regardless from which model they were derived.

A.2 DATA SOURCES

While the DEIS used data primarily in its raw form, the FEIS analysis would require more detailed information that could be applied to prototypical buildings. It was therefore necessary to reanalyze the data and investigate some new sources of data to provide inputs to the model. The following sections describe the various data sets and analytical procedures used in this analysis.

The data came primarily from four sources:

The Residential Standards Demonstration Program (RSDP)
The Tulalip Manufactured Housing Project
The Energy Efficient Manufactured Housing Demonstration (EEMHD) Project
The New Manufactured Housing Air Leakage Survey

Additional data from the Multifamily Ventilation Rate Study was reviewed but not used due to large variations in the data set.

RSDP Data. Most of the data used in this analysis was developed through Bonneville's Residential Standards Demonstration Program. This program, begun in 1984, was a field demonstration program of the Model Conservation Standards (MCS) as proposed by the Northwest Power Planning Council in 1983. Under RSDP, approximately 400 residences were constructed in compliance with the MCS in the Northwest States. These homes were matched on an aggregate basis to about 400 control homes built over the past several years in compliance with the current prevailing building codes. Construction cost data, thermal performance, and other relevant data was collected on each home.

The MCS RSDP homes were built using either of two air leakage control "packages". Package "A" air leakage control required good caulking and weatherstripping and fairly tight windows and doors. Package "C" construction required a fully continuous air barrier that virtually eliminated air leakage into the home as well as very tight windows and doors. All MCS RSDP homes were required to include mechanical ventilation with heat recovery. The current practice homes had no requirements for either tightening or ventilation.

Various air infiltration and ventilation data were collected on the RSDP homes. This data included fan pressurization test results for all homes, perfluorocarbon tracer gas measurements for about one-third of the homes, and air-to-air heat exchanger (AAHX) airflow measurements in the MCS homes (Harris 1986)

. The fan pressurization data is useful for quantifying the leakage characteristics of the buildings. The PFT measurements provide some indication of the total effective ventilation rate of the homes including the naturally induced ventilation, the operation of mechanical ventilation systems, and individual occupant usage of the house. The AAHX airflow rates provide some information on the system's mechanical ventilation capacity, and coupled with equipment usage information, some data on total mechanical ventilation. Unfortunately errors in the flow rate measurements and incomplete knowledge of the operating times of the AAHX eliminated the AAHX data from providing a useful contribution to the analysis of the total ventilation rates of the MCS RSDP houses.

Tulalip Project Data. The Tulalip project consisted of approximately 35 manufactured homes built to comply with the MCS. All of the homes were constructed by a single manufacturer to the same air leakage control standards prescribed for package A in RSDP. The homes were all sited on the Tulalip Indian Reservation in Marysville, Washington. Fan pressurization test data were available on 21 of the units (Ek 1986a).

Energy Efficient Manufactured Housing Demonstration (EEMHD) Project Data. The EEMHD project consisted of five residences manufactured to the MCS including air-tight construction features designed to achieve the same level of air tightness as the RSDP package C houses. Fan pressurization data was available for these units both before and after transportation (Ek 1986b). Some PFT data was also taken on these same homes.

New Manufactured Housing Air Leakage Survey Data. This project was designed to determine the average air leakage characteristics of typical newly constructed manufactured housing in the Bonneville service area. Fan pressurization data were available on six single wide and ninety two double wide units (Ek 1987). This data is equivalent to the RSDP current practice sample for manufactured housing. Unfortunately, there was no PFT data available in this data set.

Multifamily Data Sets. Given that it is difficult, if not impossible, to perform fan pressurization tests on multifamily dwellings, the only source of data available for this type of dwelling was some preliminary tracer gas tests from the RSDP and from two other case studies (Parker 1987). Unfortunately, the variance in the data and the small sample sizes rendered the data useless for purposes of this analysis. Therefore, all multifamily calculations were made using the RSDP single-family data scaled appropriately.

Air Leakage Characteristics Data Analysis. As discussed previously, the analysis models require air leakage characteristics for prototypical site-built, manufactured, and multifamily buildings. Given that the models would be using prototypical buildings, it was necessary to normalize the leakage characteristics of the various categories of houses tested.

In addition, the two different models used to generate the upper and lower bound estimates of the total ventilation rate required different variables from the fan pressurization database. The engineering based model required an effective leakage area (ELA) based on the LBL calculation procedure (Sherman et al. 1981). The statistical model required values for the airchange rate at 50 pascals (ACH50) from the fan pressurization test.

In order to normalize the data for single-family buildings, the appropriate ELA was divided by the gross conditioned floor area to calculate a specific leakage area (SLA). However, given that there was no suitable data set to describe the leakage characteristics for multifamily buildings, the RSDP ELAs were normalized by the exposed surface area to accommodate the differences in geometry between single-family and multifamily buildings. Accurate data for the floor areas of the New Manufactured Housing Air Leakage Survey homes was not available so the ELA data for this data set was normalized by exposed surface area as well. The ACH50 values for all of the data sets are inherently normalized by the volume of the structure and thus were not normalized further.

For each housing type, the air leakage data was segregated according to the type of air leakage control used in the building. Three distinct categories were identified for use in the EIS: "baseline" homes built to current practice, "standard" homes built with a moderate amount of air sealing beyond current practice, and "advanced" homes built to full air-tight construction standards. Baseline values were derived from the RSDP control homes for site-built and from the New Manufactured Housing Air Leakage Survey for manufactured homes. Values for "standard" air tightening were taken from the RSDP Package A homes for site-built and from the Tulalip Project homes for manufactured homes. Advanced air tightening values were taken from the RSDP Package C homes for site built and from the Energy-Efficient Manufactured Home Demonstration Project for manufactured homes.

Summary statistics for the specific leakage areas of the RSDP data set are provided in Tables A.1 and A.2 below. The results for manufactured housing are presented in Tables A.3 and A.4 below. Air changes at 50 pascals are given in Table A.5 for the RSDP data set and in Table A.6 for the manufactured housing data sets.

Table A.1. RSDP Specific Leakage Area ($\text{in}^2/100\ \text{ft}^2$)

	Current Practice	Package A	Package C
Sample Size	402	42	280
Mean	5.66	3.86	2.23
Median	5.32	3.81	1.97
Standard Deviation	3.67	2.06	1.46
Maximum	53.9	11.2	8.73
Minimum	0.11	0.34	0.11

TABLE A.2. RSDP Leakage Ratio ($\text{in}^2/100\ \text{ft}^2$)

	Current Practice	Package A	Package C
Sample Size	350	32	215
Mean	2.28	1.33	0.984
Median	2.09	1.34	0.798
Standard Deviation	1.91	0.63	0.716
Maximum	32.5	2.82	4.71
Minimum	0.33	0.18	0.088

TABLE A.3. Manufactured Housing Specific Leakage Area ($\text{in}^2/100\ \text{ft}^2$)

	Tulalip Project	EEMHD
Sample Size	21	5
Mean	4.19	2.01
Median	4.26	1.94
Standard Deviation	0.43	0.55
Maximum	4.95	2.83
Minimum	3.41	1.20

TABLE A.4. New Manufactured Housing Air Leakage Survey Data Leakage Ratios ($in^2/100\ ft^2$)

Sample Size	93
Mean	2.18
Median	2.12
Standard Deviation	0.61
Maximum	4.57
Minimum	1.16

TABLE A.5 RSDP Air Changes at 50 Pascals ($hour^{-1}$)

	Current Practice	Package A	Package C
Sample Size	338	42	248
Mean	8.33	5.87	3.36
Median	8.02	5.12	2.86
Standard Deviation	3.37	3.75	2.29
Maximum	22.7	21.1	12.1
Minimum	1.07	1.84	1.05

TABLE A.6. Manufactured Housing Air Changes at 50 Pascals ($hour^{-1}$)

	New MH AL Survey	Tulalip	EEMHD
Sample Size	122	21	5
Mean	2.28	5.36	2.94
Median	2.09	5.48	2.81
Standard Deviation	1.91	0.46	0.29
Maximum	32.5	5.95	3.25
Minimum	0.33	4.51	2.48

As can be seen from Tables 1 and 3, the Current Practice data sets for both site built and manufactured housing exhibit fairly large standard deviations. The shape of the distributions also tend to be somewhat log-normal in form. Given these characteristics, the median value was chosen to apply to the prototypes in the analysis. The data for the Package A and Package C homes are more log normal than the current practice data so median values for both of these data sets was used as well.

A.3 VENTILATION RATE MODEL

As described in Section 1.0, the methodology used to compute the total ventilation rates was designed to include two separate models, an engineering and a statistical model. The outputs of the two models would be assigned to either the upper or lower bound estimates depending on the outputs from the model. This section describes the development and structure of each of the models. A brief discussion of the necessary inputs is also included.

Engineering Model. The engineering model was constructed around the infiltration model developed at LBL. The LBL model was chosen primarily because of its widespread acceptance and its comprehensive validation. Because it has been shown to be biased somewhat high in predicting average infiltration rates (Sherman and Modera 1986), the LBL model would probably provide the upper bound estimate most of the time.

Although a more thorough treatment of the LBL model is given in reference 2, a brief discussion of the model will be given here. The LBL model uses the ELA from a fan pressurization test to model the building as an orifice that is subjected to pressure differentials from wind and stack effects. The general form of the equation is similar to that for flow through an orifice as a function of pressure drop and is given in equation 2 below.

$$Q = A * (2*dP/p)^{0.5} \qquad \text{Eq. 2}$$

where: Q is the air flow
A is the equivalent orifice area
dP is the pressure differential across the orifice
p is the density of the air

Given that the building is subjected to pressure differentials due to wind and stack, the total flow through a building is actually due to the combination of the two forces. The LBL model deals with the combined flows by calculating the flows due to wind and stack separately and then combines them in quadrature as shown below in equation 3.

$$Q = (Q_{stack}^{2} + Q_{wind}^{2})^{0.5} \qquad \text{Eq. 3}$$

The LBL model includes simplified calculations for the flows due to wind and stack so that they can be applied to standard weather data and some normalized parameters for the type of house, the terrain and shielding class of the geography surrounding the house. The simplified equation is of the form given in equation 4 below.

$$Q = L * (f_s^{2}*dT + f_w^{2}*V^{2})^{0.5} \qquad \text{Eq. 4}$$

where: Q is the total flow due to wind and stack forces
L is the ELA from the fan pressurization test
dT is the difference between indoor and outdoor temperatures
f_s is the simplified stack parameter incorporating building height and physical distribution of leakage area between floors, walls and ceilings
V is the wind speed at the house
f_w is the simplified wind parameter incorporating shielding and terrain coefficients to correct wind speed measured at a remote location to the actual site wind speed.

The basic LBL model incorporates only flows due to wind and stack forces and does not include any ventilation from occupant operation of passive (e.g. windows) or mechanical (e.g. bath fans) ventilation devices. Unfortunately there are no simplified models that can deal adequately with occupant operation of passive ventilation devices. However, there are several models described in the literature dealing with the combination of mechanical and natural air flows in buildings. Given the lack of adequate models for occupant interaction, the engineering model did not include an explicit treatment of ventilation due to occupant operation. However, since the FEIS required that various forms of mechanical ventilation systems be modeled, it was necessary to incorporate the ventilation due to whole house mechanical ventilation systems.

After reviewing the literature, it was obvious that there was a lack of consensus about the proper way to combine air flows from the mechanical ventilation system with those from natural infiltration. Although there was general agreement that balanced mechanical flows could be simply added to the natural flows, there was wide disagreement about the proper procedure for adding unbalanced mechanical ventilation.

Given this disagreement, two separate models were used to calculate the mechanical ventilation component. In both models, any balanced mechanical ventilation was assumed to simply add to the naturally occurring ventilation. However, the two models treat unbalanced mechanical ventilation such as exhaust fans differently.

The first model was developed by LBL for inclusion with their infiltration model (Modra and Peterson 1985). This model hypothesizes that airflows behave as if they are moving through an ideal orifice. Flows resulting from the combination of pressure differences from mechanical and natural forces through an ideal orifice should be added in quadrature in the same way that flows due to wind and stack are added. The LBL model is given in equation 5 below.

$$Q_{total} = (Q_{natural}^2 + Q_{unbalanced}^2)^{0.5} + Q_{balanced} \qquad \text{(Eq. 5)}$$

However, there were a number of criticisms to this model in the literature along with several alternate models (Shaw 1987, Wilson and Kiel 1987) that ranged from simple linear addition of the flows to the use of exponents derived from experimental data. Given the lack of consensus surrounding the true form of the equation, the second model included a simple relationship from the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) 1981 Handbook of Fundamentals (ASHRAE 1981). This model is given in Equation 6 and simply adds half of the unbalanced flow to the natural flow.

$$Q_{total} = Q_{natural} + 0.5*Q_{unbalanced} + Q_{balanced} \qquad \text{(Eq. 6)}$$

The total air flow computed from both models was then divided by the volume of the building to compute air change rates. When averaged over a number of time periods, the models produce an estimate of the average actual ventilation rate as shown in equation 7 below.

While the average actual air change rate is important in the FEIS for calculation of energy used to heat the ventilation air, the necessary parameter to calculate health effects is the average effective air change rate. As shown in Section 1.0, the concentration of a pollutant with a constant source strength is inversely proportional to the air change rate of the building. Using this relationship the model could be used to calculate a pseudo-concentration for an imaginary pollutant with a source rate to volume ratio of one by simply calculating the inverse of the total ventilation rate. If the time step of the weather data used for the calculations was small enough, then simply averaging the pseudo concentrations and then taking the inverse of this average would produce a reasonable estimate of the average effective ventilation rate for the given period. A similar approach was validated experimentally in the literature (Sherman and Wilson 1986). The average effective ventilation rate was computed using equation 8 below.

$$ACH_{actual} = sum (ACH_i) / N \qquad \text{Eq. 7}$$

$$ACH_{effective} = 1 / (sum (1/ACH_i) / N) \qquad \text{Eq. 8}$$

where: ACH_{actual} is the average actual air change rate

ACH_i is the air change rate computed by the model for a given time increment

N is the number of time increments in the averaging period

$ACH_{effective}$ is the average effective ventilation rate

For purposes of the FEIS, the two different models combining mechanical ventilation were used to calculate the air change rates on an hourly basis for a period of several months spanning a typical heating season. The air change rates from both models were averaged independently over this period and the results were then averaged together to produce a single estimate of the average actual and effective air change rates during the heating season.

Statistical Model. One of the more serious criticisms of the engineering approach to estimating ventilation rates is that it does not reflect the impact of occupant operation on both passive and mechanical ventilation systems within the building. There are also numerous flaws in the series of assumptions required to take the very complex interaction of physical forces at work on a house and simplify it into a simplified model of a single orifice. It would obviously be desirable to take real ventilation rate measurements and use them to predict the effects of various changes in weather, physical characteristics and occupant interaction. A review of the literature failed to produce an acceptable model that could accommodate all of those desires.

After examining several options, it was noted that the RSDP data set includes a large number of PFT measurements that are purported to be measurements of the average effective ventilation rate in those homes during the measurement period. Because the PFT measures the real effective ventilation rate it includes the occupant effects and natural interactions described previously. The RSDP data set also contains a great deal of information about the physical characteristics of the buildings, the weather during the period, and the occupants. Given the PFT measurements of effective ventilation rate and the rich data set accompanying these houses it was determined that a statistical model should be attempted. The model would have to relate the physical characteristics of the building and the occupants to the PFT ventilation rates in order to allow the model to be used for prediction of ventilation rates for a similar building with different physical features.

One other advantage to the FEIS that the statistical model would provide is delivered by means of the biases in the PFT measurements themselves. The literature has documented that errors in the PFT measurement system will tend to bias the measurement low (Sherman 1987, Dietz 1986). Previous comparisons (Parker 1987) of the PFT and fan pressurization results from the RSDP revealed a wide discrepancy between the two measurements; the PFT almost always predicting a lower air change rate than that predicted by the LBL model using fan pressurization data for the same houses. The discrepancy was larger than would be predicted by the fact that the LBL model predicts actual air change rates versus the effective air change rate measured by the PFT. These considerations made the statistical model of the effective ventilation rates a logical candidate for the lower bound estimates.

There were a number of factors to be considered in developing the statistical model. First, the uncertainty regarding the quantity of mechanical ventilation in the RSDP MCS houses (discussed in section A.2) required that the statistical analysis would have to be focused on the control homes. Second, the analysis would have to include some physical characteristic describing the air leakage of the house since that would be the primary predictive variable available from the other data sets. Third, the model would somehow have to be adjusted for mechanical ventilation in an ad hoc fashion to incorporate the effects of the proposed ventilation strategies in the FEIS. Finally, the model should be similar in form to physically known relationships between air flow and the various physical forces represented by the analysis variables.

The first step in the modeling process was to develop a consistent data base incorporating all of the pertinent data available. Table A.7 is a list of the variables included in the data base used for the analysis. One of the primary tasks at this stage was to rectify differences in volumes and floor areas between the fan pressurization test reports and those reported in the PFT reports. In order to simplify this process, the analysis focused on flows and used the PFT volumes (sum of the zone volumes) where necessary. After sorting through the available data a file was compiled that initially included 167 observations. However, after some testing it was determined that there were several data points that should be excluded from the analysis.

First, there was one PFT reading that was over 3 air changes per hour. After reviewing the test report it appeared that this particular test was abnormal due to the failure of the multizone model used to produce the test. This point was dropped from further analysis. Second, after some investigation it was determined that there was a significant number of houses that reported construction dates before 1977. Given that the older houses were not in fact representative of the housing stock being modeled in the FEIS, these points were also excluded from the analysis. After excluding these data points the remaining data set included 151 observations.

The analysis consisted of multiple variable linear regression of different explanatory variables against the flow rates measured by the PFT. The analysis was begun by first examining several different relationships between the PFT flow rates and different air leakage characteristics. The analysis looked at both normalized (by volume) and actual flows regressed against ELA, air changes at 50 pascals and flow at 50 pascals. After testing each of these regressions and examining the plot of PFT flows versus the various air leakage indicators it was determined that the best relationship was between the log of

TABLE A.7. RSDP CONTROL HOMES DATA: VARIABLE DESCRIPTIONS

Variable	Description
idnum	BPA Site ID
flarea	Floor area ft2
vol	Volume from BD file in ft3
occheat	Primary Heat from 1st Occ. Surv
noocc	Number of Occupants from 2nd Occ Surv
age	Year built
cp	Pressurized constant from BD
np	Pressurized exponent from BD
elap	Pressurized ELA at 4 Pa
achp	Pressurized ACH
cd	Depressurized constant from BD
nd	Depressurized exponent form BD
elad	Depress ELA at 4 Pa
achd	Depressurized ACH
r	LBL Model R parameter
x	LBL Model X parameter
terr	LBL Model Terrain class
shield	LBL Model Shielding Class
elev	site elevation in ft
state	ID=1, MT=2, OR=3, WA=4
cz	CLimate Zone (1,2, or 3)
sla	ELA/Floor Area in cm2/ft2
stdate	PFT measurement start date
endate	PFT measurement end date
pftach	PFT whole house air change rate
pftvole	PFT Total house volume in ft3
pflow50	Flow at 50pa press from BD
dflow50	Flow at 50pa depress from BD

avflow50	Average flow at 50pa from BD
pkflow	Calc flow from Persily/Kronval
lnflow50	Natural log of avg flow @50pa
pftflow	Whole house flow from PFT
lnpftflw	Natural log of PFT flow rate
ach50	ACH @50pa from avflow50/pftvole
forced	1=forced air heat, 0=not FA hea
start	1=PFT meas start Oct-Dec, 0=no
lnpftach	Nat. log of PFT ACH
lnach50	Nat. log of ACH50 from BD
pkach	ACH from Persily/Kronval model
deltat	Ave. Temp Diff during PFT
lndeltat	Nat.log of avg temp diff PFT
lnsla	Nat. log of Spec. Leakage Area
bsmt	Basement quest. from II Occ Surv
bsmtins	Dummy var. for presence of bsmnt
bsmtheat	Bsmnt Heat from II Occ Survey
cstat	Central thermostat from II O.S.
room	Room closure from II O.S.
wood	Wood appliance type from II O.S
wooduse	Wood app use from II OS
window	Open windows at night
windows	Dummy Var. for Open Windows
cstat2	Dummy var. for central tstat (II O.S.)
roomclos	Dummy var. for room closures

the PFT flow rates and the log of the flow rates measured by the blower door at 50 pascals.

After establishing the fundamental relationship that appeared to provide the most satisfactory fit between the air leakage characteristics of the building and the air flows, the next step was to examine the impact of other variables known to have an influence on the ventilation rate. Some of these variables were house characteristics (e.g. heating system type, house type) and others were occupant characteristics (e.g. hours of exhaust fan operation, window openings). One other class of variables was tested as well. These variables were designed to examine the impact of weather on the model (e.g. average temperature difference, start date of the test).

After testing the variables for significance and correlation with other variables, the following model was determined to provide the best explanatory power with the most logical set of variables that provided adjustments to the model in a physically consistent manner.

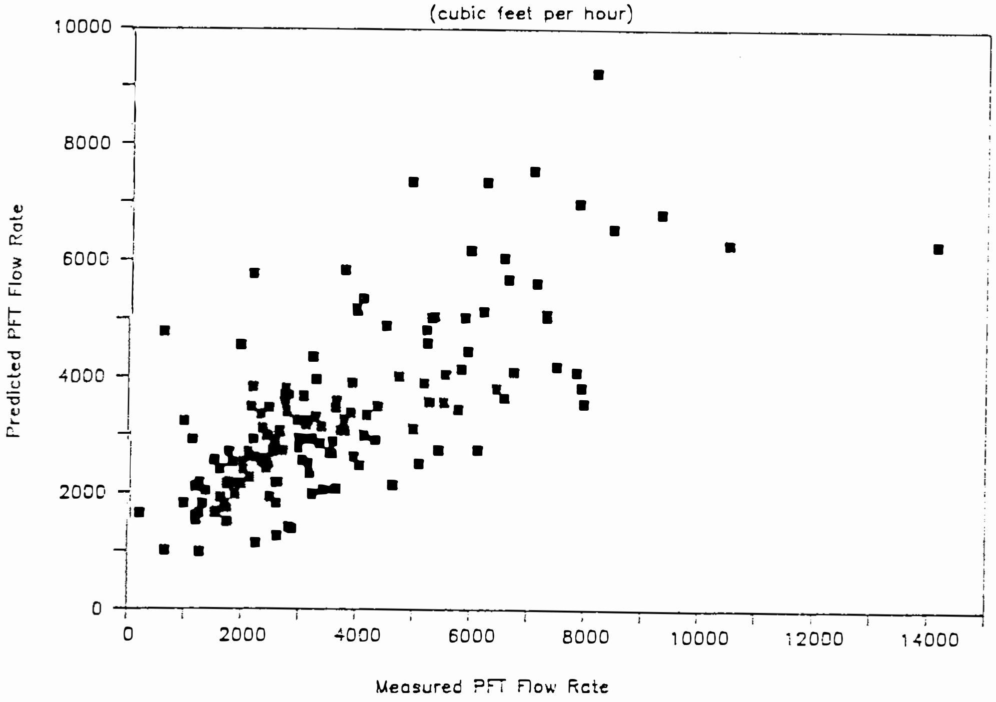
$$\ln(\text{PFT FLOW}) = C_1 * \ln(\text{FLOW50}) + C_2 * \text{FORCED?} + C_3 * \text{START} + C_4 * \text{WINDOWS?} + C_0 \qquad \text{Eq. 9}$$

where: ln(PFT FLOW) is the natural log of the whole house flow rate measured by the PFT

ln(FLOW50)	is the natural log of the flow measured by the blower door at 50 pascals pressure difference
FORCED?	is a dummy variable for the presence of a forced air heating system as determined from the first occupant survey. 1=forced air, 0=not forced air
START	is a dummy variable for the start date of the test. If the test was begun in the fall (and therefore ran through the primary part of the heating season) the value of start was 1. Otherwise start=0.
WINDOWS?	is a dummy variable for the occupant response to the question asked on the second occupant survey about whether they kept a window open in the bedroom at night while sleeping. 1=yes, 0=no.
$C_0 - C_4$	regression coefficients.

Output from the regression analysis is provided in Table A.8 and the correlation matrix of the variables is included in Table A.9. A plot of the predicted PFT flow rates versus the actual measured flow rates from the model is presented in Figure A.1. As indicated in Table A.8 the regression model was capable of explaining almost 50% of the variance in the log of the PFT flow rates. All of the variables are significant at the 90% level or better and

FIGURE A.1. MEASURED VERSUS PREDICTED PFT FLOW RATES



the model includes features that satisfy most of the criteria described previously. It includes predictor variables that are representative of the physical air leakage characteristics of the buildings, occupant interaction with the building and weather dependency. While the amount of scatter in figure one indicates that the model lacks a great deal of explanatory power, it also indicates that the model is predicting the right trends in the data and does a fairly decent job of predicting a fair number of data points. Based on the form of the model and the encouraging results form the regression analysis, it was felt that the variables included and their significance provided sufficient reason to proceed with the model.

TABLE A.8. PFT MULTIVARIATE REGRESSION

```
  Source       SS          df        MS              Number of obs =     151
---------------------------------------              F(  4,    146) =   31.85
   Model   27.0736897      4  6.76842242              Prob > F      =  0.0000
Residual   31.0240086    146  .212493209              R-square      =  0.4660
---------------------------------------              Adj R-square  =  0.4514
   Total   58.0976982    150  .387317988              Root MSE      =  .46097

Variable   Coefficient    Std. Error       t      Prob >  t        Mean
---------------------------------------------------------------------------
lnpftflw                                                          8.034428
---------------------------------------------------------------------------
lnflow50      .6775773      .0848703     7.984     0.000        7.235021
  forced      .2912196      .0938358     3.104     0.002        .2649007
   start      .2102294      .0822259     2.557     0.012        .2980132
 windows      .1689419      .1047911     1.612     0.109        .1523179
    cons      2.966614      .6059343     4.896     0.000               1
---------------------------------------------------------------------------
```

TABLE A.9. PFT REGRESSION VARIABLES CORRELATION MATRIX

```
          lnpftflw lnflow50   forced    start  windows
-------------------------------------------------------
lnpftflw   1.0000
lnflow50   0.6249   1.0000
  forced   0.4460   0.4151   1.0000
   start   0.1748   0.0095   0.0682   1.0000
 windows   0.1492   0.0638   0.0797   0.0059   1.0000
-------------------------------------------------------
```

In order to apply the statistical model developed from the regression analysis, several further steps were required. First assumptions about the response to the FORCED?, START, and WINDOWS? variables would have to be established for the general case being examined in the EIS. Second, the ad hoc adjustments to accommodate for mechanical ventilation would have to be made. Third, given that the regression was based on data that represented average effective ventilation rate the model would have to include a function that could be used to derive the average actual ventilation rate from the effective ventilation rate.

The first problem was dealt with differently for each of the variables. The START variable was true if the three month measurement period began sometime in October through December. After examining the weather data for the PFT measurement periods it was determined that those measurements for which the START variable was true was closer to the typical heating season weather than those for which the variable was false. Therefore the START coefficient would be lumped into the constant for purposes of the FEIS analysis to assume a more typical heating season.

The percentage of the population responding to the WINDOWS? question was taken from the RSDP occupant survey response and used for all housing types. Although there is some question about the representativeness of the RSDP control sample, it appears that their responses to the occupant survey indicated that they are not significantly different from other populations in their interaction with the buildings (Keating and Bavary 1986). For the FEIS analysis, ventilation rates would be calculated separately for people responding positively to the WINDOWS? question and for those responding negatively. The results would be weighted according to the percentages in the occupant survey.

Finally, the FORCED? variable was used in a similar fashion as the WINDOWS? variable but with different weightings based on the housing type being evaluated. Weightings for the FORCED? and WINDOWS? variables are given in Table A.10 below. For single and multifamily site built the weightings were based on the RSDP occupant survey results. For single family manufactured housing the weightings were based on discussions with the fifteen Northwest manufacturers.

In order to adjust the results for mechanical ventilation, the weighted ventilation rate computed from the regression model was adjusted by adding an amount of mechanical ventilation computed from the engineering model results. For each building type and package of air leakage control/ventilation system, the difference in average effective ventilation rates between the building with and without the mechanical ventilation system was computed. This difference was assumed to be the amount of average effective ventilation contributed by the mechanical ventilation system. This ventilation was then added to the results from the regression model.

Finally, the output of the regression model with mechanical ventilation had to be transformed to produce an estimate of the average actual ventilation rate. The approach that seemed most straight forward was to use the results from the engineering model to compute a ratio of average actual ventilation rate to average effective ventilation rate for each air leakage control/ventilation systems package. This ratio would then be used to multiply the output of the regression model with mechanical ventilation to compute the average actual ventilation rate for a specific set of assumptions.

One other detail that was necessary was to account for a specific feature of some of the air leakage control/ventilation system packages was a means to incorporate the effects of fresh air intake vents (discussed more thoroughly in section A.4). In order to account for this difference, the statistical model was adjusted in a fashion similar to that for the actual/effective ventilation rate adjustment. A ratio of the effective ventilation rate with and without fresh air intakes was used to multiply the effective ventilation rate from the statistical model before adding mechanical ventilation.

The final equation to calculate the average effective ventilation rate for the statistical model is of the form shown in equation 10 below.

$$\text{Qtotal effective} = ((\text{F1}*\text{Qfanw}+\text{F2}*\text{Qfaw}+\text{F3}*\text{Qznnw}+\text{F4}*\text{Qznw})*\text{Rslots})+\text{MV} \qquad \text{Eq. 10}$$

where:

Qtotal effective	is the average effective ventilation rate
F1-F4	are weighting factors for the appropriate percentages of the housing stock with the associated characteristics (Table A.10 below)
Qfanw	is the effective ventilation rate from the regression model assuming a forced air heating system and occupants that don't leave windows open at night
Qfaw	is the same as Qfanw but with no window openings at night
Qznnw	is the same as Qfanw but with zonal heat
Qznw	is the same as Qznnw but with no window openings
Rslots	Ratio multiplier for naturally induced ventilation to accommodate for the installation of fresh air intakes
MV	effective ventilation rate due to mechanical ventilation systems

The equation for average actual ventilation is given in equation 11 below.

$$\text{Qtotal actual} = \text{Qtotal effective} * \text{Ravg/eff} \qquad \text{Eq. 11}$$

where: Ravg/eff is the ratio of average to effective ventilation computed by the engineering model.

TABLE A.10. Weighting Factors for FORCED? and WINDOWS? Variables

FORCED?=1,		FORCED?=0	
WINDOWS?=1	WINDOWS?=0	WINDOWS?=1	WINDOWS?=0

Site Built Single Family	0.0798	0.490	0.0602	0.370
Manufactured Single Family	1.0	1.0	0.0	0.0
Site Built Multifamily	0.0798	0.490	0.602	0.370

A.4 MODELS INPUTS AND ASSUMPTIONS

In order for the models to provide output useful for making policy decisions, certain assumptions about the inputs have to made. For the FEIS analysis, it was necessary to make assumptions about the physical makeup of the various inputs to the models. This section describes the assumptions that were used to generate the results detailed in the following section.

Prototypes. The models were run using three prototypes, one for single-family site-built, one for single-family manufactured, and one for multifamily. The site-built prototype was a weighted composite of the same prototypes used in Bonneville's Cost-Effectiveness Evaluation (BPA 1986) and in the Council's MCS Analysis (NWPPC 1985). The manufactured home was assumed to be a double wide unit. Both the site-built and the manufactured home were assumed to be three bedroom with a combined living area of kitchen, dining, and living. The multifamily prototype was the four-plex townhouse used in the MCS Cost-Effectiveness Analysis. Given that neither model was capable of modelling multizone air flows, all prototypes including the four-plex were modeled as single zone buildings. The appropriate characteristics of the prototype buildings are presented in Table A.11 below.

TABLE A.11. Prototype Building Characteristics

	Single Family Site Built	Single Family Manufactured	Multifamily Site Built
Conditioned Floor Area	1651	1500	3456[1]
Conditioned Volume ft^3	13208	12000	29376[2]
Building height	18	10	18
Building Type	Two Story Split	Double Wide	Two Story 4-plex
Foundation Type	Crawlspace	Crawlspace	Crawlspace

1. Multifamily floor area is 1008 ft^2 per unit times four units
2. Multifamily volume is 6912 ft^2 per unit plus 1,728 ft^3 between floors

Leakage Characteristics. Given that the FEIS was designed to analyze various levels of air tightness in new homes it was therefore decided that the ventilation rate models should be exercised using one of three different levels of air leakage control. These levels would be applied to the prototype buildings for use in the models and were derived from the data sources described in section 2.0. The sources of the data are summarized in Table A.12 below. Average SLAs, LRs, and ACH50s from these sources were taken from the median values of the data sets and used to generate an appropriate equivalent leakage area for each prototype. The ELAs and ACH50s used are presented in Table A.13 below for the appropriate air leakage control package and housing type. A nominal value of 2.0 ACH50 was used for all advanced package houses for input to the statistical model assuming that this would produce the lower bound estimate.

TABLE A.12. Air Leakage Control Packages

Air Leakage Control Package	Site Built Data Source	Manufactured Data Source
Baseline	RSDP Control	Regional Test
Standard	RSDP Package A	Tulalip Project
Advanced	RSDP Package C	EEMHD

TABLE A.13. Prototype Leakage Characteristics
Equivalent Leakage Area (inches^2) and Air Changes per Hour at 50 Pascals

	Single Family Site Built		Single Family Manufactured		Multifamily Site Built	
ALC Package	ELA	ACH50	ELA	ACH50	ELA	ACH50
Baseline	87.8	8.02	89.6	8.17	131.7	5.14
Standard	62.9	5.12	63.6	5.48	84.6	3.31
Advanced	32.6	2.00	29.1	2.00	50.4	2.00

Mechanical Ventilation Systems. The FEIS was also intended to examine the effects of various types of mechanical ventilation systems on the total ventilation rate. Five types of ventilation systems were examined in combination with different air leakage control packages as described below.

1. Air-to-Air Heat Exchanger for Standard Air Leakage Control. In order to represent the effects of a balanced ventilation system, a small air to air heat exchanger was assumed to be installed in houses with standard air leakage control. These systems were assumed to be sized according to Bonneville's ventilation requirements of 10 cfm per bedroom plus 10 cfm for combined living areas. Therefore the single family units were assumed to have a 40 cfm unit and the multifamily units were assumed to have 30 cfm.

2. Exhaust Ventilation with Makeup Air Intakes for Standard Air Leakage Control. These systems consisted of the simple central exhaust fan (also serving as the spot ventilation system in the bath room) sized to meet the 10 cfm per bedroom plus 10 cfm requirement and included makeup air intakes

in each of the rooms. Due to minimum equipment sizing, the actual fan capacity was assumed to be 50 cfm. An additional effective leakage area to account for the extra area of the intakes was added to the total leakage area of the building for purposes of calculating the natural ventilation rate. The intake modelled was the Fresh 80 which has an adjustable opening that contributes from 1.2 to 1.8 inches^2 of ELA (DEC 1987). For single family site built and manufactured four intakes were assumed to be installed and operating half open in the houses with standard air leakage control. Multifamily units were assumed to have three intakes in each unit installed and operating fully open in houses with standard air leakage control packages.

3. Exhaust Ventilation without Makeup Air Intakes for Standard Air Leakage Control. These systems are identical to the system described above with the exclusion of the makeup air intakes.

4. Air-to-Air Heat Exchangers for Advanced Air Leakage Control. These systems were assumed to be central mechanical ventilation systems sized to provide a total of 0.25 ACH of balanced mechanical ventilation.

5. Exhaust Ventilation with Makeup Air Intakes for Advanced Air Leakage Control. These systems were assumed to be sized to meet the 10 cfm per bedroom plus 10 cfm requirement. Due to minimum equipment sizing, the actual installed flow rate of the exhaust fan was assumed to be 50 cfm. The makeup air intakes were assumed to be fully open in all three protoypes.

Varying control strategies for the mechanical ventilation systems were examined in the engineering model. The possible options for simulated control systems are listed in Table A.14 below.

TABLE A.14. MECHANICAL VENTILATION SYSTEMS

Control Option	Description
1	24 Hours/day continuous Operation
2	8 Hours continuous from 10 p.m. to 6 a.m.
3	8 Hours Intermittent from 6 a.m. to 8 a.m. and 4 p.m. to 10 p.m.
4	12 Hours continuous from 8 a.m. to 8 p.m.
5	Intermittent if natural ACH is less than minimum rate.

Engineering Infiltration Model Inputs. Since the engineering model is based on the LBL infiltration algorithms, it was necessary to make assumptions regarding the inputs to the LBL model that describe the locational aspects of the leaks in the building and the shielding and terrain factors of the building. For this analysis, the average values used for the RSDP were used. Table A.15 describes the various inputs and the values used for this analysis.

TABLE A.15. ENGINEERING INFILTRATION MODEL INPUTS

Input	Value
Interior Temperature	65 °F
Shielding Class	3
Terrain Class	3
Weather Station Terrain Class	2
Height of the Weather Station Wind Sensor	30 ft
Ratio of Leakage in Floors and Ceiling to Total Leakage	0.5
Ratio of the difference between Floor and Ceiling Leakage to Total Leakage	0.0

Weather Data. The engineering model was fed hourly temperature and windspeed data from typical meteorological year (TMY) tapes for Portland Oregon, Seattle Washington, Spokane Washington, Boise Idaho and Missoula Montana. The model performed calculations to determine the average actual and effective ventilation rates for the heating season defined as a period of 7 months from October through April for each location. The results from each location were then weighted together according to the weights given in Table A.16 to produce a single regional estimate of the ventilation rate for a given combination of inputs.

TABLE A.16. WEATHER FILE WEIGHTINGS

Location	Weight
Seattle	52%
Portland	28%
Spokane	12%
Boise	4%
Missoula	4%

The statistical model did not require weather data and consequently did not require weightings. However, the model coefficients were chosen to represent a typical heating season (see section A.3).

A.5 RESULTS

The engineering model was programmed into a microcomputer and exercised using various combinations of the air leakage control packages and ventilation systems described in section A.4. A copy of the program code for the engineering model is available in a report by Harris and Thor (1988). Because of its simplicity the statistical model was implemented on an electronic spreadsheet.

In all, eleven different combinations or "pathways" were analyzed along with a baseline run to establish the "current practice" ventilation rate for each housing type. A description of the features included in each pathway is provided in Table A.17. Each model ultimately produced an average actual and effective total ventilation rate for each of the pathways modeled. The report by Harris and Thor (1988) contains hardcopy output from the engineering model and the statistical model spreadsheet.

The set of predicted ventilation rates from either model that was the largest was defined as the upper bound estimate and similarly for the lower bound estimate. The results for each pathway are shown in Table A.18. All units are in air changes per hour.

Probably the most obvious conclusion one can draw from Table A.18 is that there are a few pathways that have very low ventilation rates and are probably not desirable from an environmental standpoint. Pathways 7 and 11 in all cases are considerably lower than the rest of the pathways. On the other hand, pathway 2 generally results in what might appear as over ventilation relative to current practice thus accruing an energy penalty that would offset any potential environmental benefits. Outside of these obvious conclusions, there is little distinction between the other pathways except that they can be classified into two groups: those marginally better than current practice and those marginally worse than current practice. Pathways 3,4 and 8 tend to fall into the former while pathways 1,5,6,9, and 10 tend to fall into the latter.

It is important however, to recognize that these values are estimates only and are useful primarily for comparison with similar values in the broader context of an environmental policy planning and development situation. Given the large standard deviations in the housing characteristics data and the limitations of the explanatory power of the statistical model, differences between pathways of less than 0.1 ACH should be viewed as within the error of the models and not necessarily a real difference. This information should be used to supplement applicable physical principles in the decision making process and not relied upon as a sole indicator of the true benefit or penalty associated with pursuing a given pathway.

TABLE A.17. PATHWAY DESCRIPTIONS

Pathway	Air Leakage[1]	Ventilation System[2]	Controls[3]
1	Standard	None[4]	N/A[5]
2	Standard	1. (Small AAHX)[6]	1. Continuous[7]
3	Standard	1. (Small AAHX)	3. Intermittent
4	Standard	2. (Exhaust Vent. w/Intakes)	1. Continuous
5	Standard	2. (Exhaust Vent. w/Intakes)	3. Intermittent
6	Standard	3. (Exhaust Vent. w/o Intakes)	3. Intermittent
7	Advanced	None	N/A
8	Advanced	4. (Large AAHX)	1. Continuous
9	Advanced	4. (Large AAHX)	3. Intermittent
10	Advanced	5. (Exhaust Vent. w/Intakes)	1. Continuous
11	Advanced	5. (Exhaust Vent. w/Intakes)	3. Intermittent
CP	Current Prac.	None	N/A

1. Air Leakage Control Package as defined in Table A.12
2. Ventilation System as described in section A.4
3. Control option for mechanical ventilation system as described in Table A.14
4. None includes spot ventilation (exhaust in fans in baths and kitchens) but no whole house ventilation system
5. N/A means not applicable
6. HRV means Heat Recovery Ventilator which was modeled assuming a balanced air to air heat exchanger
7. Operated approximately 8 hours per day

TABLE A.18. PATHWAY VENTILATION RATES

Site Built Single Family

	Upper Bound		Lower Bound	
Pathway	Actual	Effective	Actual	Effective
1	0.35	0.32	0.28	0.26
2	0.53	0.52	0.47	0.45
3	0.41	0.37	0.35	0.31
4	0.48	0.45	0.40	0.38
5	0.42	0.38	0.34	0.31
6	0.38	0.35	0.31	0.29
7	0.18	0.17	0.15	0.14
8	0.43	0.43	0.40	0.40
9	0.27	0.21	0.23	0.18
10	0.34	0.34	0.31	0.30
11	0.26	0.24	0.22	0.20
CP	0.49	0.45	0.38	0.35

Site Built Multifamily

	Upper Bound		Lower Bound	
Pathway	Actual	Effective	Actual	Effective
1	0.21	0.19	0.16	0.15
2	0.46	0.45	0.41	0.40
3	0.29	0.24	0.24	0.20
4	0.48	0.47	0.42	0.42
5	0.34	0.29	0.27	0.24
6	0.29	0.24	0.23	0.19
7	0.13	0.12	0.12	0.11
8	0.38	0.37	0.37	0.36
9	0.21	0.15	0.20	0.14
10	0.42	0.41	0.40	0.40
11	0.26	0.21	0.24	0.19
CP	0.33	0.30	0.22	0.20

Manufactured Single Family

	Upper Bound		Lower Bound	
Pathway	Actual	Effective	Actual	Effective
1	0.35	0.31	0.32	0.29
2	0.55	0.53	0.52	0.50
3	0.43	0.36	0.39	0.34
4	0.49	0.46	0.46	0.43
5	0.42	0.38	0.39	0.35
6	0.39	0.35	0.36	0.32
7	0.18	0.16	0.15	0.13
8	0.42	0.42	0.40	0.39
9	0.27	0.20	0.23	0.17
10	0.35	0.34	0.31	0.30
11	0.26	0.23	0.23	0.19
CP	0.46	0.41	0.45	0.41

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APPENDIX B

MODELING INDOOR POLLUTANT CONCENTRATIONS

Pacific Northwest Laboratory

B.1 INTRODUCTION

The potential effect that reduced ventilation levels in energy-efficient homes may have on indoor air pollutant levels is the key environmental impact identified in this Environmental Impact Statement. To assess this effect, we employ a steady state mass balance model to estimate changes in indoor pollutant levels resulting from the alternative pathways selected for assessment. This Appendix explains how this model works and is applied, discusses available alternative models and outlines the rationale for choosing the steady state mass balance approach to modeling.

The primary factors which influence the indoor concentration (mass/volume) of pollutants in residences are:

- Source strength or source rate of the pollutant (mass/time)
- Fresh air exchange rate (time-1)
- Home volume and mixing rate of the pollutant (volume)
- Pollutant reactivity/deposition/decay/removal (time-1)
- Outdoor concentration of the pollutant (mass/volume).

In general, analysis of empirical field measurement data of these basic factors suggests that the source emission rate, house volume and air exchange rate are the primary factors affecting long-term average pollutant concentrations in any given residence (Walsh et al. 1984). The effect of the removal/deposition/reactivity of the pollutant is generally small and highly dependent upon contributing factors such as the presence of other pollutants, indoor humidity, temperature or the structure itself. For these reasons, there is a wide range of removal/deposition/reactivity rates for indoor pollutants and these are generally a significant factor only at air exchange rates less than 0.1 ACH or when other pollutants are present in high concentrations (Walsh et al. 1984; Birensvige 1986; U.S. DOE 1987; Meyer 1983).

B.2 STEADY-STATE MODELING

The interrelationship of these basic factors is commonly explained through the use of mathematical models that are used to estimate indoor pollutant concentrations. The basic starting point for most modeling is the principle of conservation of mass, which theoretically balances the generation and loss of a pollutant within the home. The models that are the simplest and easiest to use treat the home as a single large compartment and assume that the variables remain constant over a long time period. The "steady state" equation representing this relationship is written as:

$$QCi + RCi = QCo + S/V \qquad (1)$$

Where: Q = air exchange rate
Ci = indoor concentration of the pollutant
R = pollutant removal rate (deposition/reaction/decay/adsorption)
Co = outdoor concentration of the pollutant
S = emission or source rate of the pollutant
V = volume of the home

To solve for the indoor pollutant concentration, this equation can be rewritten as:

$$Ci = \frac{QCo + S/V}{Q + R} \qquad (2)$$

Two other basic assumptions (in addition to time independence) are used to develop this model. One assumption is complete mixing of the pollutant, that is, the pollutant concentration does not vary spatially within the home. This assumption is valid over long time periods during which the source rate of the pollutant does not vary. The other assumption is that the removal of the pollutant (R) is represented as a single parameter representing all removal mechanisms.

If one assumes that the removal term (R) is small and the outdoor concentration (Co) is also small and insignificant, the equation can be reduced to the following:

$$Ci = S/VQ \qquad (3)$$

This equation is identical to equation 2.1 in the EIS.

This model (in various forms) has been used for several years by researchers to describe the relationship between air exchange rate and indoor and outdoor air pollutant concentrations and to reasonably calculate the average concentration of pollutants expected to be found indoors given the model parameters (Walsh 1984; Wadden and Scheff 1983; U.S. DOE 1985; Sexton et al. 1983; Fleming and Associates 1985; Woods et al. 1981; BPA 1984). For example, this steady state equation has been used to determine the indoor concentration of nitrogen dioxide, a combustion pollutant, to evaluate the potential health effect of human exposure to this pollutant (U.S. DOE 1985). Equation 1 was also the basis for the development of the ASHRAE 62-81 ventilation standards for acceptable indoor air quality (ASHRAE 1981).

B.3 DYNAMIC MODELING

This mass balance equation can also be written as a dynamic time-dependent model to show the effect of varying the parameters over time (such as the air exchange rate or pollutant source emission rate). This model is useful for determining peak concentrations and the time these peak concentrations occur.

Equation 1 can be written in differential form as follows:

$$\frac{dCi}{dt} = QC + \frac{S}{V} - (Q+R)\ Ci \tag{4}$$

Equation 4 can be solved for the indoor pollutant concentration as a function of time. The resulting equation contains both a steady-state portion and a transient portion and looks like the following:

$$Ci(t) = \frac{QC + S/V}{Q + R}\left[1-e^{-(Q+R)t} + Ci(0)\ e^{-(Q+R)t}\right] \tag{5}$$

Both the steady state and dynamic models serve the purpose of qualitatively determining indoor levels of pollutants in any given home. These models have broad applicability, relative simplicity and general accuracy in predicting average long-term pollutant concentrations given any of the input parameters. These models avoid introducing more complex factors such as nonuniform mixing, multiple compartments, and spatial distribution that, if incorporated into the model, would not qualitatively improve the results (pollutant concentration determination) over a long time period. More complex modeling would also require the use and expense of large capacity computer systems to run the model as well as a thorough understanding of the correct input parameters and interpretation of the output values which scientists have not yet developed.

B.4 SENSITIVITY ANALYSIS

Using the mass balance model, an analysis was performed to determine the sensitivity of the indoor pollutant concentration to the various factors that affect it (i.e. house volume, air exchange rate, reactivity, outdoor concentration, source emission rate) (Wadden and Scheff 1983; U.S. DOE 1985). The analysis indicated that the relative importance of the parameters are:

1. Source emission rate
2. House volume
3. Outdoor concentration
4. Air exchange rate
5. Reactivity or removal rate.

For any given pollutant in any given house or structure, if one assumes a constant source emission rate (S), constant house volume (V), constant outdoor pollutant concentration (Co) and complete mixing, the indoor pollutant concentration (Ci) is inversely proportional only to the air exchange rate and the reactivity or removal rate. (The removal rate refers to plateout or filtration or to a removal technique other than ventilation).

For most pollutants in the indoor environment, the significance of the removal term on the indoor concentration is small compared to the effect of the air exchange rate, except at very low air exchange rates (less than 0.1 ACH) (U.S. DOE 1985). And, as shown in the sensitivity analysis, the removal term is dominated by the source term for most pollutants.

For example, the indoor radon concentration in homes has been modeled using the above mass balance equation (Walsh et al. 1984; Abu-Jarad and Fremlin 1982; Figley 1986). The removal term (decay constant and progeny plateout on surfaces) for the indoor radon ranges from 0.0075 to 0.011 h-1, or approximately 10% of the total ventilation rate in a home with an air exchange rate of 0.1 ACH. Therefore, ignoring this term, and assuming a constant source emission rate and constant outdoor concentration, would result in an equation that shows the pollutant concentration inversely proportional to the air exchange rate only.

B.5 COMPARISONS WITH EMPIRICAL OBSERVATIONS

It is important to recognize in this discussion that no field study reported to date has shown that indoor pollutant concentrations behave exactly as Equation 1 would predict. This is primarily due to the unsteady state nature and unpredictability of the source term (S) and the removal term (R). However, in most field studies, for most pollutants of concern indoors, the observed increase in pollutant concentrations is generally consistent with a decrease in air exchange rate.

For example, in a recent study conducted for the Electric Power Research Institute, a home was retrofitted with measures to reduce the air exchange rate. Pollutants were monitored before and after retrofitting and with and without the use of an air-to-air heat exchanger (AAHX) (EPRI 1985). The observed changes (increases and decreases) in the gaseous pollutant concentrations (radon, formaldehyde, CO, NO2) were generally consistent with the changes in air exchange rate predicted by Equation 1 although not exactly proportional. For formaldehyde and NO2, tightening the house to reduce the air exchange rate did not significantly increase the pollutant levels; however, operation of the AAHX (to increase the air exchange rate) did significantly decrease the concentrations of these pollutants. For CO and radon, the reduction of the air exchange rate due to tightening increased these pollutant concentrations by an amount consistent with the decrease in the air exchange rate, although not proportional to amounts predicted by Equation 1.

A series of mass balance models similar to equation 1 have recently been used to examine radon control measure effectiveness (Green et al. 1986). In this study each of the three common radon progeny species found indoors were modeled using three equations. After the first equation for each species, the supply rate (source) of radon in each subsequent equation is simply the decay rate of the parent of the particular species. The modeling results in a series of coupled, linear differential equations which are solvable by separation of variables techniques. This approach accounts for the "aging" of the radon gas indoors to form the radon daughters, the radon species that attach to particles inhaled by the occupants. This is the form of radon that contributes most of the radiation dose to lung tissue and leads to lung cancer.

In these analyses, a constant source emission rate (S) of radon gas into the home is assumed and the effect of air exchange rate (Q) on indoor radon concentration is determined. The results indicate a high sensitivity of indoor radon concentration to the air exchange rates, even greater than the expected inverse relationship. This was attributable to the dual beneficial effects of air exchange with relatively pure (outdoor) air. The results also indicated that increasing the air exchange rate not only dilutes the radon species concentration proportionally, but also reduces the "age" of the air indoors which in turn reduces the residence time of the radon (parent) gas. This means that the radon gas entering the home is less likely to decay to the radon progeny (daughters) before being released into the indoor environment.

These results indicate that, with a constant source emission rate, an increase in air exchange rate will more than proportionally decrease radon levels indoors. Therefore, one can predict radon levels indoors under varying air exchange rates with confidence using equation 1 even if the removal term is ignored.

In its Technical Guidance Handbook for Radon Reduction Techniques for Detached Houses, the U.S. EPA also indicates that the proportional inverse relationship between air exchange rate and radon concentration is valid in homes with a low initial air exchange rate (0.1-0.6 ACH) (EPA 1986). However, this relationship may not hold for homes with air exchange rates greater than 1 ACH.

If this inverse relationship is therefore a valid relationship for predicting pollutant levels, and for evaluating the effect of air exchange rate on indoor air pollutant levels, then why do field experiments in large samples of homes suggest that the relationship does not hold true? The answer is relatively straightforward and refers to the development and assumptions of the mass balance modeling approach in Equation 1.

As stated, indoor pollutants exhibit widely variable source emission rates and can emanate from a number of locations in a home. This is not only true of pollutants that are primarily occupant-generated (such as carbon monoxide and nitrogen oxides), but is also true for pollutants such as radon and formaldehyde that are not primarily occupant-generated. For example, the primary source for radon is from the soil and the source strength (emission rate indoors) is dependent upon ground moisture, indoor-outdoor pressure differences and the pathways in the foundation and floor through which the radon enters the home (EPA 1986).

It is true that in any given home, for any measurement period, one may find that the indoor concentration of pollutants of interest are not significantly affected by the air exchange rate. Studies by Lawrence Berkeley Laboratory have shown that indoor radon concentrations in a home do not change significantly after weatherization and tightening to reduce the air exchange rate or when there is an observed variation in the air exchange rate over several measurement periods (Nazaroff et al. 1985; Turk et al. 1986).

The large variations seen in the measurements of radon vs. air exchange rate also suggest there may be significant uncertainties in measuring the radon concentrations and corresponding air exchange rates (Piersol 1986).

The highly variable pollutant sources and source emission rates are the primary reasons the inverse relationship between indoor pollutant concentration and air exchange rate does not appear to be proportional across a large sample of homes (Harris 1987). In particular, significant variations in radon source strengths due to atmospheric conditions (which influence the soil emanation rate and pressure-driven flow indoors) cannot be easily incorporated into a model and can confuse any results from radon control measure studies (Green et al. 1986; Turk et al. 1986). Formaldehyde source rates are influenced by temperature and humidity levels and these factors are incorporated into models to determine the source emission rate (Wadden and Scheff 1983; Green et al. 1986).

Empirical observations (field measurements) do not negate the physics of Equation 1 which state that the indoor concentration is affected proportionally and inversely by the air exchange rate. The equation must still balance and the indoor concentration of a pollutant will still be affected by the ventilation rate in any given time period. Rather, the observations indicate that one of the other terms in the equation (source emission rate, outdoor concentration or pollutant removal rate) has likewise (along with the ventilation rate) changed. In the studies identified above, the researchers speculate that the source term is changing due to a change in indoor-outdoor pressure differences (influenced by the tightening in one study and fireplace operation in the other) and/or from changing soil or weather conditions.

B.6 RATIONALE FOR THE STEADY STATE MASS BALANCE APPROACH

Our intention in this EIS is to make comparisons between alternatives and pathways rather than predicting the absolute pollutant concentrations. The use of a dynamic model to predict concentration levels may or may not change the absolute pollutant concentrations predicted for each of the pathways compared to the steady-state model, but will not change the relative relationship of pollutant concentrations associated with each pathway.

Analysis has been based on actual data collected from homes throughout the Pacific Northwest. Radon measurements were taken using the Track-Etch method and formaldehyde was measured using passive samplers. Both of these techniques provide a time integrated average concentration. To use these data with anything but a steady-state model would require manipulating the data and increasing the uncertainty of our assessment. Alternative sources of pollutant data in Northwest homes that could be more applicable to a dynamic model are from a much smaller sample of homes and are not as representative of new homes.

As indicated, scientists do not understand the factors that cause changes in source terms and therefore either use a model that relates concentrations and air exchange rates based on site-specific data or generalize by using the steady state model. In our application, developing a more complex model would require additional expense that would not result in increased accuracy or proficiency.

Based on the available empirical data for homes in this region, an incomplete understanding of pollutant source terms and the factors influencing these source terms, the increased cost of developing a dynamic model, and the comparative (rather than predictive) nature of our analysis, we believe that the steady state model is best suited for this analysis.

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APPENDIX C

INDOOR AIR POLLUTANT LEVELS AND ESTIMATED REGIONAL HEALTH EFFECTS

Pacific Northwest Laboratory

To determine the indoor air pollutant levels in new homes and to estimate the regional health effects of these pollutant levels in homes built to current construction methods and to Model Conservation Standards (MCS), a computer model was developed. The computer program was written to estimate the impact of various house tightening and indoor air quality (IAQ) mitigation measures on occupants of new homes. The impacts were given in terms of the number of occupants who, during their lifetime, develop cancer from exposure to radon and formaldehyde in the homes. This appendix documents the input data used in these calculations and describes the calculations used in the computer model and the cases that were modeled.

C.1 DATA

Pollutant concentrations for formaldehyde, radon, and nitrogen oxides and air exchange rates are presented in Section C.1. Concentration data available both in 1985 and 1986 are presented to show how the number of data points in the data sets increased from 1985 to 1986. The concentration and air exchange data specifically used for the computer model are presented in Section C.1.5. In Sections C.1.6 through C.1.9 data for pollutant risk factors, housing specifications, occupancy forecasts, and housing forecasts are presented.

C.1.1 Formaldehyde Data

Several sources of formaldehyde data were analyzed prior to choosing the data to be used as input to calculate the estimated regional health effects. The studies from which the data were selected were those by Reiland, McKinstry, and Thor (1985); Lawrence Berkeley Laboratory (1985); Parker (1986); Clark (1983); and BPA (1987).

The studies measured concentrations in both homes constructed to the prevailing construction practices and homes constructed to meet the MCS. The homes were located in three climate zones: Climate Zone 1 - $\leq$ 6000 heating degree days; Climate Zone 2 - 6000 to 8000 heating degree days; and, Climate Zone 3 - $>$ 8000 heating degree days. In the Residential Standards Demonstration Project (RSDP) some control and MCS homes were designated to be matched pairs. Matched pair homes are similar in design details except that one home meets prevailing building code and the other meets MCS. If the data set of matched pairs were large enough, this would have been an ideal data set to use to compare the effects of current code to those of MCS construction practices in regard to indoor IAQ.

C.1.1.1 Formaldehyde Data for Site-Built Homes

The formaldehyde concentration data collected in 1985 by the Bonneville Power Administration (BPA) in the RSDP single-family residences are listed in Table C.1 (Reiland et. al 1985). The data are grouped by climate zone and home construction method.

Data collected by the BPA in the RSDP in 1986 are listed in Table C.2. This data set augments the 1985 data shown in Table C.1. Data are available for both single-family and multifamily homes by climate zone and construction method.

TABLE C.1. Summary of 1985 RSDP Formaldehyde Concentration Measurements

Case	Number of Observations	Formaldehyde Concentration, ppm Median	Mean + Std Dev	Max	Min
Zone 1 MCS(a)	90	0.100	0.114 ± 0.058	0.376	0.033
Zone 1 Cont(b)	235	0.086	0.091 ± 0.043	0.245	0.021
Zone 2 MCS	40	0.099	0.100 ± 0.051	0.282	0.028
Zone 2 Cont	43	0.080	0.086 ± 0.033	0.204	0.030
Zone 3 MCS	52	0.117	0.120 ± 0.047	0.252	0.041
Zone 3 Cont	70	0.113	0.103 ± 0.045	0.199	0.027

(a) MCS - Constructed to Model Conservation Standards.

(b) Cont - Constructed to 1983 practice.

TABLE C.2. 1986 RSDP Formaldehyde Concentration Data

	1983 Practice				MCS			
Climate Zone	Sample Size	HCHO Conc., ppm Mean	Min	Max	Sample Size	HCHO Conc., ppm Mean	Min	Max
Single-family								
1	160	0.09	0.02	0.21	168	0.09	0.02	0.27
2	31	0.09	0.03	0.17	54	0.08	0.02	0.19
3	38	0.08	0.03	0.15	60	0.09	0.03	0.19
Total	229	0.09	0.02	0.21	282	0.09	0.02	0.27
Multifamily								
1	12	0.12	0.05	0.18	90	0.07	0.02	0.21
2	3	0.07	0.06	0.09	15	0.05	0.02	0.09
3	0	----	----	----	0	----	----	----
Total	15	0.11	0.05	0.18	105	0.07	0.02	0.21

Formaldehyde concentration data from the New Home Indoor Air Quality Study, a study conducted by Lawrence Berkeley Laboratory (LBL), are listed in Tables C.3 and C.4. In the study, concentrations were measured in homes constructed to the prevailing construction practices and homes constructed to meet the MCS. The homes studied were located in only two climate zones: Climate Zone 1 (≤ 6000 heating degree days) and Climate Zone 2 (6000 to 8000 heating degree days). No homes in Climate Zone 3 (> 8000 heating degree days) were included in the study. This study did not attempt to match homes of similar design in the control and MCS groups. To determine the effects of higher formaldehyde concentrations, two formaldehyde concentration ranges were specified: concentrations ≤ 0.1 ppm and concentrations ≥ 0.1 ppm. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) recommend a 0.1 ppm ceiling for continuous exposure to formaldehyde (Wehner et al. 1986).

In climate zone 2, only one data point fell into the high concentration level. Since so few data points were available, all the data were grouped together by concentration levels. No air exchange rates were measured when LBL collected the formaldehyde data.

TABLE C.3. Summary of Formaldehyde Concentration Data from the LBL New Home Indoor Air Quality Study

		Formaldehyde Concentration, ppm					
		MCS Home			Control Home		
Climate Zone	Sample Description	Size	Mean	Std. Dev.	Size	Mean	Std. Dev.
1	≤ 0.1 ppm	8	0.071	0.020	10	0.059	0.023
1	≥ 0.1 ppm	8	0.172	0.078	8	0.147	0.036
2	≤ 0.1 ppm	12	0.064	0.020	13	0.059	0.019
2	≥ 0.1 ppm		No Data Points		1	0.158	-----

TABLE C.4. Analyzed Formaldehyde Concentration Data From the LBL Study

	Formaldehyde Concentration, ppm					
	MCS Home			Control Home		
Sample Description	Size	Mean	Std. Dev.	Size	Mean	Std. Dev.
≤ 0.1 ppm	20	0.067	0.029	23	0.059	0.020
≥ 0.1 ppm	8	0.172	0.078	9	0.149	0.034

The data in Table C.3 were evaluated to determine the percentage of homes in each climate zone that have either low or high formaldehyde concentration levels. The data were assumed to provide a statistically valid sample from the population of homes. This summary is presented in Table C.5.

TABLE C.5. Distribution of Homes With High and Low Formaldehyde Levels

Climate Zone	Percentage of Homes ≤0.1 ppm	 > 0.1 ppm
1	53	47
2	54	46
Total	72	28

C.1.1.2 Formaldehyde Data for Manufactured Homes

Parker (1986) measured the formaldehyde concentrations and air exchange rates in five new MCS manufactured homes constructed with low formaldehyde-emitting products. The measurements are summarized in Table C.6. Data from Weyerhaeuser listed only air exchange rates for manufactured homes (Clark 1983). The measurements were acquired in 1982 and are listed in Table C.7.

TABLE C.6. New Manufactured Home Data

Air Exchange Rate, ACH			Formaldehyde Concentration, ppm		
Number	Mean	Std Dev	Number	Mean	Std Dev
16	0.131	± 0.073	16	0.111	± 0.051

TABLE C.7. Weyerhaeuser Mobile Home Air-Exchange Data

Category and Number of Homes Measured	Infiltration Rates, ACH
Overall average 22 homes, 23 measurements	0.28
Average of measurements at ≤8 km/hr wind; 15 homes	0.24
Average of measurements at > 8 km/hr wind; 7 homes, 8 measurements	0.35
Average of transported mobile homes; 11 homes	0.26
Average of mobile homes measured at manufacuring site; 11 homes	0.26

C.1.2 Radon Data

Three studies to measure the radon concentration in homes were conducted: Preliminary Radon Testing Results for the Residential Standards Demonstration Program (Reiland, McKinistry and Thor 1985); New Homes Indoor Air Quality Study (Lawrence Berkeley Laboratory 1985); and 1986 RSDP Data Base compiled by New Residential Construction Branch, Division of Residential Programs (BPA 1987). All three studies measured concentrations in homes built to both 1983 practice and to the MCS in all three climate zones. These homes formed the group from which the formaldehyde data were obtained.

C.1.2.1 1985 RSDP Radon Data

The radon concentration data collected by BPA in 1985 in the RSDP are listed in Table C.8. Two radon concentration levels were specified, although most homes were found to have radon concentrations ≤5 pCi/l, a small fraction of the homes had radon concentrations > 5 pCi/l.

TABLE C.8. Summary of Single-Family Housing Radon Testing Results for the RSDP in 1985

		MCS Home			Control Home		
			Radon Conc. (pCi/l)			Radon Conc. (pCi/l)	
Climate Zone	Sample Description	Sample Size	Mean	Std. Dev.	Sample Size	Mean	Std. Dev.
1	Matched	3	1.43	1.15	1	1	---
1	Mat + Unmat ≤ 5 pCi/l	51	0.751	0.842	72	0.818	0.773
1	Unmatched > 5 pCi/l	5	8.34	3.24	2	17.2	11.1
2	Matched	2	2.60	2.00	2	0.750	0.050
2	Mat + Unmat ≤ 5 pCi/l	28	2.03	1.42	14	1.85	1.41
2	Unmatched > 5 pCi/l	7	11.9	3.89	3	9.63	5.36
3	Matched ≤ 5 pCi/l	2	2.05	0.150	3	3.33	1.02
3	Matched > 5 pCi/l	2	8.45	1.15	2	9.15	3.25
3	Mat + Unmat ≤ 5 pCi/l	38	2.43	1.24	38	2.64	1.19
3	Mat + Unmat > 5 pCi/l	12	10.1	6.31	16	11.3	5.06

C.1.2.2 1986 RSDP Radon Data

The radon concentration data collected by BPA in 1986 in the RSDP are listed in Table C.9. Since the 1986 sample size for the single-family homes is much larger than that available in 1985, median values are presented instead of mean values for single-family homes. Median values are used because an extremely high concentration does not affect the median value as much as it affects the mean value. Since much smaller data sets were available for multifamily homes, mean instead of median values are used. Data are grouped by climate zone, construction method, radon concentration level, and housing type. Data are available for both single-family and multifamily homes. Two radon concentration levels were specified; although most homes were found to have radon concentrations ≤ 5 pCi/l, a small fraction of the single-family homes had radon concentrations > 5 pCi/l. No multifamily homes were found with radon concentrations above 5 pCi/l.

TABLE C.9. 1986 RSDP Radon Levels by Climate Zone

		Single-Family Homes			
		1983 Practice		MCS	
Climate Zone	Sample Description (pCi/l)	Sample Size	Median (pCi/l)	Sample Size	Median (pCi/l)
1	≤ 5	268	0.40	189	0.39
1	> 5	5	9.88	5	7.22
2	≤ 5	37	1.51	48	1.42
2	> 5	10	9.65	13	8.07
3	≤ 5	53	2.09	48	2.34
3	> 5	18	9.65	21	7.67

		Multifamily Homes			
		1983 Practice		MCS	
Climate Zone	Sample Description (pCi/L)	Sample Size	Mean (pCi/l)	Sample Size	Mean (pCi/l)
1	≤ 5	10	1.49	61	0.50
1	> 5	0	--	0	--
2	≤ 5	4	1.35	13	0.91
2	> 5	0	--	0	--
3	≤ 5	0	-- (a)	0	-- (a)
3	> 5	0	--	0	--

(a) Data from Climate Zone 2 used for Climate Zone 3

C.1.2.3 LBL Radon Data

The radon concentration data collected by LBL in the New Homes Indoor Air Quality Study are listed in Table C.10. This study did not attempt to match homes of similar design. The percentage of homes in each climate zone that have either low or high radon concentration levels was determined from the data in Table C.9 and is presented in Table C.11. The data were assumed to be a statistically valid sample from the population of homes. From the data set of 89 multifamily homes, none had high radon concentrations.

TABLE C.10. Summary of Radon Concentration Data in Single-Family Homes from the New Home Indoor Air Quality Study (LBL 1985)

		MCS Home			Control Home		
			Radon Conc. (pCi/L)			Radon Conc. (pCi/L)	
Climate Zone	Sample Description	Sample Size	Mean	Std. Dev.	Sample Size	Mean	Std. Dev.
1	≤ 5	16	1.39	1.07	18	1.24	0.820
1	> 5	1	7.60	--	No	Data	Points
2	≤ 5	9	1.37	0.952	11	2.75	1.19
2	> 5	3	12.3	5.40	3	12.0	2.39

TABLE C.11. Distribution of Homes Between High and Low Radon Levels

	Percentage of Single-Family Homes	
Climate Zone	≤5 pCi/l	>5 pCi/l
1	98	2
2	79	21
3	72	28

	Percentage of Multifamily Homes	
Climate Zone	≤5 pCi/l	>5 pCi/l
1	100	0
2	100	0
3	100	0

C.1.3 Nitrogen Dioxide Data

A small amount of data was available which documented the amount of nitrogen dioxide in homes built to the current construction codes and to the MCS. The source of the data was the New Homes Indoor Air Quality Study (LBL 1985).

The LBL nitrogen dioxide concentration data are presented in Table C.12. The data are grouped by climate zone and type of construction. No data measurements were made in climate zone 3. The data were divided into two nitrogen dioxide levels ≤ 4.0 ppm and > 4.0 ppm based on our evaluation of the data set spread and a comparison with data for the effects of short-term exposures to nitrogen dioxide (Wehner et al. 1986). Eighty-one (81) percent of the measurements were ≤ 4.0 ppm. No air exchange rates were measured when LBL collected the nitrogen dioxide data.

TABLE C.12. Summary of NOx Concentration Data from the LBL New Home Indoor Air Quality Study

		MCS Home			Control Home		
Climate Zone	Sample Description	Sample Size	NOx Conc. (ppm) Mean	NOx Conc. (ppm) Std. Dev.	Sample Size	NOx Conc. (ppm) Mean	NOx Conc. (ppm) Std. Dev.
1	≤ 4.0 ppm	13	2.02	0.95	16	2.02	0.82
1	> 4.0 ppm	3	5.60	1.02	2	5.75	1.65
2	≤ 4.0 ppm	9	2.12	0.82	10	2.11	0.73
2	> 4.0 ppm	3	5.50	0.94	3	5.80	0.78

C.1.4 Air Exchange Data

Two methods were used to estimate the air exchange rates in homes: the blower door technique and the perflurocarbon tracer technique.

C.1.4.1 Blower Door Air Exchange Rates

The average air exchange rates associated with the 1985 RSDP data set (Table C.1 for formaldehyde data and Table C.10 for radon data) are presented in Table C.13. Due to the small size of the data set, mean values are presented for the 1985 data.

Since the size of the 1986 data set is much larger than the 1985 data set, the median air exchange rates associated with the 1986 RSDP data set (Table C.2 for formaldehyde data and Table C.9 for radon data) are presented in Table C.14. Median values are presented instead of mean values because an extremely high air exchange rate does not affect the median value as much as it affects the mean value. Almost no data are available for multifamily homes.

TABLE C.13. Average Air Exchange Rate for 1985 RSDP Data (Blower Door Technique)

	Air Exchange Rate, ACH	
Climate Zone	1983 Practice	MCS Construction
1	0.56	0.27
2	0.44	0.23
3	0.43	0.23

TABLE C.14. Median Air Exchange Rate for 1986 RSDP Data Set (Blower Door Technique)

Climate Zone	Single-Family House Air Exchange Rate, ACH			
	Radon Level 1 ≤5 pCi/l		Radon Level 2 >5 pCi/l	
	Control	MCS	Control	MCS
1	0.56	0.22	0.52	0.22(a)
2	0.36	0.20	0.53	0.24
3	0.42	0.24	0.35	0.21

Climate Zone	Multifamily House Air Exchange Rate, ACH			
	Radon Level 1 ≤5 PCi/l		Radon Level 2 >5 pCi/l	
	Control	MCS	Control	MCS
1	----	0.33	----	----
2	----	----	----	----
3	----	----	----	----

(a) No data available, value from Radon Level 1 substituted.

C.1.4.2 Perfluorocarbon Tracer (PFT) Gas Air Exchange Rates

The median air exchange rates associated with the 1986 RSDP data set (Table C.2 formaldehyde data and Table C.9 radon data) are presented in Table C.15. Median values are presented instead of mean values because an extremely high air exchange rate does not affect the median value as much as it affects the mean value. Almost no data are available for multifamily homes.

TABLE C.15. Median Air Exchange Rate for 1986 RSDP Data (Perfluorocarbon Tracer Technique)

Climate Zone	Single-Family House Air Exchange Rate, ACH			
	Radon Level 1 ≤5 pCi/l		Radon Level 2 >5 pCi/l	
	Control	MCS	Control	MCS
1	0.33	0.26	0.59(a)	0.26(b)
2	0.20	0.17	0.18	0.43(a)
3	0.18	0.23	0.19	0.25

Climate Zone	Multifamily House Air Exchange Rate, ACH			
	Radon Level 1 ≤5 pCi/l		Radon Level 2 >5 pCi/l	
	Control	MCS	Control	MCS
1	----	0.54	----	----
2	----	----	----	----
3	----	----	----	----

(a) Not large enough sample, value from Radon Level 1 substituted.

(b) No data available, value from Radon Level 1 substituted.

C.1.4.3 Air Exchange Data Used For Analysis

Upon review of results from both the blower door and PFT tests and review of the literature, BPA selected an upper and lower bound of ventilation to bound the Baseline. The rates are listed in Table C.16. The rates given in Table C.16 are effective rates so as to incorporate the diurnal and seasonal variation in ventilation rates. For more information on how the rates were determined, see Appendix A.

C.1.5 Summary of Concentration and Air Exchange Data Used for Analysis

C.1.5.1 Data Used for Formaldehyde Analysis

The RSDP formaldehyde concentrations in current practice houses, shown in Table C.2, are used as input to formaldehyde health effects calculations. The formaldehyde concentrations are taken from the 1986 RSDP data, the most complete data set available. The concentration values from these homes were used to characterize both types of homes. MCS concentrations were scaled by volume and ventilation rate/concentration from the data for each climate zone and housing type. Since no data were available for manufactured homes that was representative throughout the climate zones, single-family data were scaled by volume to represent a data set for current practice manufactured homes. (See Section C.2.1.1.)

TABLE C.16. Expected Effective Air Exchange Rates for Northwest Homes Constructed to 1983 Building Practice

Housing Type	Upper Bound ACH	Lower Bound ACH
Single-family	0.45	0.35
Multifamily	0.30	0.20
Manufactured	0.41	0.41

C.1.5.2 Data Used for Radon Analysis

After further review of radon data collected under RSDP, it was decided the health effects analysis procedure should be based only on data collected from homes built to 1983 practice--mainly because RSDP was considered a demonstration program. As such, data collected from homes built to MCS are not considered representative of what might be found under normal conditions. The data used in the analysis are listed in Table C.17.

Table C.17. Median Radon Concentration Levels by Climate Zone for Single-Family Homes

Climate Zone	Conc. (≤5 pCi/l) Sample Size	Conc. (≤5 pCi/l) Value	Conc. (>5 pCi/l) Sample Size	Conc. (>5 pCi/l) Value
1	263	0.41	4	10.52
2	35	1.51	10	9.56
3	52	2.23	17	9.76

These values are slightly different from those in Table C.9. Some of the data, upon further review, were considered questionable and were removed from the sample. These concentrations were considered representative of conditions occuring in single-family homes built to 1983 building practice and not dependent on ventilation rate. Concentrations for other housing types were obtained by scaling the values in Table C.9 by the appropriate prototypical volume.

The data were used to characterize the radon concentrations in both 1983 construction and energy-efficient homes. Since no measured data were available for manufactured homes that were representative throughout the climate zones, single-family data were scaled by volume to represent a data set for current HUD code manufactured homes. (See Section C.2.1.1.)

C.1.5.3 Data Used for Air Exchange Rates

Data used for the health effects calculations were those listed in Appendix A. Effective rates were used to account for diurnal and seasonal variation of the natural infiltration rate.

C.1.6 Risk Factors

A risk coefficient is used to model the lifetime risk of exposure to a particular substance to general populations. For this analysis, we determined that the most appropriate factor to estimate the lifetime radon risk is 2.1×10^{-3} per pCi/l (Wehner et al. 1986). This risk coefficient accommodates the age of the occupants at first exposure to increased levels of indoor radon and increased mobility of populations. For example, the earlier in a person's life they are exposed to increased levels, the higher the probability of developing lung cancer. National age statistics were used to develop a single value for the region. The estimated number of lifetime lung cancers is considered to be conservative.

For this analysis, we determined that the most appropriate factor to estimate the formaldehyde lifetime risk is 1.09×10^{-3} per ppm. For more information about these risk factors and other health effects, see Sections 3.7 and 3.8 in the FEIS, and Appendix B, Potential Health Effects of Certain Indoor Air Pollutants, in Volume II of the DEIS.

C.1.7 Housing Specifications

Three types of houses were included in the model:

- Single-family
- Multifamily
- Manufactured housing.

The prototypical sizes and volumes were obtained from the Northwest Power Planning Council and are presented in Table C.18. The houses were assumed to have 8-ft ceilings. For more information about the area of the homes, see Appendix A, The New Homes Conservation Resource, in Volume II of the DEIS.

TABLE C.18. Prototypical Areas and Volumes

Type	Area, ft^2	Volume, ft^3
Single-Family	1,400	11,200
Multifamily	840	6,720
Manufactured Housing	1,170	9,360

C.1.8 Occupant Data

The number of occupants per house was provided by BPA. The data for Invester Owned Utilities were used for the analysis, as listed in Table C.19.

C.1.9 Housing Forecasts

Two housing forecasts were used to describe construction alternatives:

- Housing Forecast Assumption 1: Baseline
- Housing Forecast Assumption 2: MCS with Incentives through 1988.

The data for new electric additions are presented in Tables C.20 through C.22. The forecasts span the period from 1986 through 2006, a period of 21 years. The information in Table C.22 incorporates the assumption that not all utilities, or local jurisdictions, will adopt MCS and the fact that some residences built to MCS will not meet the desired thermal specifications.

TABLE C.19. Number of Occupants per Housing Type per Year

Year	Number of Occupants		
	Single-family	Multifamily	Manufactured Housing
1986	3.1	1.7	2.4
1987	3.1	1.7	2.4
1988	3.1	1.7	2.4
1989	3.1	1.7	2.4
1990	3.1	1.6	2.4
1991	3.0	1.6	2.4
1992	3.0	1.6	2.4
1993	3.0	1.6	2.3
1994	3.0	1.6	2.3
1995	3.0	1.6	2.3
1996	3.0	1.6	2.3
1997	3.0	1.6	2.3
1998	2.9	1.6	2.3
1999	2.9	1.6	2.3
2000	2.9	1.6	2.3
2001	2.9	1.6	2.3
2002	2.9	1.6	2.3
2003	2.9	1.6	2.2
2004	2.9	1.6	2.2
2005	2.9	1.5	2.2
2006	2.9	1.5	2.2

C.2 COMPUTER CODE

A computer code was written to calculate the number of lifetime cancers induced from formaldehyde and from radon concentrations present in homes with electric space heat to be constructed in the Pacific Northwest from 1986 to 2006.

The code evaluates the number of lifetime cancers induced from pollutant concentrations for various housing types and construction methods from 1986 through 2006. The methodology used to calculate the number of lifetime cancers induced is discussed in Section C.2.1. The cases modeled are described in Section C.2.2.

C.2.1 Methodology for Calculations

The pollutant concentration data were used as the basis for estimating the number of lifetime cancers induced for the various cases to be evaluated. Data for formaldehyde and radon are grouped by climate zone (CZ) and pollutant concentration level (RL).

TABLE C.20. Housing Forecast Assumption 1: Baseline

	New Electric Additions								
	Climate Zone 1			Climate Zone 2			Climate Zone 3		
Year	Single	Multi	Manuf	Single	Multi	Manuf	Single	Multi	Manuf
1986	14506	10208	5663	7333	3107	3084	1005	300	422
1987	17510	12475	6517	8851	3797	3549	1213	366	486
1988	16707	11867	6300	8446	3612	3431	1158	349	470
1989	20651	15131	7338	10439	4606	3996	1431	444	547
1990	18449	12843	6846	9326	3909	3728	1278	377	510
1991	19049	13261	7046	9630	4037	3837	1320	390	525
1992	17414	11829	6722	8803	3601	3661	1207	347	501
1993	17604	11927	6835	8899	3631	3722	1220	350	510
1994	18515	12609	7121	9360	3838	3878	1283	370	531
1995	17916	12127	7052	9057	3692	3841	1241	356	526
1996	18083	12360	7149	9141	3762	3893	1253	363	533
1997	18074	12349	7205	9137	3759	3924	1252	363	537
1998	18429	12689	7349	9316	3863	4002	1277	373	548
1999	18011	12377	7318	9105	3768	3985	1248	364	546
2000	18201	12611	7476	9201	3839	4071	1261	370	557
2001	18531	12818	7732	9368	3902	4211	1284	377	576
2002	19643	13755	8106	9930	4187	4414	1361	404	604
2003	18802	13208	7944	9505	4021	4326	1303	388	592
2004	18749	13281	8040	9478	4043	4378	1299	390	599
2005	18903	13540	8249	9556	4122	4492	1310	398	615
2006	19370	14043	8572	9792	4275	4668	1342	412	639

C.2.1.1 Pollutant Concentrations for Housing Types

For formaldehyde, concentration data are available only for single-family homes. For radon, concentration data are available for both single-family and multifamily homes. The source of concentration data used for each type is summarized in Table C.23. To determine the pollutant concentration levels in types for which no measured data were available, concentration data were scaled by volume.

Concentration is assumed to be proportional to the pollutant source strength, divided by the home volume and the number of air changes per hour, or

$$Ci = S/VQ$$

where: Ci = long-term concentration; units Mass/Volume
V = volume of home; units $Mass^3$
S = source strength; units Mass/T
Q = air changes per hour; units 1/T

TABLE C.21. Housing Forecast Assumption 2: Model Conservation Standards With Incentives

	New Electric Additions								
	Climate Zone 1			Climate Zone 2			Climate Zone 3		
Year	Single	Multi	Manuf	Single	Multi	Manuf	Single	Multi	Manuf
1986	15959	10256	5663	8068	3122	3084	1106	301	422
1987	19166	12548	6517	9689	3820	3549	1328	369	486
1988	17138	11915	6300	8663	3627	3431	1188	350	470
1989	16291	15045	7338	8235	4580	3996	1129	442	547
1990	13554	12744	6846	6852	3879	3728	939	374	510
1991	13634	13151	7046	6892	4003	3837	945	386	525
1992	12142	11716	6722	6138	3566	3661	841	344	501
1993	11960	11801	6835	6046	3592	3722	829	347	510
1994	12213	12477	7121	6174	3798	3878	846	366	531
1995	11448	11984	7052	5787	3648	3841	793	352	526
1996	11605	12216	7149	5867	3719	3893	804	359	533
1997	11659	12207	7205	5894	3716	3924	808	359	537
1998	11913	12551	7349	6022	3821	4002	825	369	548
1999	11674	12246	7318	5901	3728	3985	809	360	546
2000	11839	12480	7476	5985	3799	4071	820	367	557
2001	12106	12684	7732	6120	3861	4211	839	373	576
2002	12910	13611	8106	6526	4143	4414	895	400	604
2003	12414	13070	7944	6275	3979	4326	860	384	592
2004	12385	13142	8040	6261	4000	4378	858	386	599
2005	12472	13399	8249	6305	4079	4492	864	394	615
2006	12775	13896	8572	6458	4230	4668	885	408	639

Assuming that the source strengths and air exchange rates are constant and the same in each housing type, the ratio of concentrations reduces to, for example:

$$\frac{\text{Conc MFD}}{\text{Conc SFD}} = \frac{1/\text{Vol MFD}}{1/\text{Vol SFD}} = \frac{\text{Vol SFD}}{\text{Vol MFD}}$$

where SFD = single-family home and MFD = multifamily home; the concentration data are listed in Tables C.2 for formaldehyde and C.9 for radon. Volume data are listed in Table C.18.

This approach was used to calculate the radon and formaldehyde concentrations for the control and MCS homes by climate zone and to calculate the radon concentration level when measured concentration data for a specific housing type, climate zone, or radon level were not available.

The Proposed Action includes a radon package, which is applied to all the pathways. Builders have two options: to control the source or to monitor and then add mitigation measures if the radon concentration is above 5 pCi/l. These two options form the basis of the "Radon Package". The estimated adoption rates for the radon package options over time are listed in Table C.24.

TABLE C.22. Housing Forecast Assumption 2: Model Conservation Standards With Incentives With Assumed Adoption Schedule

	Climate Zone 1			Climate Zone 2			Climate Zone 3		
Year	Single	Multi	Manuf	Single	Multi	Manuf	Single	Multi	Manuf
1986	2394	1538	57	1210	468	31	166	45	4
1987	6708	4392	65	3391	1337	35	465	129	5
1988	7712	5362	63	3899	1632	34	534	157	5
1989	8145	7522	73	4118	2290	40	564	221	5
1990	8132	7647	68	4111	2328	37	564	225	5
1991	8180	7891	352	4135	2402	192	567	232	26
1992	7285	7029	538	3683	2140	293	505	206	40
1993	7176	7081	752	3627	2155	409	497	208	56
1994	7328	7486	997	3704	2279	543	508	220	74
1995	8586	8988	1199	4340	2736	653	595	264	89
1996	8704	9162	1501	4400	2789	818	603	269	112
1997	8744	9155	1801	4420	2787	981	606	269	134
1998	8935	9413	2131	4517	2865	1161	619	276	159
1999	8756	9185	2488	4426	2796	1355	607	270	186
2000	8880	9360	2841	4489	2849	1547	615	275	212
2001	9079	9513	3093	4590	2896	1684	629	279	231
2002	9683	10208	3405	4895	3107	1854	671	300	254
2003	9310	9803	3495	4707	2984	1904	645	288	261
2004	9289	9856	3698	4696	3000	2014	644	290	276
2005	9354	10049	3959	4729	3059	2156	648	295	295
2006	9581	10422	4286	4843	3172	2334	664	306	320

TABLE C.23. Source of Concentration Data

Home Type	Formaldehyde	Radon
Single-family	Measured	Measured
Multifamily	Scaled from Single-family	Measured
Manufactured Housing	Scaled from Single-family	Scaled from Single-family

For those homes built under the source control option, the homeowner is offered monitoring. If the radon concentration is greater than 5pCi/l, the homeowner has the option to implement mitigation measures.(*) For those homes built under the monitoring option, the builder must implement measures if the concentration is above 5 pCi/l. The radon concentration in all homes that mitigate was assumed to be reduced by 70%.

(*)a. Information contained in Vol. I of the FEIS, Section 4.1.2 (Estimated Pollutant Concentrations) provides assumed percentages of those homeowners choosing monitoring and of those implementing mitigation measures.

C.2.1.2. Air Exchange Rates. If the air exchange rates being modeled differ from those presented in Table C.13, the pollutant concentrations are scaled according to ventilation rate. This is essentially the measured, or scaled, concentration multiplied by the ratio of the air exchange rate for the alternative or pathway to the Baseline's air exchange rate.

TABLE C.24. Radon Package Adoption Rates

	Percent of Builders	
Time Period	Monitor/Mitigate	Source Control
1987 - 1992	25	75
1993 - 2002	40	60
2003 - 2006	80	20

C.2.1.3. Estimated Lifetime Cancers

To estimate the number of lifetime cancers resulting from the pollutant concentration in a home, the following set of formulas was used:

For formaldehyde

$$CC1 = RF*FORM(CZ,DT,FT,RL)*F1(Y,CZ,DT,1)*OC(Y,DT)*FR(CZ,RL,DT)$$

$$CC2 = RF*FORM(CZ,DT,FT,RL)*(F2(Y,CZ,DT,1)-F2(Y,CZ,DT,2))*OC(Y,DT)*FR(CZ,RL,DT)$$

$$MCS2 = RF*MFORM(CZ,DT,FT,RL)*F2(Y,CZ,DT,2)*OC(Y,DT)*FR(CZ,RL,DT)$$

For radon

$$CC1 = RF*RADON(CZ,DT,FT,RL)*F1(Y,CZ,DT,1)*OC(Y,DT)*FR(CZ,RL,DT)$$

$$CC2 = RF*RADON(CZ,DT,FT,RL)*(F2(Y,CZ,DT,1)-F2(Y,CZ,DT,2))*OC(Y,DT)*FR(CZ,RL,DT)$$

$$MCS2 = RF*MRADON(CZ,DT,FT,RL)*F2(Y,CZ,DT,2)*OC(Y,DT)*FR(CZ,RL,DT)$$

where CC1 and CC2 are the number of lifetime cancers in baseline homes and MCS2 is the number of lifetime cancers in MCS homes as a function of:

- year (y)
- climate zone (cz)
- pollutant level (FORM, MFORM, RADON, MRADON)
- housing type (DT)
- foundation type (FT)
- adoption schedule (F_1,F_2)
- occupancy (OC).

CC1 is based upon Housing Forecast 1, Baseline (Table C.20)

CC2 is based upon Housing Forecast 2, MCS with Incentives (Table C.21)

MCS2 is based upon Housing Forecast 2, MCS with Incentives (Table C.22)

RF is used to denote risk factor for formaldehyde and radon:

For formaldehyde

$RF = 1.09 \times 10^{-3}$ cancers per ppm of formaldehyde

For radon

$RF = 2.1 \times 10^{-3}$ cancers per pCi/l of radon

The housing forecast for new electric additions is the total number of current practice and MCS homes to be constructed annually. The number of MCS homes to be constructed annually is listed under the adoption schedule given in Table C.22. The number of homes not constructed to MCS annually equals number of New Electric Additions minus Adoption Schedule, or

F2(Y,CZ,DT,1) - F2(Y,CZ,DT,2) for Forecast 2.

The array for number of occupants per home is

OC(Y,DT) (Table C.19)

When DT = 1, the new single-family data are used,
DT = 3, the multifamily data are used,
DT = 4, the manufactured housing data are used.

No data were provided for DT = 2 single-family attached.

The array for the fraction of homes in each pollutant level is

FR(CZ,RL,DT) (Table C.10 for radon)

In the model all of the formaldehyde concentrations were included in one range.

C.2.1.4 Lifetime Cancer Rate

To calculate the rate of lifetime cancers estimated to occur per a group of 100,000 people, the number of occupants associated with each pollutant calculation was required. The following equations are associated with each of the equations listed in section C.2.1.2.

OC1 = F1(Y,CZ,DT,1)*OC(Y,DT)*FR(CZ,RL,DT)
OC2 = (F2(Y,CZ,DT,1)-F2(Y,CZ,DT,2))*OC(Y,DT)*FR(CZ,RL,DT)

OM2 = F2(Y,CZ,DT,2)*OC(Y,DT)*FR(CZ,RL,DT) where OC1 and OC2 are the number of occupants in current practice homes and OM2 is the number of occupants in MCS homes. These relate directly with CC1, CC2, and MCS2.

To calculate the rate of lifetime cancers per 100,000 people:

$$\text{LIFETIME CANCER RATE} = \frac{\text{NUMBER OF CANCERS* 100,000}}{\text{NUMBER OF OCCUPANTS}}$$

This technique normalizes the results so comparisons can be made across alternatives and pathways. The results are provided in Chapter 4 of Vol. I of the FEIS.

C.2.1.5 Summary Tables

Intermediate results for each case to be modeled are presented in a series of tables for each housing type (see Section C.3.1). The initial conditions for the modeled cases are summarized in Table C.25.

C.2.2 Computer Cases Modeled

In this section the various ventilation scenarios modeld are described. The Baseline is modeled using both an upper and lower bound estimate of ventilation.

- Upper Bound

- Single-Family	0.45 ACH
- Multifamily	0.30 ACH
- Manufactured Homes	0.41 ACH

- Lower Bound

- Single-Family	0.35 ACH
- Multifamily	0.20 ACH
- Manufactured Homes	0.41 ACH

For the No Additional Action Alternative the ventilation rates are assumed to be the same as the Baseline. The estimated number of lifetime cancers differs from the Baseline, however, as fewer electrically heated homes are estimated to be built. For the Proposed Action Alternative, 11 distinct pathways were considered. They have the following characteristics:

TABLE C.25. Initial Conditions for Intermediate Results of Each Modeled Case

Table	Climate Zone	Formaldehyde Pollutant Conc., RL[(a)]	Housing Type
1	1 <6000 hdd[(b)]	1	Single-family Detached
2	2 6000-8000	1	"
3	3 >8000 hdd	1	"
1	1 <6000 hdd	1	Multifamily
2	2 6000-8000	1	"
3	3 >8000 hdd	1	"
1	1 <6000 hdd	1	Manufactured Housing
2	2 6000-8000	1	"
3	3 >8000 hdd	1	"

Table	Climate Zone	Radon Pollutant Conc., RL[(a)]	Housing Type
1	1 <6000 hdd[(b)]	1	Single-family Detached
2	1 "	2	"
3	2 6000-8000	1	"
4	2 "	2	"
5	3 >8000 hdd	1	"
6	3 "	2	"
1	1 <6000 hdd	1	Multifamily
2	1 "	2	"
3	2 6000-8000	1	"
4	2 "	2	"
5	3 >8000 hdd	1	"
6	3 "	2	"
1	1 <6000 hdd	1	Manufactured Housing
2	1 "	2	"
3	2 6000-8000	1	"
4	2 "	2	"
5	3 >8000 hdd	1	"
6	3 "	2	"

- Pathway 1 - Minimum MCS construction for air leakage control with no mechanical ventilation system.

(a) Pollutant concentration (RL) for formaldehyde: category 1: all concentrations; for radon: category 1 ≤5 pCi/L, category 2 >5 pCi/L.

(b) Hdd = Heating Degree Days

- Pathway 2 - Minimum MCS construction for air leakage control with mechanical ventilation with heat recovery (AAHX), which operates continuously.
- Pathway 3 - Minimum MCS construction for air leakage control with mechanical ventilation with heat recovery (AAHX), which operates intermittently.
- Pathway 4 - Minimum MCS construction for air leakage control with exhaust system with ports, which operates continuousoy.
- Pathway 5 - Minimum MCS construction for air leakage control with exhaust system with ports, which operates intermittently.
- Pathway 6 - Minimum MCS construction for air leakage control witi exhaust system without ports, which operates intermittently.
- Pathway 7 - Continuous air barrier with no mechanical ventilation system.
- Pathway 8 - Continuous air barrier with mechanical ventilation with heat recovery (AAHX), which operates continuously.
- Pathway 9 - Continuous air barrier with mechanical ventilation with heat recovery (AAHX), which operates intermittently.
- Pathway 10 - Continuous air barrier with exhaust system with ports, which operates continuously.
- Pathway 11 - Continuous air barrier with exhaust system with ports, which operates intermittently.

In Tables 2.1, 2.2, and 2.3 of Vol. I of the FEIS the air exchange rates associated with each of the 11 pathways for single-family, multifamily and manufactured homes are listed. The ratio of the pathway's air exchange rates (PW) to the Baseline's air exchange rates (BL) can be computed (PW/BL Ratio). This ratio will permit comparison of the changes between the upper and lower bound estimates for each pathway. For single-family homes, the Baseline air exchange rate (upper bound) is 0.45 ACH. The upper bound air exchange rate for pathway 1 is 71 % of the Baseline air exchange rate of 0.45 ACH (0.32/0.45=0.71); and the lower bound air exchange rate for pathway 1 is 74% of the Baseline's lower bound air exchange rate of 0.35 ACH (0.26/0.35=0.74); therefore, pathway 1's lower bound will provide 3% more air changes per hour in comparison with its Baseline than will the upper value in comparison with its Baseline.

C.2.3 The Preferred Alternative

This alternative considered aspects of heath effects, energy savings/energy consumption, and flexibility. Based on these criteria, BPA chose various pathways of the Proposed Action Alternative to form the Preferred Alternative.

The pathways of the Proposed Action Alternative included in the Preferred Alternative are 3, 5, 6, 8, and 10.

The contribution of each pathway to the Preferred Alternative is provided in Table C.26.

TABLE C.26. Penetration Percentages for Preferred Alternative,%

Pathway	1986-1992	1993-2002	2003-2006
3	30	10	5
5	45	50	20
6	5	10	5
8	20	25	40
10	0	5	30

C.3 SUMMARY OF RESULTS

C.3.1 Pollutant Concentrations

Radon and formaldehyde concentrations are presented by housing type, climate zone, baseline concentration level, and pathway. As an example, we present pollutant concentrations for single-family homes for pathway 1 of the Proposed Action Alternative (see Table C.27). Radon concentrations are presented for the following cases:

- BASE RADON: Radon concentration in baseline homes

- MCS MRADON: Radon concentration for homes built to MCS.

TABLE C.27. Radon and Formaldehyde Concentrations for Single-family Homes for Upper (UB) and Lower (LB) Ventilation Estimates

			RADON CONC. (pCi/l)				FORMALDEHYDE CONC. (ppm)		
PROPOSED PATHWAY	RL	CZ	CASE RADON	MCS MRADON	1986 MRADON	1993 MRADON	2003 MRADON	BASE FORMALDEHYDE	MCS MFORMALDEHYDE
UB 1	1	1	0.400	0.563	0.563	0.563	0.563	0.091	0.127
1	2	1	9.880	13.894	12.122	11.643	10.365		
1	1	2	1.510	2.123	2.123	2.123	2.123	0.090	0.127
1	2	3	9.560	13.444	11.730	11.266	10.029		
1	1	3	2.190	2.939	2.939	2.939	2.939	0.090	0.127
1	2	3	9.650	13.570	11.840	11.372	10.123		
LB 1	1	1	0.400	0.500	0.500	0.500	0.500	0.090	0.113
1	2	1	9.880	12.350	10.775	10.349	9.213		
1	1	2	1.510	1.887	1.887	1.887	1.887	0.090	0.113
1	2	2	9.560	11.950	10.426	10.014	8.915		
1	1	3	2.090	2.613	2.613	2.613	2.613	0.090	0.113
1	2	3	9.650	12.062	10.525	10.108	8.999		

C.3.2 Final Summary Tables

Final summary tables were prepared for all 11 pathways of the Proposed Action Alternative. We reproduce one summary table (Table C.28) for illustration.

TABLE C.28. Estimated Lifetime Cancers for Radon (Pathway 2) for Single Family Homes

	Upper Bound Ventilation Cancers / 100,00			Lower Bound Ventilation Cancers / 100,000		
Climate Zone	Baseline	MCS	Total	Baseline	MCS	Total
1	117.9	98.1	105.7	117.9	98.2	99.6
2	692.4	545.5	601.9	692.4	490.3	567.8
3	857.3	681.2	748.7	857.3	612.2	706.2
Total	334.9	267.4	293.3	334.9	240.3	276.6

C.3.4 Preferred Alternative

Estimated lifetime cancers for the Preferred Alternative for single-family, multifamily, and manufactured homes are presented in Tables C.29 for radon. This summary provides information on the cancer rate per 100,000 people.

Table C.29. Estimated Lifetime Cancers by Residence Type

	Upper Bound Ventilation Cancers/100,000			Lower Bound Ventilation Cancers/100,000		
Housing Type	Baseline	MCS	Total	Baseline	MCS	Total
Single-Family	334.9	362.1	351.6	334.9	330.8	332.4
Multifamily	305.5	302.9	303.9	305.5	234.1	259.7
Manufacturered	413.0	402.4	410.5	413.0	438.3	419.0

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APPENDIX D

HUMAN RISK ASSESSMENT RECONSIDERED

Pacific Northwest Laboratory

All societies and individuals recognize exposure to personal risk as a normal part of life. Risk, which is usually described in terms of death, is a part of voluntary actions such as rock climbing, flying in airplanes, and smoking, or involuntary situations such as being trapped in a burning building. By comparing risks, a person should be able to make an informed decision regarding which activities he is willing to undertake in comparison with the probability that he will suffer death. This comparison can be made over two time horizons: 1) over a lifetime or 2) over a single year. The probability of death from any action, either voluntary or involuntary, over the course of a person's lifetime is referred to as the "lifetime risk." Most risk assessments consider lifetime risk for the general population, realizing that a specific factor could be used for any one individual. Both time horizons are used because some of the possible voluntary actions, such as rock climbing or flying in airplanes, are not normal events that occur on a routine basis each year. Also, some health risks are calculated for a lifetime of exposure rather than for an annual exposure.

The activity associated with a new energy-efficient home is exposure to certain concentrations of pollutants. This activity will be compared to other activities that in most cases are considered to be voluntary in nature (Table D.1). The risk of death for each activity is one person for every 100,000 persons participating in the activity, or 0.00001 for any one person (1/100,000). Notice the dimensions of time are used in various fashions for the activities. For example, the exposure of pollutant concentrations is for life, whereas traveling by air or automobile has no units of time associated with them because the risk of death from these activities is based on "lifetime occurrence" of the activity. That is, for each 100,000 people traveling 600 miles by automobile during their lifetimes, one person is expected to die from an accident. On an individual basis, for every 600 miles a person travels by automobile during his lifetime, there is a 0.001% chance that he will die from an accident.

The information in Table D.1 allows readers to compare lifetime activity levels that should result in death, and decide which ones they will accept. This will be illustrated by an example.

1. Because each of the activities listed in Table D.1 has the same individual risk factor (0.00001), any one may be compared with any other. For example, compare breathing 0.0048 pCi/l of radon for life to smoking 10 to 30 cigarettes, or breathing 0.0048 pCi/l of radon = 10 to 30 cigarettes over a lifetime = 0.00001 chance of death.

A level of 0.0048 pCi/l is very dilute, well below the detectable level of most measurement devices. Therefore, we must normalize this level to one that is more consistent with levels usually found in residences. This can be accomplished by dividing the given concentration level by the identical value so the result will be unity, or a more appropriate concentration level. So:

TABLE D.1. Voluntary Activities that Carry a Risk of One Death for Each 100,000 People Participating

Activity	Cause of Death
Breathing 0.0048 pCi/l radon for life	Lung cancer
Traveling 7000 miles by air	Accident
Crossing the ocean 10 times by air	Cancer from cosmic rays
Traveling 600 miles by automobile	Accident
Living for 2 years in Denver	Cancer from cosmic rays
Living for 2 years in a stone building	Cancer from radioactivity
Working for 15 weeks in a typical factory	Accident
Working for 30 hours in a coal mine	Accident
Smoking from 10 to 30 cigarettes	Cancer, heart-lung disease
Rock climbing for 15 minutes	Accident
3 hr being a man aged 60	Mortality from all causes

Sources: BPA 1984; Upton 1982.

2. Divide by 0.0048.

   0.0048/0.0048 pCi/l of radon = 10/0.0048 to 30/0.0048 cigarettes

3. Complete the operation.

   1 pCi/l of radon = 2,083 to 6,250 cigarettes

4. The exposure to radon is considered to occur continuously during a lifetime. We can then normalize the comparison made to a daily basis.

   a) 50 yr of smoking = 18,250 days if you assume 365 days per year

   b) 70 yr of smoking = 25,550 days if you assume 365 days per year

5. Revise comparison to yearly basis.

   1 pCi/l of radon = 2,083 to 6,250 cigarettes/18,250 days (50 yr)

   1 pCi/l of radon = 2,083 to 6,250 cigarettes/25,550 days (70 yr)

6. Summarize the results of Step 5:

   a) for 50 yr of smoking

   Breathing 1 pCi/l of radon = smoking about 1/4 cigarette/day

   b) for 70 yr of smoking

   Breathing 1 pCi/l of radon = smoking about 1/6 cigarette/day.

The nature of the calculation is such that comparison of other concentration levels can be made. For example, if a more appropriate value is breathing 2 pCi/l for life, the comparison with smoking becomes 1/2 and 1/3 of a cigarette/day for 50 and 70 years of smoking, respectively. That is, a factor of 2 has been multiplied by both sides of the equation.

This exercise has allowed us to compare the lifetime risk of an involuntary activity (breathing 1 pCi/l of radon) to a voluntary action (smoking cigarettes). That is, an individual breathing 1 pCi/l of radon for a lifetime has the same risk of dying from lung cancer as a person who smokes somewhere between 1/4 and 1/6 cigarette per day, depending on whether a 50- or 70-yr lifetime is assumed. Put in different terms, if a person smokes, there is no reason why he should consider the risk of dying from the exposure to 1 pCi/l of radon to be greater than the smoking itself.

A similar exercise can be repeated for other pollutants for which risk factors are known, or for other activities. The basic concept is that individuals themselves can choose, based on their lifestyles, if they can accept the risk of dying from lung cancer as the result of exposure to increased radon levels that may be found in a new energy-efficient home compared to normal risks they take.

Another method of comparison relates activities that occur on an equal time-of-exposure basis (Table D.2). This comparison is not made on the absolute amount of the activity, but provides a comparison of the relative risk factors on the basis of equal time. This allows an individual to determine which activities, either involuntary or voluntary, are more risky. For example, the risk of fatality from a motor vehicle accident is 25 times greater than a fatality from firearms.

It should be noted that several methods exist for estimating the occurrence of lung cancer as the result of exposure to radon. The approach taken in this document is an absolute risk projection model, in which it is assumed the observed annual numerical excess cancer risk per unit of exposure continues throughout life. The other approach is a relative risk projection model that assumes the observed percent age increase of the baseline cancer risk per unit of exposure is constant with time (NAS 1980). The relative risk projection model and the absolute risk projection model should not be confused with two approaches to defining a risk coefficient that is used for a risk projection model. The first is a specific risk coefficient that is based on one set of epidemiological studies on the incidence of lung cancer from exposure to various levels of radon in mine workers. This can be compared against a relative risk coefficient, developed by Thomas et. al (1985), that is based on a reanalysis of various epidemiological studies of groups of miners exposed to various levels of radon.

A relative risk model leads to larger estimated risks than an absolute risk model because of the generally increasing incidence of lung cancer with increasing age. (See Harley and Harley (1986) for a comparison of risk estimates.) Because of this, regulatory agencies such as the Environmental Protection Agency (EPA) are more comfortable using the relative risk model (EPA 1979), which leads to a higher estimate than BPA's estimate, which is based on NCRP (1984) estimates. EPA has prepared a document for the general public to explain and compare risks of exposure to various radon levels (EPA 1986a). Table D.3 is a table from that document comparing the estimated occurrences of lung cancer from various long-term radon concentration levels to comparable radon exposure levels and risk.

It is not meaningful to debate here whether an absolute or relative risk projection model is more appropriate. In fact, the following statement from an EPA document (EPA 1986b) is appropriate: "Readers should bear in mind that estimating radiation risks is not a mature science and that the evaluation of the risk due to radon-222 decay products (progeny) will change as additional information becomes available". The purpose of the analytic effort for the New Energy-Efficient Homes Program is to compare the impacts, in terms of estimated lung cancers, that occur in excess of those estimated for baseline conditions.

TABLE D.2. Average Risk of Fatality by Various Causes

Accident Type	Deaths/Year per U.S. Population	Deaths/Year per 100,000 People
Motor vehicle	55,791	25
Falls	17,827	8
Fires and hot substances	7,451	3.4
Drowning	6,181	2.8
Firearms	2,309	1
Breathing 0.3 pCi/l radon for life		<1
Air travel	1,778	0.8
Falling objects	1,271	0.58
Electrocution	1,148	0.52
Lightning	160	0.07
Tornadoes	91	0.04
Hurricanes	93	0.04

Sources: BPA 1984; NRC 1975.

Table D.3. Radon Risk Evaluation Chart (EPA 1986a)

pCi/l	WL	Estimated Number of Lung Cancer Deaths Due to Radon Exposure (out of 1000)	Estimated Lung Cancers Based on Absolute Model[a]	Comparable Exposure Levels	Comparable Risk
200	1	440-770	420	1000 times average outdoor level	More than 60 times nonsmoker risk
100	0.5	270-630	210	100 times average indoor level	4 pack-a-day smoker 20,000 chest x-rays/yr
40	0.2	120-380	84		
20	0.1	60-210	42	100 times average outdoor level	2 pack-a day smoker
10	0.05	30-120	21	10 times average indoor level	1 pack-a day smoker
4	0.02	13-50	8.4		5 times nonsmoker risk 200 chest x-rays/yr
2	0.01	7-30	4.2	10 times average outdoor level	
1	0.005	3-13	2.1	Average indoor level	Nonsmoker risk of dying from lung cancer
0.2	0.0001	1-3	0.4	Average outdoor level	20 chest x-rays/yr

(a) This column is from BPA's analysis and is based on NCRP's approach (relative risk); absolute value is 2.1 x 10^{-3} for 1 pCi/l of exposure.

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APPENDIX E

PATHWAY EQUIPMENT EXPENDITURES

Pacific Northwest Laboratory

E.1 INTRODUCTION

Region-wide equipment expenditures required under BPA's New Energy-Efficient Homes Program depend on a variety of economic and engineering factors. These include the rate at which the program penetrates the region, the growth of housing, purchase costs of the various equipment, and the scope of the actual radon problem in the northwest. This appendix examines the equipment expenditures required by each pathway under a consistent set of behavioral and engineering factors.

The focus of the appendix is to develop a sense of relative expenditures required for each of the pathways as well as the preferred and no additional action alternatives. The results of this appendix do not include all of the elements needed for a cost-effectiveness analysis.

As the program is currently structured, participating builders have a choice of whether to install radon mitigation measures in the houses they build. Figure E.1 shows how new program housing will fit into builders' choices. These assumptions are documented in Love (1987).

In the first stage the number of builders choosing to build in source control is expected to decrease over time. From 1987 to 1992, 75% of the builders are expected to build in source control measures. This drops to 60% between 1992 and 2002, and to 20% after 2002. This decrease is matched by a corresponding increase in those choosing the "monitor and mitigate" option. This change is assumed to occur in conjunction with the developing capability to map areas with high concentrations of radon. It will thus be possible to better determine what type of construction is appropriate for a given site.

Of those who build in source control measures, 70% are assumed to also monitor the homes. Of the 70% who monitor, 8.97% are believed to find that they have a radon problem; 45.83% of these are assumed to be in homes with crawlspaces and 54.17% in slab homes. This ratio was found by the RSDP's data base (BPA 1986a).

The number of people who activate their radon control measures is expected to vary with the intensity of the radon problem. This analysis assumes that 50% of the problem houses will be between 5 and 10 pCi/l; 10% of these homeowners are expected to activate their measures. Forty percent of the houses are assumed to be between 10 and 20 pCi/l; 30% of these homeowners are assumed to take action. Only 10% of the problem homes are assumed to have concentrations above 20 pCi/l; because the concentration is so high, 75% of these homeowners are expected to take action. Given the level of uncertainty about both the actual scale of the regional radon problem and about the behavioral response of homeowners, these figures must be considered best information assumptions. They are meant to provide a consistent, and to the extent possible, reasonable, behavioral basis from which to measure the expected equipment expenditures on a pathway by pathway basis.

A separate path is possible for builders who do not believe that radon is a threat on their building site. Following the monitor side of the figure shows that the number of builders choosing to monitor is expected to grow over time. Again, 8.97% of the homes are expected to discover a radon problem. They too will take action, depending on the level of radon in the house. The ratios are the same as the source control groups laid out above.

The actions laid out above form the basis for the behavioral portion of the regional cost estimate. It is assumed that a radon mapping capability will allow builders to better discern when building mitigation measures into a structure is appropriate. Homeowners should be responsive to the degree of exposure to radon, and the greater the exposure, the more likely they are to take action. However, the exact percentages which will follow each path is not yet well understood. As a result, assumptions which are based on the best information available (even it is slim indeed) form the quantitative portion of the behavioral aspect of regional equipment expenditures. As a result, the absolute level of the estimated regional expenditures is suspect. However, since the assumptions are consistent across the different pathways, it seems likely that relative ordering of the pathways will be robust to these assumptions.

E.2 BASE CASE EXPENDITURES

Regional equipment expenditures of each of the proposed pathways are analyzed through a comparison between the pathway and the current practice home. The expenditure on each pathway is constructed by adding the costs of the different sets of mitigation and construction strategies to the current practice home. One difference is shared by each of the different pathways. Each has a higher level of insulation than the current practice house. This insulation package separates the pathways from the current practice. This analysis will assume that the average regional residential unit is 1400 sq ft. Table E.1 shows these alternatives and their per house costs. Each is assumed to have the same real cost throughout the 20-year study horizon.

Since this is an equipment expenditure analysis rather than a life cycle cost analysis, only the purchase price will be included in the expenditure analysis.

Moving from unit to regional estimates requires that the housing forecast be integrated with purchase costs. Given the housing forecast and penetration schedules for the program, the total units (regional purchases) are found by multiplying the purchase cost for each unit times the forecasted houses. When this process is completed for each of the 20 years in the forecast, the stream of regional purchase expenditures is revealed. This stream is reduced to a single figure by taking the present value of the stream. A real discount rate of 3% is assumed in this analyses. Table E.2 shows the regional present values of purchase for each of the measures.

TABLE E.1. Purchase Cost of Potential Pathway Measures

Measure	Cost
Large AAHX[a]	$1,274.00
Small AAHX[b]	814.00
Exhaust Fans with Ducting[c]	301.50
Exhaust Fans[c]	65.00
Air Barriers[d]	577.50
Sub-Slab Gravel[c]	100.00
Crawlspace Ventilation[e]	20.00
Radon Monitoring[e]	20.00
Blower Door Test	125.00
Portals	118.50
Insulation Package	
Single-Family	1,250.00
Multifamily	493.00
Manufactured Housing	1,402.00

Source of Costs

a - BPA (1986b)
b - BPA (1986c)
c - Harris (1987)
d - BPA (1986d)
e - Rowan (1987)

TABLE E.2. Present Value of Purchase Expenditures

Measure	Present Value of Regional Cost ($ millions)
Large AAHX	268
Small AAHX	171
Exhaust Fans	14
Exhaust Fans with Ducting	63
Air Barriers	122
Sub-Slab Gravel	21
Crawlspace Ventilation	4
Radon Monitoring	4
Blower Door Testing	26
Portals	25
Insulation Package	200

E.3 REGIONAL EQUIPMENT EXPENDITURES

Each of the components of the pathways contributes to the regional equipment expenditures required by the program over the next 20 years. In this analysis the components were examined individually. The purchase cost for both retrofit and original construction cases were weighted by the number of houses in each category over the 20-year forecast period to find the regional expenditure stream associated with each component. The present value of this regional cost stream was found using a discount rate of 3%. The exception to this procedure was the insulation package. The insulation package is needed for each of the pathways since they are all based on a tighter house than current practice. Table E.3 shows the resulting regional expenditures by both component and pathway.

Several pathways are "paired" in the sense that the difference between the pathways is the number of hours the AAHX or exhaust system operates is the only difference between them. Since this analysis does not account for either energy savings or energy costs of the equipment these pathways will have identical equipment expenditures.

The most expensive pathways are numbers 8 and 9 at $522 million in equipment expenditures. Pathways 1 and 2 are slightly less expensive at $497 million in equipment expenditures. Pathways 10 and 11 are about $100 million less than the first group. The rest of the pathways are, in descending order in expenditure, 10 and 11, 7, 4, 6, and 5, and finally, pathway 1. These run between $390 million and $229 million. The Preferred Alternative is expected to have expenditures of $379 million. The no additional action alternative is expected to have expenditures of $233 million.

TABLE E.3. Regional Cost of the Alternatives (1986 Millions $)

Measure	No Additional Action	Proposed Action Alternative											Preferred Alternative
		Pathway 1	Pathway 2	Pathway 3	Pathway 4	Pathway 5	Pathway 6	Pathway 7	Pathway 8	Pathway 9	Pathway 10	Pathway 11	
Large AAHX		$0	$268	$268	$0	$0	$0	$0	$0	$0	$0	$0	
Small AAHX 8 hr		$0	$0	$0	$0	$0	$0	$0	$171	$171	$0	$0	
Exhaust Fan with ports 24 hr		$0	$0	$0	$14	$0	$0	$0	$0	$0	$14	$0	
Exhaust Fan with ports 8 hr		$0	$0	$0	$0	$14	$0	$0	$0	$0	$0	$14	
Air Barrier		$0	$0	$0	$0	$0	$0	$122	$122	$122	$122	$122	
Exhaust Fan With ducting		$0	$0	$0	$0	$0	$63	$0	$0	$0	$0	$0	
Ventilated Crawlspace		$4	$4	$4	$4	$4	$4	$4	$4	$4	$4	$4	
Gravel		$21	$21	$21	$21	$21	$21	$21	$21	$21	$21	$21	
Monitoring		$4	$4	$4	$4	$4	$4	$4	$4	$4	$4	$4	
Insulation Package		$200	$200	$200	$200	$200	$200	$200	$200	$200	$200	$200	
Blower door test		$0	$0	$0	$0	$0	$26	$0	$0	$0	$0	$0	
Ports		$0	$0	$0	$25	$25	$8	$0	$0	$0	$25	$25	
Regional Expenditure	$233	$229	$497	$497	$268	$268	$326	$351	$522	$522	$390	$390	$379

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APPENDIX F

EMPLOYMENT EFFECTS OF MCS

Pacific Northwest Laboratory

Adopting and implementing the MCS would affect existing employment levels in the Northwest if either an energy surplus or an energy deficit existed. The relative effects would depend on which alternative resource (coal, hydro, etc.) is compared with impacts created by MCS. For example, some alternative resources, such as the MCS, are more labor-intensive, while others, such as coal-fired plants, require more materials and outside services. The impacts also could be compared with the employment levels that would occur if no energy surplus or deficit existed.

To date, two relevant studies have been completed which estimate impacts on employment: one estimates the effects of implementing a regional weatherization program (Charles River Associates 1984), and the other of adopting MCS (Sims 1984). These studies were based on the conditions laid out in the first regional power plan (NWPPC 1983). The focus of the Charles River Associates (CRA) study was to determine the employment effects of conserving energy compared with the effects of constructing a coal plant. Both the CRA and Sims studies concluded that conservation would provide greater employment benefits to the region than would coal plant construction. However, both options resulted in negative net employment because both conservation and construction have rate effects that cause jobs to be lost. Conservation, however, showed substantially fewer negative effects than coal plant construction. Both studies noted that if the current surplus continued and neither MCS nor alternative resources were required, regional employment would be even greater. Under these conditions, if the public spent disposable income on goods and services, a higher employment level would be produced than if they had used those funds to acquire energy from either MCS or other resources (see Figure F.1).

Because the Sims report (1984) provided the best available information on the effects of MCS at the time this EIS was prepared, it was used as the basis for considering employment effects likely to result from BPA's New Homes Programs. The assumptions used in the Sims report and their expected effects on employment are presented below.

F.1 THE SIMS REPORT

The Sims report (1984) drew on the methodology developed by Charles River Associates (CRA 1984) for a study conducted for BPA. The Sims report evaluated investment alternatives to the increased costs that homeowners would pay for homes built to the MCS. The CRA report focused more on employment impacts and cost dynamics in the construction industry.

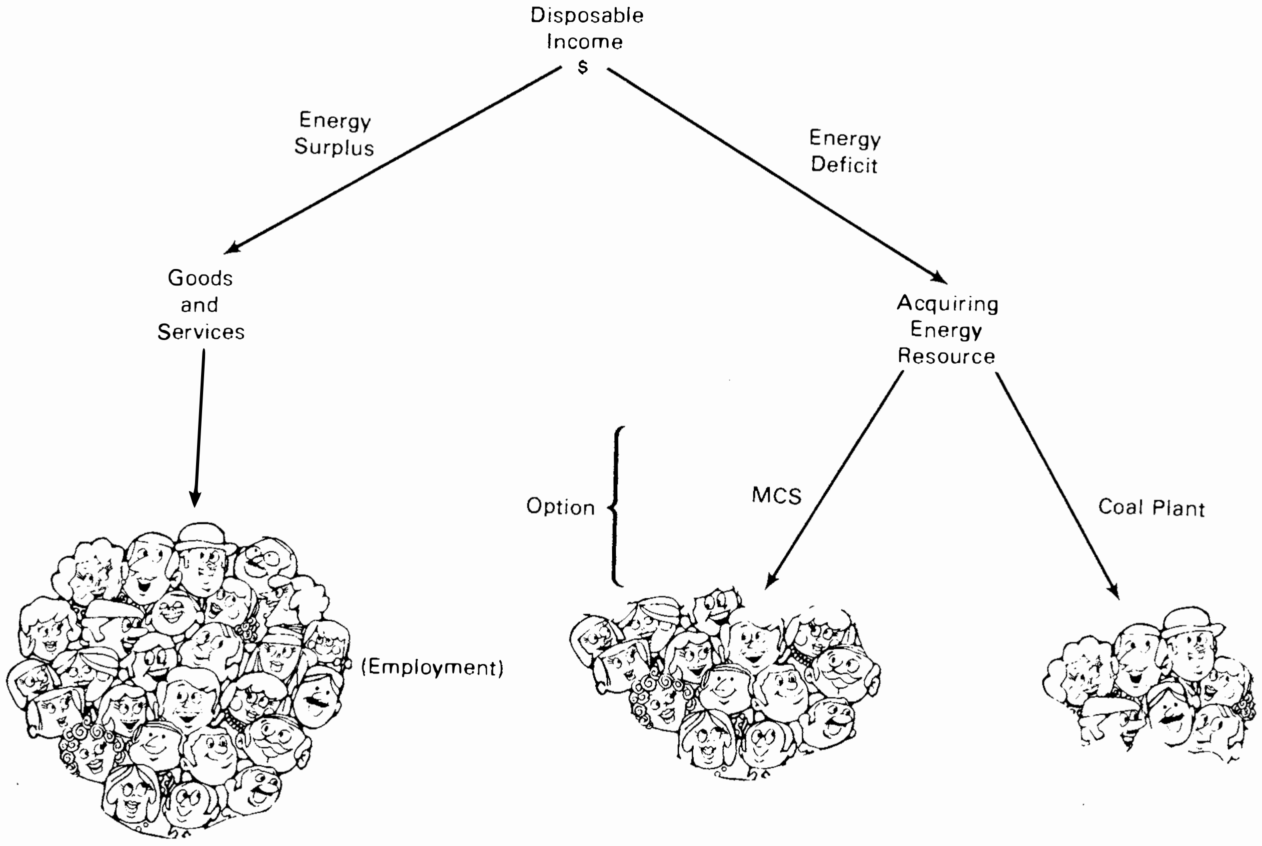

FIGURE F.1. Impacts of Disposable Income on Employment

The overriding assumption of the Sims report was that an energy deficit must be met either by implementing conservation programs or building new generating facilities. Other key assumptions used in the analysis are described on the following pages.

- Employment figures are given at the aggregate, regional level; they are not distributed by state. Employment would be dispersed throughout each state as determined by the location of new housing starts.

- All employees would be drawn from within the existing labor pool. Workers would not migrate to the region or between states to exploit employment opportunities.

- The analysis covers 1986 to 2002, although the full costs and benefits of conservation measures and their alternatives were considered over their lifetimes, and discounted to a present value. Within the 1986-2002 time frame, savings are assumed to accrue only if MCS were needed to reduce energy deficits.

- Adding income to the region from sales of exported power during a period of surplus power and purchasing needed power during a power deficit were not considered.

- Only information on nominal employment was used because of the uncertainty regarding the appropriateness of discounting future employment.

- Purchase of imported goods and services from the economic savings gained were not considered to have any value to the national economy.

- The installation of air-to-air heat exchangers (AAHX) was not considered in the Sims report. (If they are used in the New Homes Programs, the levelized cost under MCS would be higher and the net impacts on employment levels would be greater.)

The Sims study concluded that if an energy deficit occurred, employment would decline from levels estimated for baseline conditions since more employment would be generated if the public purchased goods and services than if they acquired additional energy from MCS or other resources. If coal plants were constructed to meet the energy deficit instead of adopting MCS to meet that deficit, the employment loss would be even greater because coal plants cost more and will thus result in higher bills. If no deficit occurred, both options would reduce employment levels. The study predicts that, at some point, energy deficits will occur and the future cost of meeting those deficits will be greater than acquiring MCS conservation resource now. It further concludes that impacts on employment would be minimized by acquiring the available resource now, compared with acquiring it during periods of energy deficits.

F.2 APPLICATION OF SIMS REPORT TO THE NEW HOMES PROGRAM

The Sims study can be used to determine the relative order of magnitude of the impacts resulting from adoption of the various alternatives and pathways for the New Homes Programs as shown in Table F.1. However, the conditions on which the Sims study were based are not the same as those outlined in the present power plan (NWPPC 1986), so the results cannot be applied directly to the BPA New Homes Programs. In order to compare estimated employment effects of the alternatives, a re-evaluation of the results would be required, including changing the MCS penetration rate from 90% to 75% However, for this EIS a comparative assessment of the employment effects, using the Sims report as a basis, is all that is necessary. What follows in Table F.1 is a qualitative assessment of the relative order of magnitude of the employment effects for the No Additional Action Alternative and the 11 pathways.

TABLE F.1. Employment Effects of Adopting Alternatives/Pathways for the New Homes Program

Alternative/Pathway	Impact
Baseline	None
No Additional Action Alternative	
Exhaust System with Ports	Slightly reduced employment in both energy surplus and deficit because electric bills are higher than in baseline; thus consumers spend less on other goods and services.
AAHX with Air Barrier	Larger net negative employment compared with the exhaust system because AAHXs cost more; therefore, it will have greater effect on electric bills and consumers' ability to spend on other goods and services as larger number of AAHX systems are installed.
Proposed Action Alternatives	
Pathway 1	Employment reductions are less than under No Additional Action because mechanical ventilation is not required; thus, costs are lower, bills are lower, and the reduction in spending on goods and services is less.
Pathways 2 and 3	Similar to the AAHX option under No Additional Action, but since there is no air barrier, net negative effects would be less.
Pathways 4 and 5	Similar to the exhaust system option under No Additional Action.
Pathway 6	Similar to Pathway 1, with slightly more unemployment.
Pathway 7	More unemployment than Pathway 1 because of requirement for air barrier, which increases costs, and bills, and thus decreases expenditures on goods and services.
Pathways 8 and 9	Similar to the AAHX option under No Additional Action.
Pathways 10 and 11	Similar to Pathways 4 and 5 but negative is greater because of the costs of the air barrier.

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APPENDIX G

ENERGY SAVINGS

Pacific Northwest Laboratory

G.1 INTRODUCTION

In the Final EIS the energy savings calculations were determined for the eleven proposed pathways using upper and lower bounds of ventilation rates. The basic procedures and assumptions have remained the same as those presented in Appendix A of Volume II of the DEIS (New Homes Conservation Resource). The basic steps used to predict energy savings are presented in this Appendix, including a more detailed explanation of any differences between these calculations and those presented in the DEIS. The reader should refer to the DEIS Volume II document for further information on assumptions or detailed procedures.

Information on the methodology used to estimate the amount of energy saved by current practice and energy efficient homes can be found in Appendix A of Volume II of the DEIS. These calculations were used to predict regional energy savings in the DEIS. In Appendix F to that document, scaling factors were applied to the energy savings calculations to determine energy savings for the five pathways proposed in the DEIS.

G.2 ASSUMPTIONS USED IN DETERMINING ENERGY SAVINGS

The basic assumptions used to determine energy savings are those describing the base case prototypes, the way the prototype is simulated to use energy, the weighting factors that describe how the prototypes are distributed by size and climate zone, and the MCS adoption rates for the region.

G.2.1 Base Case Prototypes

The prototypes used in the Final EIS, described in Chapter 3, are the same as those used in the DEIS. Drawings and descriptions of the prototypes can be found in Appendix D to Appendix A of Volume II of the DEIS.

G.2.2 Heat Loss Calculations

The base case prototypes described in Section 3.2 of the final EIS were simulated assuming different levels of insulation and ventilation describing current practice, state codes and MCS. The thermal characteristics for each of these scenarios are found in Tables 3.2, 3.3 and 3.4 of the Final EIS. When the analysis for the DEIS was being completed, the Washington and Oregon State codes had not been implemented so they were not considered in the determination of current practice.

A factor in determining how much energy a house uses is the air exchange rate of the dwelling. This ventilation rate changes for each of the pathways presented in Chapter 2. The presence or absence of air barriers, air-to-air heat exchangers or exhaust fans causes this number to vary. These rates also vary between the upper and lower bound ventilation rates. The analysis of energy savings uses the average ventilation rates for all three prototypes. These are given in Table G.1.

These ventilation rates are what differentiate each of the pathways from one another. Insulation levels are the same for all the pathways. The base case ventilation rates are the same for current practice and state codes; only the insulation levels vary among these prototypes.

G.2.3 Building Simulation

The computer model Sunday, used in the analysis for the DEIS, was also used to determine energy usage in this analysis. All inputs to the model, except UAs, were identical to those used in the DEIS. For an explanation of these inputs see Section 5.1.2 of Appendix A to Volume II of the DEIS.

Because of the large number of UAs resulting from six prototypes in three climate zones for three base case scenarios and eleven pathways defined by two ventilation rates, simulating each of these scenarios became impractical. For this reason, sample simulations which describe the range of UAs for a given prototype were input into the model. A curve was then fit through the results using the method of least squares. The resulting linear or quadratic function was used to determine energy consumption for each discrete UA value. UA values resulting from this process are found in Tables G.2 and G.3.

G.2.4 Weighting Factors

The weighting factors used to describe the distribution of prototypes by size and climate zone are the same as those used in the DEIS. Zone allocation assumptions can be found in Table 5.8 in Appendix A of the DEIS for single and multifamily prototypes and in Section 5.4.2.4 for manufactured housing.

TABLE G.1. Average Ventilation Rates Used in Energy Analysis

Pathway	Single Family		Multifamily		Manufactured Housing	
	Fan	PFT	Fan	PFT	Fan	PFT
1	.35	.28	.21	.16	.35	.29
2	.38	.38	.28	.28	.35	.35
3	.34	.34	.22	.22	.31	.31
4	.48	.40	.48	.42	.49	.46
5	.42	.34	.34	.27	.42	.39
6	.38	.31	.29	.23	.39	.33
7	.18	.15	.13	.12	.18	.11
8	.25	.25	.20	.20	.21	.17
9	.18	.18	.13	.13	.14	.12
10	.34	.31	.42	.40	.35	.27
11	.26	.22	.26	.24	.26	.19
Current Practice	.49	.38	.33	.22	.38	.32

TABLE G.2. Comparison of UA Values in Current Practice and Energy Efficient Prototypes Based on Upper Bound Ventilation Rates

SINGLE FAMILY

		Climate Zone		
Sq.ft.	Alternative	ZONE 1	ZONE 2	ZONE 3
1344	BASELINE	481	464	382
1344	OREGON	426	389	
1344	WASHINGTON	382	382	
1848	BASELINE	593	576	468
1848	OREGON	521	463	
1848	WASHINGTON	468	468	
2352	BASELINE	762	754	545
2352	OREGON	687	530	
2352	WASHINGTON	649	555	
1344				
	PATH 1	295	279	259
	PATH 2	301	285	265
	PATH 3	293	277	257
	PATH 4	320	304	285
	PATH 5	308	292	273
	PATH 6	300	285	265
	PATH 7	261	246	226
	PATH 8	275	259	240
	PATH 9	261	246	226
	PATH 10	293	277	257
	PATH 11	278	261	242
1848				
	PATH 1	359	339	319
	PATH 2	367	346	326
	PATH 3	356	335	315
	PATH 4	394	372	352
	PATH 5	378	350	336
	PATH 6	367	340	326
	PATH 7	314	287	272
	PATH 8	333	305	291
	PATH 9	314	272	272
	PATH 10	356	315	315
	PATH 11	335	314	294
2352				
	PATH 1	425	411	392
	PATH 2	435	422	402
	PATH 3	422	408	389
	PATH 4	469	456	436
	PATH 5	449	435	416
	PATH 6	435	422	402
	PATH 7	367	354	335
	PATH 8	391	378	358

TABLE G.2 (Cont.)

PATH 9	367	354	335
PATH 10	422	408	389
PATH 11	394	381	362
MULTIFAMILY			
BASELINE	2358	2308	1836
OREGON	2053	1855	1836
WASH	1836	1836	
PATH 1	1387	1277	1214
PATH 2	1503	1393	1329
PATH 3	1404	1293	1230
PATH 4	1833	1723	1660
PATH 5	1602	1492	1429
PATH 6	1569	1459	1396
PATH 7	1255	1145	1082
PATH 8	1371	1260	1197
PATH 9	1255	1145	1082
PATH 10	1734	1624	1561
PATH 11	1470	1360	1296
MANUFACTURED HOUSING			
SINGLE	377	377	377
DOUBLE	472	472	472
PATH 1	217	214	207
PATH 2	217	214	207
PATH 3	212	209	201
PATH 4	236	232	225
PATH 5	226	223	216
PATH 6	222	219	212
PATH 7	194	191	184
PATH 8	198	195	188
PATH 9	189	186	179
PATH 10	217	214	207
PATH 11	205	202	195
PATH 1	263	260	251
PATH 2	263	260	251
PATH 3	255	252	244
PATH 4	290	287	278
PATH 5	277	273	265
PATH 6	271	268	259
PATH 7	230	227	218
PATH 8	236	233	224
PATH 9	224	221	213
PATH 10	263	260	251
PATH 11	246	242	234

TABLE G.3. Comparison of UA Values in Current Practice and Energy Efficient Prototypes Based on Lower Bound Ventilation Rate

SINGLE FAMILY

		Climate Zone		
Sq.ft.	Alternative	ZONE 1	ZONE 2	ZONE 3
1344	BASELINE	460	442	361
1344	OREGON	404	367	
1344	WASHINGTON	361	361	
1848	BASELINE	563	547	439
1848	OREGON	492	434	
1848	WASHINGTON	439	439	
2352	BASELINE	724	717	508
2352	OREGON	650	493	
2352	WASHINGTON	612	518	
1344				
	PATH 1	282	265	246
	PATH 2	301	285	265
	PATH 3	293	277	257
	PATH 4	305	289	269
	PATH 5	292	277	257
	PATH 6	286	271	252
	PATH 7	255	240	220
	PATH 8	275	259	240
	PATH 9	261	246	226
	PATH 10	287	271	252
	PATH 11	270	254	234
1848				
	PATH 1	341	320	300
	PATH 2	367	346	326
	PATH 3	356	335	315
	PATH 4	372	351	331
	PATH 5	356	329	315
	PATH 6	348	321	307
	PATH 7	306	279	264
	PATH 8	333	305	291
	PATH 9	314	272	272
	PATH 10	348	307	307
	PATH 11	325	303	283
2352				
	PATH 1	401	388	369
	PATH 2	435	422	402
	PATH 3	422	408	389
	PATH 4	442	428	409
	PATH 5	422	408	389
	PATH 6	411	398	379
	PATH 7	357	344	325
	PATH 8	391	378	358

TABLE G.3 (Cont.)

PATH 9	367	354	335
PATH 10	411	398	379
PATH 11	381	367	348

MULTIFAMILY

BASELINE	2176	2127	1654
OREGON	1871	1673	1654
WASH	1654	1654	
PATH 1	1305	1194	1131
PATH 2	1503	1393	1329
PATH 3	1404	1293	1230
PATH 4	1734	1624	1561
PATH 5	1486	1376	1313
PATH 6	1420	1310	1247
PATH 7	1239	1128	1065
PATH 8	1371	1260	1197
PATH 9	1255	1145	1082
PATH 10	1701	1591	1528
PATH 11	1437	1326	1263

MANUFACTURED HOUSING

SINGLE		375	375	375
DOUBLE		470	470	470
	PATH 1	213	210	203
	PATH 2	217	214	207
	PATH 3	212	209	201
	PATH 4	232	228	221
	PATH 5	222	219	212
	PATH 6	218	215	208
	PATH 7	190	187	180
	PATH 8	198	195	188
	PATH 9	189	186	179
	PATH 10	212	209	201
	PATH 11	201	198	191
	PATH 1	257	254	246
	PATH 2	263	260	251
	PATH 3	255	252	244
	PATH 4	284	281	273
	PATH 5	271	268	259
	PATH 6	265	262	253
	PATH 7	224	221	213
	PATH 8	236	233	224
	PATH 9	222	219	211
	PATH 10	255	252	244
	PATH 11	240	237	228

Weighting factors used to disaggregate single family homes by prototype are found in Table 5.10 in Appendix A of the DEIS, manufactured housing disaggregation is found in Section 5.4.2.4.

G.2.5 MCS Adoption Rates

The rate at which builders choose to build homes to MCS, State code and current practice levels plays an important part in determining energy savings for the region. In the DEIS the state codes were not considered in the MCS adoption assumptions. The adoption rates used for single and multifamily residences in this analysis are listed in Table G.4. These penetration rates were applied to the forecast that assumes MCS adoption (Table 3.9 in Final EIS).

Since different states within the region have adopted different state energy codes and have different current building practices, the percent of builders in each climate zone who will build to a particular code is assumed. These assumptions by zone can be found in Table G.5. In the baseline forecast, which is based on no MCS adoption, 33% of the builders were assumed to build to current practice levels and 67% were assumed to comply with state energy codes. These assumptions were based on information supplied by BPA. Because the MCS do not apply to manufactured homes at this time, only a baseline forecast is assumed for this housing type. A penetration schedule was applied to the baseline forecast for manufactured housing to estimate energy savings from this housing type if a portion of the housing stock complies with MCS. This adoption schedule is found in Table G.6.

TABLE G.4. MCS Adoption Assumptions (Single and Multifamily Homes)

	Percent Penetration[a]		
	MCS	Washington/ Oregon Codes	Current Practice
1986	15	55	30
1987	35	50	15
1988	45	45	10
1989	50	45	5
1990	60	35	5
1995	75	25	0
2000-2006	75	25	0

(a) Based on the medium case forecast.

TABLE G.5. Assumed Compliance To State Codes By Climate Zone

Climate Zone 1		Climate Zone 2		Climate Zone 3	
Oregon Code	29%	Wash./Oregon Code	84%	Montana Code	100%
Washington Code	71%	Idaho Code	16%		

TABLE G.6. MCS Adoption Assumptions (Manufactured Housing)

Year	Percent Penetration
1986	1
1987	1
1988	1
1989	1
1990	1
1991	5
1992	8
1993	11
1994	14
1995	17
1996	21
1997	25
1998	29
1999	34
2000	38
2001	40
2002	42
2003	44
2004	46
2005	48
2006	50

G.3 RESULTS

After the energy consumption was determined for each prototype and weighted by prototype size and zone allocation, the consumption of the energy efficient prototypes were subtracted from the consumption of the baseline prototypes to determine energy savings. Table G.7 displays the annual energy consumption for the current practice and MCS prototypes. Table G.8 displays the resulting energy savings in Kwh.

The energy consumption for those pathways which include the use of exhaust fans (pathways 4, 5, 10, 11) was determined by adding the estimated consumption of the exhaust fans to the consumption of the home. The exhaust fans used intermittently were assumed to use 97 Kwh, the exhaust fans used continuously were assumed to use 291 Kwh. The AAHX fan energy was assumed to enter the air as heat or was accounted for in the inefficiency of the heat exchanger.

TABLE G.7. Annual Energy Consumption (Kwh) by Prototype for Current Practice and Energy-Efficient Prototypes

	Single Family		Multifamily		Manufactured Housing	
	Upper	Lower	Upper	Lower	Upper	Lower
Current Practice	7909	7255	1659	1242	8264	7960
Pathway						
1	4253	3794	301	212	2910	2719
2	4448	4448	448	448	3060	2911
3	4185	4185	320	320	3060	3060
4	5395	4870	1040	846	2862	2862
5	4781	4257	603	433	4046	3897
6	4519	4060	552	348	3505	3356
7	3111	2914	165	151	3356	3207
8	3570	3570	282	282	2217	2068
9	3386	3386	189	189	2365	2365
10	4259	4063	830	770	2343	2310
11	3661	3399	403	360	3157	2959

TABLE G.8. Annual Energy Savings (Kwh) by Prototype

	Single Family		Multifamily		Manufactured Housing	
	Upper	Lower	Upper	Lower	Upper	Lower
Pathway						
1	3656	3461	1358	1029	5354	5241
2	3461	2807	1211	793	5204	5049
3	3724	3069	1338	921	5204	4900
4	2514	2384	619	395	5402	5098
5	3128	2998	1055	808	4218	4063
6	3390	3195	1106	893	4759	4604
7	4798	4340	1493	1090	4908	4753
8	4339	3685	1377	959	6047	5892
9	4523	3869	1469	1052	5899	5595
10	3650	3192	828	471	5921	5650
11	4248	3856	1255	881	5107	5001

The mechanical ventilation rates assumed for an AAHX pathway were multiplied by (1-the efficiency of the heat exchanger) and added to the assumed natural infiltration of the AAHX pathway.

These energy consumption values were then multiplied by BPA's 1986 medium forecast to determine regional energy savings over the 20-year period.

G.3.1 Baseline

Because homes are constructed to current code requirements, no energy savings are gained. It is expected, however, that in time home construction will move toward the MCS requirements. This expectation has not been factored into the energy savings calculations. The region is predicted to consume 583 MW (based on upper bound estimates) and 537 MW (lower bound).

G.3.2 No Additional Action Alternative

For this alternative the energy efficient prototype is assumed to be a combination of Pathway 5 and Pathway 8. The energy consumption determined for this prototype was subtracted from the consumption determined for the baseline prototypes. Exclusive of manufactured housing, the estimated energy savings for the region, under No Additional Action, would be 132 MW assuming upper bound ventilation rates and 118 MW assuming lower bound ventilation rates.

G.3.3 Proposed Action Alternative

The same approach used to determine energy savings for the No Additional Action Alternative was used for this alternative. However, various pathways were possible depending on options available to home owners. Descriptions of the eleven pathways are found in Chapter 2 of the Final EIS. Energy savings for each of these pathways were determined using upper and lower bound ventilation rates. Results of these calculations are presented in Table 4.18 in the Final EIS.

G.3.4 Preferred Alternative

The Preferred Alternative consists of the several pathways preferred by the Bonneville Administrator. These preferred pathways are 3,5,6,8 and 10. Because more than one pathway was chosen, assumptions were made as to how builders would choose among the different pathways. The regional energy savings for the Preferred Alternative are based on these assumptions (found in Table G.9). The predicted regional energy savings from this distribution of the preferred pathways is 141 MW based on upper bound ventilation rates and 124 MW based on the lower bound exclusive of manufactured housing.

TABLE G.9. Percent of Builders Choosing Each of the Preferred Pathways by Year

	Percent Penetration		
Pathway	1987 - 1992	1993 - 2002	2003 - 2006
3	30	10	5
5	45	50	20
6	5	10	5
8	20	25	40
10	0	5	30
TOTAL	100%	100%	100%

APPENDIX H

THE RADON PACKAGE
Bonneville Power Administration

In the Environmental Impact Statement (EIS) for New Homes Programs the health effects of 11 separate pathways or program options are assessed. Each of these 11 pathways include the Radon Package which is a mandatory program element designed to reduce radon levels, as necessary, in homes built under The Bonneville Power Administration's (BPA's) New Homes Programs. The package consists of alternative actions which are displayed in Figure H.1 in the form of a decision tree. The possible alternatives of the Radon Package are described in this Appendix.

A major source of radon in residential structures is the soil beneath or in the immediate vicinity of the structure. The best technique for controlling radon is source control. The Radon Package is based on the known characteristics of radon and on recently developed source control strategies.

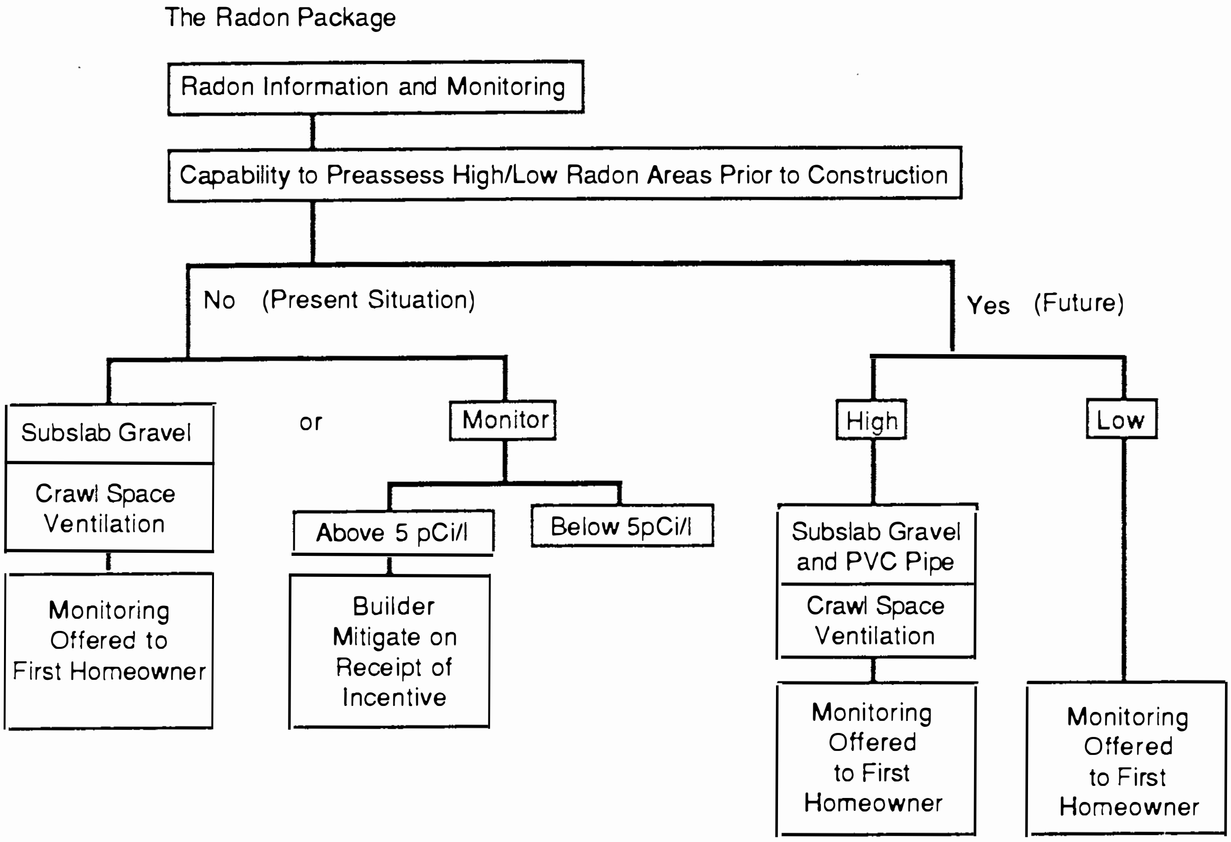

Figure H.1: Radon Package

H.1 RADON INFORMATION AND MONITORING

The Radon Package includes Bonneville's consumer booklet, "Issue Backgrounder --Energy-Efficient Homes and Indoor Air Pollutants," July 1985. Bonneville programs require the builder to give the consumer this information. Builder incentive payments are withheld until compliance with this requirement is verified through site inspection or other approved methods.

The Radon Package also allows for free post-construction monitoring with passive alpha track monitors. The offer of radon monitoring to the consumer is a program requirement and is made through utilities and other program operators. Once offered, the choice to actually monitor is up to the consumer. The radon monitor is installed for a minimum of three months during the period of September through March within 12 months of completion of the home, or as approved by Bonneville for the monitor being used.

The offer for radon monitoring need not be made to an individual homeowner if the builder chooses to monitor and mitigate for radon instead of installing sub-slab gravel or crawlspace ventilation. (See Section H.3 of this Appendix for details.)

H.2 CAPABILITY TO ASSESS HIGHER/LOWER RADON AREAS.

As designed, the Radon Package includes the capability to assess site soils for the presence of radon prior to construction. Bonneville recognizes that it is less expensive to install radon source control measures during construction of the residence than to add them after construction has been completed. The ideal approach to the radon package is to assess soils for radon availability before construction. Then the builder can make an informed decision about the installation of radon control features.

However, the capability to assess soils prior to construction does not yet exist. Bonneville is conducting joint research with the U.S. Geological Survey (USGS) and others to develop this capability. Therefore, the Radon Package includes strategies with and without this capability to allow for its future development.

Bonneville has not yet developed specific definitions and criteria for "higher" versus "lower" radon areas.* For purposes of informal discussion, a "higher radon area" is a location where more than 10% of the homes are likely to have radon readings which exceed Bonneville's action level of 5 pCi/l.

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* Bonneville is collecting and mapping radon monitoring data by range and township based on data from its residential programs. These data, combined with the Weatherization Program data, have allowed mapping of over 40,000 data points.

This type of mapping has not yet proved adequate to establish criteria that distinguish "higher" and "lower" radon emitting areas. Data are being shared with the USGS to determine whether a "radon susceptibility map" of the Pacific Northwest can be developed.

"Lower radon area" refers to locations where fewer than 10% of the homes have radon concentrations which exceed the action level. Depending upon the results of further studies, this language may change.

H.3 NO CAPABILITY TO IDENTIFY HIGHER/LOWER RADON AREAS (CURRENT SITUATION)

Without the capability to assess the radon content of soils onsite before construction, the builder can choose one of two strategies in the Radon Package. The builder can either install preparatory radon source control measures (i.e., sub-slab gravel or crawlspace ventilation), or monitor after construction and mitigate if monitoring results exceed 5 pCi/l. This is how the Bonneville programs (i.e., Early Adopter Program and Super GOOD CENTS) currently operate. This is also the basis for the analyses in this EIS.

H.3.1 Preparatory Measures for Radon Reduction

The first strategy consists of preparatory radon source control measures. These measures are not intended to actually reduce the level of radon entry into the structure. They are intended to allow for cost-effective radon reduction systems if post-construction monitoring shows radon levels above the action level of 5pCi/l. In other words, a Model Conservation Standards house has "preparatory" features that enable radon reduction systems to be installed later at less cost than if no preparatory steps were taken.

If the builder chooses the preparatory measures strategy, the appropriate Radon Package feature (i.e., either sub-slab gravel or crawlspace ventilation or both) will be integrated into the house design. When this is done, the builder's program responsibilities relating to radon will have been fully met.

H.3.1.1 Sub-Slab Gravel as a Preparatory Measure

Four inches of sub-slab gravel is to be used under flat slab or concrete basement construction. If post-construction monitoring informs the occupant that the radon level is high, and the occupant chooses to mitigate, an area suitable for air distribution has already been provided, by the gravel, for installation of a sub-slab ventilation system. Significant time and cost savings are achieved because with a gravel underlayer only a small hole is required through the concrete slab, generally just large enough for a 4-inch polyvinylchloride (PVC) pipe to penetrate. Absence of the gravel underlayer would require a more extensive entry into the sub-slab area to establish provisions for adequate air distribution. Without an increased airflow, the capability of the system may be insufficient to reduce radon entry. Without the sub-slab gravel preparatory measure, the cost and time required to create access to adequate airflow will be higher.

H.3.1.2 Crawlspace Ventilation as a Preparatory Measure

Crawlspace ventilation requirements may provide some radon reduction value to the consumer if a radon problem exists. At least 1 sq. ft. of net free area (openings in the crawlspace wall to the exterior) for every 300 sq. ft. of crawlspace area is to be provided for ventilation purposes. This requirement is consistent with the Uniform Building Code (UBC) to a point. However, because the UBC crawlspace ventilation requirement is intended to remove moisture, not radon, the Building Official may allow crawlspace ventilation area to be less than the stated minimum 1:300 ratio, on a case-by-case basis, if it is determined that a moisture problem will not occur as a result. No such exceptions are allowed by Bonneville when crawlspace ventilation is required to reduce radon levels.

However, the consumer will not be able to determine whether this feature, in itself, has actually reduced radon levels until post-construction radon measurements are made. Depending upon the results of the radon measurements (e.g., magnitude of the problem), the consumer may decide that existing 1:300 ratio of passive crawlspace ventilation is adequate, or the consumer may decide to invest in an active ventilation system (i.e., sealing the crawlspace area off from the living area; installation of a fan system hard-wired to a separate circuit breaker in the main electrical panel; system labeling).

H.3.2 Monitor and Mitigate Option

If the builder chooses not to install preparatory measures for reducing radon during house construction, he can monitor and mitigate after construction. Under the "monitor and mitigate" option, the builder is responsible for installing and paying for mitigation if post-construction monitoring shows radon exceeds 5pCi/l.*

In the EIS we assume that mitigation systems reduce radon levels by 70% This assumption is based on field studies of these systems by Lawrence Berkeley Laboratory (Turk et al. 1987). After a mitigation system is installed, retesting would be useful to determine system performance. Bonneville does not currently provide any follow-up testing and follow-up testing policy has not been established.

H.4 Capability to Assess Radon in Soils Prior to Construction

In the future, the capability to assess radon levels before construction for a specific site may become available, and we allow for this possibility in the Radon Package. When this capability is available, the builder will be able to determine if radon features should be integrated into the construction, and to budget and plan accordingly.

When pre-construction assessment is capable of determining radon levels, the Radon Package mitigation features are more demanding. They are no longer simply preparation for the possibility of radon reduction systems in the future; they are elements of active radon reduction systems.

If the area is known to have high levels of radon, a network of PVC pipe would be laid with the sub-slab gravel before the slab is poured. Although the crawlspace ventilation requirement is the same, the builder would

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* If this responsibility to mitigate is ignored by the builder, all rights to the program's builder incentive payments are forfeited.

incorporate electrical wiring for the crawlspace exhaust fan(s) into the design. This additional electrical wiring into the main circuit panel is also required for sub-slab systems.

It is unlikely that basement pressurization would be affected by a future assessment capability. If basement pressurization is warranted by the structure's characteristics, pressurization capability can be easily retrofitted. Therefore, this particular radon reduction method would not necessarily be affected by a capability enhancement.

H.5 Operation and Maintenance

The Radon Package does not include operation and maintenance of radon reduction systems beyond initial operation by the builder to ensure that the system is activated. The consumer may pursue the free monitoring offered, and if monitoring shows that high levels of radon still exist, further mitigation is the consumer's choice.

The Environmental Protection Agency (EPA) is currently pursuing an extensive field study of long-term effectiveness of radon reduction systems. Although this field study will not be completed until mid-1988, it is anticipated that the most prevalent cause of system failure will be inoperation of the fan(s) (e.g., occupants will fail to periodically check the fan to see if it is operating). Until study results are available, however, EPA is not discounting the possibility of that radon reduction system may fail due to changing entry patterns of radon into structures.

H.6 Costs

The following is a breakdown of cost estimates and assumptions upon which these estimates are based. The costs stated are average costs and will increase or decrease depending upon local conditions and case-by-case assumptions.

	INSTALLED COST[1]		OPERATING COST[2]
TECHNIQUE	BY HOMEOWNER	BY CONTRACTOR	(ANNUAL)
SUBSLAB GRAVEL	0[3] - $150	$200	NONE
VENTILATED CRAWLSPACE			
Passive	0[4] - $ 20[5]	$ 50	NONE
Active	$ 60[6]	$110	$21.46
SUBSURFACE SYSTEM	$125[7]	$400[8]	$21.46
BASEMENT PRESSURIZATION	$100[9]	$375	$21.46
SEALING[10]	N/A	N/A	N/A

These cost are based on the following assumptions:

1 Assumes $18 per hour labor and overhead and profit at 20 percent.

2 Assumes a fan capacity of 70 watt hours; 3.35¢/kWh; low continuous operation.

3 Assumes sub-slab gravel is consistent with local building practices due to soil type and condition.

4 Assumes that ventilation requirement in code meets or exceeds new energy-efficient homes programs requirement.

5 Assumes vent area hardware.

6 Assumes average fan cost of $60.

7 Assumes $60 1 fan system with 2 interconnected pipes and electrical materials.

8 Assumes inclusion of minimal design time preconstruction and electrical.

9 Assumes independent fan and wiring versus forced air heating system tie-in.

10 Sealing cost estimates have not been included because of variations in baseline construction practices. Sealing should be considered in two main contexts: (1) Structural component sealing which includes caulking of penetrations as well as slab cracks and component joints; and (2) sealing off of living areas as a source control measure (e.g., plastic membrane).

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APPENDIX I

CODE AND MECHANICAL VENTILATION
Bonneville Power Administration

I.1 INTRODUCTION

The Uniform Building Code (UBC) is a national code of minimum requirements for building practices. The current UBC, Section 1205(a) "Light and Ventilation," requires exterior openings for natural ventilation in residential buildings. The code states that a mechanical ventilation system may be installed in lieu of exterior openings for ventilation purposes. In contrast, the Bonneville Power Administration (BPA) supports minimum mechanical ventilation capability as a requirement in all residential structures.

This Appendix will: (1) further describe current UBC requirements for ventilation in residential structures, (2) outline Bonneville's concerns with current code, and (3) summarize related Bonneville actions.

I.2 CURRENT CODE AND MECHANICAL VENTILATION

During the latter part of the 19th Century, the UBC addressed ventilation in code for the first time. The initial ventilation requirement was a specific volume per occupant. However, since the main purpose of early code was fire safety and control, the focus of the ventilation requirement was soon changed from volume per occupant to large areas of glazing. Operable windows allowed for natural ventilation as well as a means of egress in a fire situation.

These code requirements for ventilation in residential structures have remained unchanged during the past 100 years. Section 1205(a) Light and Ventilation contains the following:

> "All bathrooms, water closet compartments, laundry rooms, and similar rooms shall be provided with natural ventilation by means of operable exterior openings with an area not less than one-twentieth of the floor area of such rooms with a minimum of 1½ square feet.
>
> All guest rooms, dormitories, and habitable rooms within a dwelling unit shall be provided with natural ventilation by means of operable exterior openings with an area of not less than one-twentieth of the floor area of such rooms with a minimum of 5 square feet.
>
> In lieu of required exterior opening for natural ventilation, a mechanical ventilating system may be provided. Such system shall be capable of providing 2 air changes per hour in all guest rooms, dormitories, habitable rooms, and in public corridors. One-fifth

> of the air supply shall be taken from the outside. In bathrooms, water closet compartments, laundry rooms, and similar rooms a mechanical ventilation system connected directly to the outside, capable of providing 5 air changes per hour, shall be provided."

Thus, very little has changed over the century except for the option of substituting some mechanical ventilation for exterior openings.

I.3 BONNEVILLE'S PERSPECTIVE

In recent years, scientists have gained a better understanding of indoor air quality (IAQ) and ventilation. Businesses are responding to this increased understanding by supplying more and more residential mechanical ventilation technologies.

For the past 6 years, Bonneville has been concerned with energy-efficient new home construction because of its commitment to the Northwest Power Planning Council's Model Conservation Standards. Bonneville has learned many lessons during this time regarding indoor air quality and ventilation of energy-efficient as well as current practice residential structures. In Bonneville's Residential Standards Demonstration Program (RSDP), indoor air quality and ventilation rates were monitored in over 800 energy-efficient and current practice homes. Through the Residential Construction Demonstration Program (RCDP), Bonneville is continuing to study natural ventilation rates as well as the effectiveness of various mechanical ventilation technologies.

Scientific findings on IAQ and ventilation and Bonneville's experiences permit the following statements.

(1) IAQ can be a problem in residential structures, regardless of their energy efficiency.

(2) Pollutant source control is the most effective solution to IAQ problems.

(3) Moisture and odors are two specific IAQ problems that can be effectively controlled by exhaust ventilation (spot ventilation).

(4) Builders are building tighter homes. The typical home being built today under current practices tends to have a natural ventilation rate (air infiltration occurring through normal penetrations and leakage areas in the structure) of 0.45 air changes per hour.

(5) Natural ventilation from operable windows is an unreliable means of controlling indoor air pollutants.

(6) Minimum mechanical ventilation is essential in <u>all</u> new homes.

(7) Therefore, Bonneville is concerned about the inadequacy of current code regarding ventilation.

Bonneville's concern about current code is rooted in the realization that constructing energy efficiency into new homes according to the MCS is a way of supplying the agency's ratepayers with a cost-effective electric power source. The ratepayer's investment in MCS as a power resource relates to building codes in two ways.

First, the investment should be protected. New homes built to MCS levels are expected to last at least 50 years as a viable resource. Thus, kitchens and bathrooms of all MCS homes require minimum spot ventilation as a moisture protection measure. Structural degradation is more likely to occur in homes without such minimum mechanical ventilation because of moisture retention and thus wood rot potential.

Secondly, BPA believes that resolution of differences between current code and MCS can facilitate regional acceptance of MCS as code in the region. If current code can be upgraded to include minimum mechanical ventilation in all dwelling units, an important similarity and congruence between code and MCS will be established.

I.4 BONNEVILLE'S RESPONSE

For the past three years, BPA has been working with the two main organizations responsible for maintaining building codes. The International Conference of Building Officials (ICBO) maintains the Uniform Building Code. The Council of American Building Officials (CABO) maintains the Model Energy Code. The responsibilities for maintaining code include evaluating code change proposals and code challenges, and is commonly termed "code development".

Bonneville's code development efforts reinforce the Council's long-term objective of achieving MCS as code by striving to integrate major components of MCS into national code. The positive effect of these efforts should be to increase penetration of MCS-level code adoption by local jurisdictions in Washington, Idaho, Montana, and Oregon, as well as to encourage statewide adoption of MCS-level code.

A brief description of two elements of code development is necessary in order to understand BPA's code development work. First, code change develops in 3-year cycles. This schedule allows for code growth and development while maintaining periods of stability. Secondly, code must be written so that it is enforceable by building officials. Sections of code are commonly identified for change during the enforcement process. Code intent is interpreted and applied, and sections that are clarified by this interpretation/application process are prime candidates for code change in any given cycle.

Since 1986, BPA has sponsored an energy code "Clearinghouse, which has helped identify code sections affected by the interpretation/application process." One component of the Clearinghouse is a toll-free hotline to assist code enforcement officials throughout BPA's service area. Energy code questions and answers are recorded in a data base maintained by ICBO's Northwest Regional Office. This data base of code interpretations/applications is printed and distributed to all code enforcement personnel in the region as updates to a "Manual of Accepted Practices". These interpretations/applications are compiled according to State energy code sections as well as the MCS equivalent code format.

In 1987, BPA sponsored the translation of the MCS into enforceable code language, which is now known as the Northwest Energy Code (NWEC). With MCS in an enforceable code format, and with a data base of interpretations/applications expanded by the hotline, BPA was able to identify entire sections of the NWEC to propose as code changes to the code development committees of ICBO and CABO. Minimum mechanical ventilation requirements in all homes is an example of such a proposal.

Bonneville is actively seeking code change and for the past two years has presented a code challenge to the ICBO code development committee's current recommendation for section 1205(a). Under an ICBO process providing for national code change proposals, BPA has submitted a code change proposal for minimum mechanical ventilation. ICBO's submission deadline for such proposals to their code development committee for the 1990 code change cycle was August 15, 1987.

Bonneville's proposal will be studied and discussed by the committee at a code development meeting in January 1988. The committee will recommend approval, approval as revised, disapproval, or further study. The committee's recommendation will be published and distributed to ICBO's national membership, and will be discussed (and potentially challenged) at annual ICBO business meetings scheduled for September 1988, and September 1989. By September 1990, all changes and subsequent challenges will be discussed and a vote, by ICBO members only, will be taken. At that time, assuming a positive vote, BPA's active support for minimum mechanical ventilation could result in a change in national code requirements.

APPENDIX J

POTENTIAL HEALTH EFFECTS RELATED TO RESIDENTIAL FIBER GLASS EXPOSURE

Pacific Northwest Laboratory

The discovery of serious health hazards from past exposure to asbestos insulation fibers has prompted concerns about health risks associated with fiber glass and other man-made mineral fibers (MMMF) used as insulation material. Investigations into the health effects of fiber glass dust were begun in the 1930s and have continued intermittently until the present. For the most part, these studies have found little evidence of adverse health effects from exposure to MMMFs, including fiber glass. However, several recent studies, though yet inconclusive, suggest a possible link between exposure to respirable MMMFs and lung cancer and other diseases. While considerable evidence has been amassed in recent years in support of this effect, the validity of some of the conclusions drawn from the data is still questioned.

Several studies have been conducted in which fiber glass and other MMMFs have been surgically implanted into the bodies of rats, hamsters, guinea pigs, and other laboratory animals (Schepers and Delahant 1955; Davis 1972). While these studies determined conclusively that MMMFs can cause cancers in laboratory animals when artificially implanted into their bodies, they did not conclusively determine whether inhalation of the glass fibers also presented a health risk, and whether these results could be applied to humans as well. Attempts to extrapolate results from these animal studies to humans are suspect, as these animals are known for developing cancers in response to implantation of most foreign substances, including many normally benign substances such as salt water. Furthermore, the path, and degree, of exposure in these animal studies does not relate to possible human fiber glass exposure (Milne 1976; Gross 1976). In other, more realistic, studies animals were continuously exposed to high concentrations of fine airborne glass fibers for periods of up to several years to determine whether inhaled fiber glass dust poses a health risk. While no correlation was found between the length and intensity of exposure to airborne fiber glass and an increased risk of cancer, other less serious problems such as respiratory tract irritation did develop in some animals (Gross 1976).

A number of long-term studies of workers in MMMF manufacturing plants have been conducted to determine how exposure to fiber glass dust can affect humans (Dement 1975; Moulin et al. 1986; Wright 1968; Hill 1973; Enterline et al. 1983). Most such research has found no increased cancer risk associated with exposure to respirable glass fibers. Some research, however, indicates an increase in respiratory disease, including lung cancer, relative to a control group of production workers who have worked in the manufacture of glass and mineral fibers for many years. A slight excess in deaths due to nonmalignant respiratory diseases, including influenza, pneumonia, and chronic bronchitis, were observed in two studies of fiber glass production workers reported in 1975 and 1976. While these and other previous studies found no indications of carcinogenicity, two more recent studies did. The first, conducted by an epidemiologist for the U. S. insulation industry, did report a slightly increased incidence of lung cancer related to MMMF exposure in workers in one production plant out of the eleven that he studied (Enterline 1983). Enterline and other researchers report that while there is some increased health risk with long-term MMMF exposure, most currently used insulation products are safe for residents when properly applied. The insulation industry believes that the higher than normal incidence of lung cancer found in the particular facility in Enterline (1983) is probably unrelated to fiber glass, but more likely due to exposure to asbestos fibers, produced in that facility for a short period, and to the sporadic testing of various carcinogenic chemicals in various manufacturing processes there as well (Meier 1987).

In a study conducted by the National Institute for Research in Safety and Occupational Health of France, a large sample of French MMMF production workers with an average exposure time in excess of 9 years was observed (Moulin 1986). While the sample population did not show a higher than normal incidence of lung cancer, the group was found to have an abnormally high incidence of oral and laryngeal cancers which did not seem to be related to other potential causes such as alcohol or tobacco consumption. The report notes that while the concentrations of respirable glass fibers in the factory studied were low, fibers entering through the mouth may have contributed to the elevated rate of upper respiratory tract cancer.

It has been suggested that some forms of MMMFs other than glass fibers may present a more significant health risk than fiber glass; for example, ceramic fibers, which have been widely marketed since the 1970s as a substitute for asbestos, are of particular concern. However, little data are available regarding their potential hazard because of their relatively recent introduction. Risk of cancer is not the only concern with ceramic fiber insulation. A 1986 report by Browning-Ferris Industries warned that ceramic fibers used in the linings of furnaces may decompose to form cristobalite, a material that has been linked to silicosis (Meier 1987).

Some studies have confirmed that inhaled glass fibers are biologically inert, are easily removed in the body's normal respiratory clearing process, and seem to present no health hazard to humans (Gross 1979). Other researchers believe that MMMFs are not benign, and that the potential toxicity of glass, ceramic, and other MMMFs may be related more to their physical characteristics than to their chemical properties. They believe that long, thin, and durable fibers that may be easily inhaled and subsequently lodged in the lungs present the greatest health risk. If so, this may be of particular concern to installers of blown-in fiber glass insulation, which often contains a high percentage of particles in the size range generally considered most hazardous.

Little data have been gathered on health hazards to occupants living in homes insulated with fiber glass because of the very low density of airborne glass particulates in most homes of this type, especially as compared to the fiber glass manufacturing sector; risk to occupants is thought to be negligible.

One report, however, details an instance where domestic exposure to airborne fiber glass may also present a health hazard (Newball and Brahim 1976). In this case, a home air conditioner duct, internally lined with glass wool insulation, was improperly installed, resulting in severe constriction in at least one area. The resulting air turbulence within the duct caused an extremely high level of glass fiber emission into the family's living space, and caused respiratory tract irritation in each of the four family members. Upon recognition and correction of the problem, including sealing the air conditioner vents and thorough cleaning of the home, each of the family members' symptoms abated, leaving no apparent long-term adverse health effects.

While the questions related to health risks from MMMF exposure have not yet been resolved, it would be prudent to minimize contact with these materials wherever possible. The levels of airborne fibers in homes insulated with glass or mineral wool are generally much less than those faced by MMMF production workers, and for the present, fiber glass remains a safe and effective insulation material for walls, ceilings, floors, and appliances (Chest Committee Report 1976). The use of glass or mineral wool as an interior lining in HVAC ductwork should probably be avoided wherever possible. It is also suggested that insulation installers take precautions by wearing protective clothing and respiration equipment when working with any type of MMMF insulation, and particularly the blown-in variety. Persons working with this type of insulation should be advised of the potential health hazard, and receive close medical supervision.

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APPENDIX K

ENVIRONMENTAL TOBACCO SMOKE: AN UPDATE

Pacific Northwest Laboratory

The effects of environmental tobacco smoke (ETS) on human health were reviewed as a part of the Draft Environmental Impact Statement (DEIS) on New Energy Efficient Homes Program. The authors of this report concluded that "no meaningful risk assessments for ETS exposures and quantifications of health effects can be made at this time" (Wehner et al. 1986). The report was published as Appendix B of Volume II of the DEIS.

This conclusion was reached because of difficulties in the following areas: 1) obtaining meaningful concentration measurements, 2) developing standards for normalizing exposures under widely varying conditions, 3) conducting "perfect" epidemiological studies, 4) developing a consensus interpretation of study results, and 5) resolving existing disagreements and controversy surrounding the issue (Wehner et al. 1986).

Since the release of the DEIS, additional studies have been conducted by the National Research Council (NRC) (NRC 1986), the U.S. Department of Health and Human Services (DHHS) (DHHS 1986), the Environmental Protection Agency (EPA), and by the Surgeon General (Surgeon General 1986). The conclusions of these studies support earlier studies reviewed in the DEIS and are summarized below.

The study by the NRC, Environmental Tobacco Smoke: Measuring Exposures and Assessing Health Effects, written under contract to the EPA and the DHHS, has several important findings. The most significant of these are: 1) children raised by parents who smoke are more likely to have respiratory problems and require medical attention than those raised by nonsmokers; 2) adults who have never smoked face a 34% greater risk of developing lung cancer if married to a smoker than if married to a nonsmoker; and 3) many people suffer severe eye and nose irritation when exposed to tobacco smoke. By increasing the ventilation rate by a factor of five, the irritation can be relieved (NRC 1986).

Integration of Risk Factor Interventions, prepared under contract for the Office of Disease Prevention and Health Promotion, states that cigarette smoking is the major source of air pollution because Americans spend 90 percent of their time indoors (DHHS 1986). The findings indicate that a nonsmoker's lifetime risk of lung cancer from on-the-job passive smoking is about 250 per 100,000 person-years of exposure. As a reference, the acceptable level of risk from environmental carcinogens is about 1 death per 100,000 person-years. Achieving this acceptable level would take a 270-fold increase in effective ventilation over current standards at an estimated cost of $28,000 per smoker (DHHS 1986). The report does not provide any risk factors for residential exposure.

The Surgeon General's report (Surgeon General 1986) concluded the following:

> Cigarette smoke is well established as a human carcinogen. The chemical composition of ETS is qualitatively similar to mainstream smoke and sidestream smoke and also acts as a carcinogen in bioassay systems. For many nonsmokers, the quantitative exposure to ETS is large enough to expect an increased risk of lung cancer to occur, and epidemiologic studies have demonstrated an increased lung cancer risk with involuntary smoking. In examining a low-dose exposure to a known carcinogen, it is rare to have such an abundance of evidence on which to make a judgement, and given this abundance of evidence, a clear judgement can now be made: exposure to ETS is a cause of lung cancer.

Although the Surgeon General concludes that ETS is a cause of lung cancer, the report also concluded that there is not enough known to develop a numeric risk factor for quantifying health effects.

The EPA's Preliminary Assessment for the U.S. EPA Indoor Air Program, Vol. I: Information Assembly and Synthesis, acknowledges the findings by the Surgeon General, but falls short of using these findings to set policy. The report states that better information on the degree and variability of ETS exposure is needed to predict the number of deaths with confidence.

Although the report is still in its preliminary draft stage, a conversation with Dr. Harriet M. Ammann, project officer for the report at EPA, indicates that these decisions will be maintained in later versions of the report.

All studies conducted to date conclude that despite significant findings which have been made recently, more research on the assessment of human exposure to ETS is needed. The conclusions stated in the DEIS, Vol. II, are consistent with these studies. Although ETS is recognized as a carcinogen, information is not yet available for quantifying either health effects or changes in health effects from building energy efficient homes. In fact, at least one health professional stated that "ETS has little effect on IAQ provided ventilation systems are functioning properly." (Sterling 1987). It is therefore recommended that no further action be initiated until conclusive research is completed or the EPA and other cognizant agencies make firm policy decisions.

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APPENDIX L

UNCERTAINTY IN REPORTED DATA

Pacific Northwest Laboratory

This appendix will present a brief discussion to help understand some of the uncertainty in reported data and to aid the reader in making an intelligent evaluation of the validity of conclusions based on such data.

An error is defined as the difference between a calculated or reported value and the true value. Unfortunately, the true value is usually the quantity being sought, so there is no way of immediately determining the amount of error associated with a measured value. These errors generally fall into one of three classifications: (1) illegitimate errors, which originate from mistakes in measurement or calculation and are usually easily found as obviously incorrect or meaningless data points; (2) systematic errors, which result from faulty instrument calibration or from a biased measurement process; and, (3) random errors, which are the fluctuations in observations which yield results that differ between measurements and require repeated experimentation to give precise results. While steps are normally taken to ensure the highest degree of accuracy in a reported experimental value, errors will always be present in the measured data.

The uncertainty in any experimental result arises from the errors inherent in the measurement process. If the experiment is repeated, the results will generally differ somewhat from those of the first experiment. Only through repeated experimentation can a result be reported with a high level of certainty. Uncertainties can be minimized by choosing random samples from the population of interest, by increasing the precision of the individual measurements, by increasing the sample population size, by repeating the experiment over the same sample population, by controlling the conditions of the experiment so that each measurement is taken under conditions as similar as possible, and by eliminating any potentially biasing factors. The reliability of primary measured data is generally considered superior to that taken from a secondary source, as its quality can be more tightly controlled, and its uncertainties accounted for.

When a number is reported, it is generally the result of several steps used in its generation. Each step in the process may be associated with a quantifiable level of uncertainty. A mathematical model which makes use of such information carries through and compounds the uncertainties in an often very complex statistical process until the final result. The number of steps in a process which make use of measured values, and the manner in which they are related contribute to the overall level of uncertainty in the final result.

As an example of how uncertainties may be propagated through a model to a final reported value, recall the equation for estimating the pollution concentration levels which was given in Chapter 4 of the Final EIS. This relation was expressed:

$$C = \frac{S}{VI}$$

where C = pollutant concentration
S = source emission
V = volume
I = ventilation rate

In this example, assume that the source emission, S, is determined to have a mean value of 5 mg/hr, with an associated uncertainty of 5 percent; the ventilation rate, I, is 210 m^3/hr with an uncertainty of 10 percent; and the volume, V, is 420 m^3, and has no associated level of uncertainty. The reported pollutant concentration would be reported as 5.7×10^{-5}mg/m^3 with an uncertainty of ±5.1 percent.

Efforts are routinely made to arrive at the most reliable and accurate results, however, it must be remembered that even the best reported results are only estimates of the quantities under investigation. It should also be understood that the reported range of uncertainty of any result is also only an estimate, one which has been derived so as to have a high probability of including the "true" value. Statistical models can thus be a valuable aid in understanding a process and arriving at an informed decision based on the measured data, but they are only a guide. Any conclusions based upon a statistical model must be made in conjunction with real-world experience.

APPENDIX M

Addendum to
INDOOR AIR QUALITY MITIGATION TECHNOLOGIES
DEIS, VOLUME II, Appendix C
Pacific Northwest Laboratory

M.1 INTRODUCTION

Appendix C in the DEIS (Volume II) presented information about IAQ and examined the effectiveness of mitigation technologies -- in particular source control, air cleaning, and increased ventilation -- to reduce the concentration of specific indoor pollutants. This update to that Appendix presents information what was not available in time to be reviewed and included in the draft document. The purpose of this update is to present the results of more recent studies, available up to early 1987, which address mitigation technologies applicable to improving IAQ.

The three most relevant documents that have been published since Appendix C was completed are:

- Research Review: Indoor Air Quality Control Techniques (Fisk 1986)
- Radon Reduction Techniques for Detached Houses (EPA 1986)
- Indoor Air Quality Environmental Information Handbook Building System Characteristics (Mueller 1987).

While most of the information presented in these reports duplicates information presented in Appendix C, these reports offer more detailed information, and additional, new, information on the following topics:

- Source Control
  - Exclusion
  - Basement Overpressurization
  - Active Avoidance of House Depressurization

- Increased Ventilation
  - Whole House Ventilation
  - Active Ventilation of Hollow Block Basement Walls

- Pollutant Specific Reduction Techniques
  - Radon
  - Organic Compounds
  - Allergens and Pathogens.

Fisk (1986) addresses radon, formaldehyde, and combustion product source control, ventilation, and air cleaning.

Topics discussed in EPA (1986) include: natural and forced air ventilation, forced air ventilation with heat recovery, active avoidance of house depressurization, sealing major radon sources, sealing radon entry routes, drain tile soil ventilation, active ventilation of hollow-block basement walls and ventilation of sub-slab.

Topics discussed in Mueller (1987) include: source control and mitigation techniques for radon, formaldehyde, organic compounds, combustion gases respirable suspended particles, and allergens and pathogens.

Two references cited in Appendix C, Indoor Air Quality Control Techniques: A Critical Review and Control of Respirable Particles and Radon Progeny with Portable Air Cleaners have been reissued as BPA documents Fisk et al. (1985) and Offermann et al. (1985). These two references include most of the new information to be presented in this update on IAQ mitigation techniques and have been cited in the more recent documents by Mueller (1987) and Fisk (1986).

M.2 MITIGATION TECHNOLOGIES

M.2.1 Source Control

In the area of source control, the more recent literature has additional and updated information about source exclusion, basement overpressurization, and active avoidance of house depressurization. Mueller (1987) provides a table (see Table M.1) of the effects of building characteristics on IAQ. This information shows how decisions about a building's structure, design, construction and operation influence the concentrations of various pollutants in the home. This information can be used to exclude sources of radon and radon daughters, formaldehyde, nitrogen oxides, carbon oxides, respirable particles, and allergens and pathogens from dwellings. BPA (1985) provides a similar overview of indoor air pollutants, potential health effects and ways to reduce exposure. This overview is presented in Table M.2.

Basement overpressurization is suggested as a method to reduce radon infiltration (Mueller 1987). The technique consists of tightening the basement to reduce air leakage to the upstairs and outdoors, then using a blower fan to pressurize the basement space with respect to the interstitial soil pore pressure. In one study, basement overpressures of 2-3 pascals appeared sufficient to reduce radon levels below 5 pCi/l. The method may be a low-cost solution in homes with tight, closeable basements; however, it may increase the house's overall ventilation rate, and is easily disrupted by certain occupant interference.

A house's living space may be depressurized when certain household appliances that use and exhaust house air to the outside are operated and when unbalanced ventilation (natural or forced air) is applied. This condition occurs naturally in the winter as a result of rising heated indoor air and its loss or exfiltration to the outdoors (EPA 1986).

TABLE M.1. Effects of Building Characteristics on Indoor Air Quality (Mueller 1987)

Building Structure, Design, Construction, and Operation	Pollutants Influenced						Indoor Air Quality Considerations
	Radon and Radon Daughters	Formaldehyde and Other Organic Compounds	Nitrogen Oxides	Carbon Oxides	Inhalable Particles	Allergens and Pathogens	
Pier Foundations	●	●	●	●	●	●	Greatly reduce radon entry rate. Generally increase air exchange rate, which reduces other pollutant levels.
Crawl Spaces	●	●	●	●	●	●	When well ventilated, reduce radon entry rate. House air exchange rate also generally higher than with other foundation types.
Slab-on-Grade	●						Radon can enter through cracks and openings in slab.
Basements and Masonry Foundations	●						Radon can enter through cracks and openings in slab and walls. Moisture that comes from soil can encourage mold and fungus growth.
Earth Sheltered Housing	●	●	●	●	●	●	Generally, lower air exchange rates increase concentrations of all indoor-generated pollutants. Radon and moisture are potentially problems because of large percentage of building shell on contact with soil.
Surrounding Soil	●						In some locations soil gas is a significant source of radon gas.
Concrete, Brick, and Rock	●						These materials can be, although not commonly, sources of radon gas.
Gypsum Board	●						In rare cases has been a source of low to moderate levels of radon.
Roofing Materials					●		Can contain asbestos, although not commonly a source of indoor contamination.
Building, Pipe, and Duct Insulation		●		●	●		Can be a source of asbestos or other particles, especially when disturbed. Formaldehyde given off by urea-formaldehyde foam.
Caulks, Sealants, and Adhesives		●					Can be sources, especially early in their life, of many volatile organic compounds.
Pressed Wood Products		●					Can be a source of formaldehyde, especially in the first several years after a home is built.
Solid Fuel Space Heaters		●	●	●	●		Can be a source of indoor pollution when improperly installed or operated or poorly maintained, when stoking or when wind causes backdrafts.
Vented Appliances		●	●	●	●		Can be a source of indoor pollution when improperly installed or operated. Adequate make-up air must be available for draft.
Unvented Appliances		●	●	●	●		Pollutant levels depend on time used, type of burners, size of rooms and many other factors.
Paints		●					Fresh paint can be a source of volatile organic compounds. Old paint sometimes contained lead, but greatest health threats from ingestion not inhalation.
Floor Coverings, Carpets and Vinyl Products		●			●		Rugs and carpeting significant contribution of particles in some cases. All can be sources of volatile organic compounds.
Garages		●	●	●	●		Attached garages can be significant sources especially if cars are allowed to run inside, or solvents are stored and used.

TABLE M.2. Overview of Indoor Air Pollutants, Potential Health Effects, and Ways to Reduce Exposure (BPA 1985)

Pollutant	Description	Health Effect	Sources in Homes	To Reduce Exposure
Radon (See Page 12)	Odorless, colorless, radioactive gas, a decay product of radium, which occurs naturally in the earth's crust.	Believed responsible for about 5% of all lung cancers.	Earth and rock beneath home.	● Design and build your home with plenty of foundation vents. ● Tightly seal floors over crawlspaces. ● Pour slabs to resist cracking, and seal openings. ● Depressurize the ground beneath the slab. ● Install an air-to-air heat exchanger.
Formaldehyde (See Page 15)	Strong-smelling, colorless, water soluble gas, a component of some insulation and of glues used in making plywood, particle board and textiles.	Nose, throat and eye irritation, possibly nasal cancer.	Various materials, including urea-formaldehyde foam insulation (UFFI), particle board, plywood, furniture, drapes and carpet.	● Use materials that are relatively low in formaldehyde. Examples are particle board which meet HUD standards, or materials made with exterior type glues which releases less formaldehyde than interior types. ● Increase air exchange rates. ● Seal formaledehyde sources. ● Install a dehumidifier.
Combustion gases: Carbon monoxide (See Page 17)	Colorless, odorless, tasteless gas from all fuel burning.	Lung ailments. Impaired vision and brain functioning. Fatal in very high concentrations.	Kerosene heaters, wood stoves, unvented gas stoves, attached garages.	● Properly size and install wood stoves. ● Install exhaust fan above gas stove. ● Keep gas appliances properly adjusted. ● Properly vent space heaters. ● Supply outside air directly to wood stove & fireplace firebox. ● Clean chimneys. ● Do not let fires smolder. ● Do not leave car idling in garage.
Nitrogen Oxides (See Page 17)	Colorless, tasteless gas formed during combustion.	Lung damage. Lung disease after long exposure.	Kerosene heaters, unvented gas stoves.	● Install exhaust fans above gas stove. ● Keep gas appliances properly adjusted. ● Increase ventilation.
Respirable Suspended Particulates (RSP). (See Page 20)	Particles in the air small enough to be inhaled.	Nose, throat and eye irritation, lung cancer, emphysema, heart disease, bronchitis, respiratory infections.	Tobacco smoke, wood smoke, unvented gas appliances, kerosene heaters, asbestos construction materials, house dust.	● Avoid smoking tobacco inside or smoke near open window. ● Be sure wood stove doors and flues do not leak. ● Vent combustion appliances outdoors. ● Change air filters regularly. ● Increase ventilation. ● Supply outside air directly to wood stove and fireplace firebox.
Benzo-(a)-pyrene (BaP) (See Page 20)	A tarry organic particle from incomplete combustion.	Nose, throat and eye irritation, lung cancer, emphysema, heart disease, bronchitis, respiratory infections.	Wood smoke, tobacco smoke.	● Avoid smoking tobacco inside or smoke near open window. ● Be sure wood stove doors and flues do not leak. ● Vent combustion appliances outdoors. ● Change air filters regularly. ● Increase ventilation. ● Supply outside air directly to wood stove and fireplace firebox.
Household Chemicals (See Page 21)	Organic compounds found in household products.	Irritation of skin, eyes, nose and throat, effects on central nervous system and metabolic processes.	Synthetic materials, pesticides, aerosol sprays, cleaning agents, paints.	● Follow directions on labels for use. ● Use chemicals only in well ventilated areas. ● Store chemicals in a garage or outdoor shed and keep locked up. ● Substitute less hazardous products.
Moisture (See Page 22)	Excessive humidity and trapped water.	Contributes to growth of micro-organisms. Acts as solver for other pollutants.	Breathing and perspiring, laundry, dishwashing, bathing, cooking, leaks, soil beneath home.	● Install ground cover. ● Install exhaust fans in bathrooms, kitchens, and other moisture producing areas. ● Vent moisture producing appliances such as dryers. ● Install a dehumidifier or air-to-air heat exchanger. ● Properly drain ground around home.

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) has recommended provision of outside makeup air for combustion appliances, such as furnaces and water heaters since 1981. Other appliances affecting indoor air ventilation (e.g., intermittently used local exhaust fans) are not mentioned by ASHRAE and are not as important as combustion appliances in affecting ventilation or house depressurization (EPA 1986).

The major effect of providing makeup or combustion air to household appliances is to prevent additional house depressurization and hence to prevent increasing pressure-driven flows of soil gas-borne radon into the house. While there is high confidence that this pressure-driven flow is the major mechanism of radon entry, quantitative evidence of the radon-reduction benefit of avoiding appliance depressurization effects is variable, 1 to 50 %. The variability probably reflects the specific appliance's operating conditions, varying indoor conditions, and differences in radon source strength (EPA 1986).

Installation costs will be associated with providing small dampered duct work systems for indoor air consuming appliances, such as furnaces, fireplaces, and (perhaps) clothes dryers (EPA 1986).

M.2.2 Air Cleaning

No updated information related to air cleaning was found in the literature review. Many of the topics included in Appendix C are also discussed by Mueller (1987) and Fisk (1986). These topics include mechanical and electrostatic filtration, absorption and adsorption systems.

M.2.3 Increased Ventilation

On the subject of increased ventilation, the literature review yielded additional and updated information about whole house ventilation, active ventilation of hollow-block basement walls, and exhaust fans.

Mechanical ventilation is the forced movement of air by fans into and out of a building. A schematic design for a heating, ventilation, air-conditioning and air cleaner system is presented in Figure M.1 (Mueller 1987). This schematic illustrates the relationships between local ventilation for source control infiltration, forced-air ventilation, and removal control. A variety of locations are shown for air cleaners.

The centers of concrete blocks used to construct many basement walls contain voids. These voids are generally interconnected both vertically and horizontally within a wall. The principle of block wall ventilation is to sweep the soil gas out of these voids by drawing suction on or by blowing air into this void network.

This type of wall ventilation system would be most applicable to:

- Concrete block basement houses that have reasonably accessible top voids, no exterior brick veneer, and no fireplace structure within a block wall; or

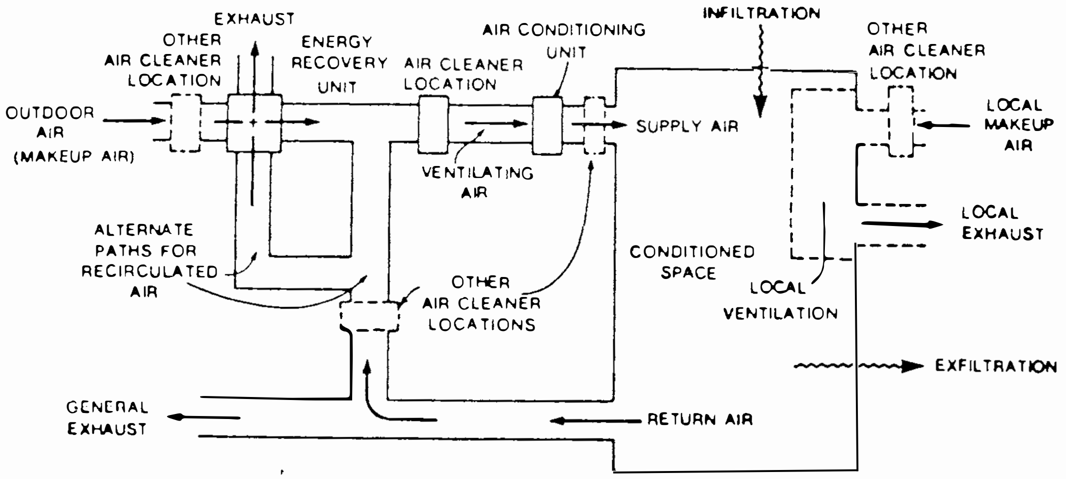


FIGURE M.1. Schematic Design for Incorporating Heating, Ventilation, Air-Conditioning and Air Cleaning for Indoor Air Quality Control (Mueller 1987)

- Houses fitting the above description, with French drains.

In a field study of exhaust fans for mitigation of IAQ problems, Grimsrud et al. (1986) examined the effects of small, continuously operating exhaust fans on pollutant concentration and energy use in residences. Results of the study, which included four dwellings, showed that the amount of ventilation provided by the fans was detectable. This is consistent with their role of supplying "fill ventilation," a minimum amount of ventilation when the infiltration drops near zero, due to weather conditions.

Passive pollutant samplers in the dwelling demonstrated that air quality was not adversely affected by exhaust fans. Conversely, the measurements did not demonstrate a significant improvement in IAQ when exhaust fans were used. Results from real-time radon samplers demonstrated that the source strength of the radon was not increased when exhaust fans were used. This demonstrates that depressurization in the dwelling due to the operation of the exhaust fan was minimal and did not increase the radon concentration.

The daily increase in energy use for the four houses from exhaust fan use was 1.5 kWh. This assumes an average indoor-outdoor temperature difference of 10 C. The energy increase represents approximately 3% of the daily energy use in these homes.

M.2.4 Pollutant Specific Reduction Techniques

Additional information was found on mitigation of radon, organic compounds, and allergens and pathogens in EPA (1986) and Mueller (1987). The EPA report Radon Reduction Techniques for Detached Houses (1986) presents a comprehensive review of mitigation methods applicable to detached houses. A summary of the EPA radon reduction techniques presented in that document is given in Table M.3. In the table, the estimated percentage of annual average concentration reduction is listed for the mitigation technologies. Methods which have been shown to reduce radon concentrations by 90% or more are summarized in Table M.4.

The EPA report also includes estimated installation costs and annual operating costs for the mitigation technologies. Installation costs range from under $100 to $5,000 depending upon the complexity of the required modifications; while operating costs are minimal -- usually $15 for fan energy and up to $125 for supplemental heating, if required.

Consumer awareness is the best method to reduce health risks from exposure to organic compounds. Attention to warning labels and instructions for storage and use are important, especially regarding ventilation conditions. Substitution of less hazardous forms of products is also suggested such as using a liquid or dry form instead of an aerosol spray (Mueller 1987).

Because many allergens and pathogens originate outdoors, attempts to reduce the ventilation rate may lower indoor pollutant concentrations. Reduction in fresh air exchange should be supplemented by a carefully filtered air source. Ultraviolet light has been used to inactivate viruses in air (Mueller 1987).

M.2.5. Non-heat Recovery Mechanical Ventilation Systems

In the implementation of its Super Good Cents Program, BPA has developed a non-heat recovery ventilation option which is capable of providing a minimum rate of ventilation air to the whole-house and an increased ventilation rate, on an intermittent basis, for exhausting indoor contaminants in kitchens and bathrooms (spot ventilation), when required. These options are not applicable to buildings using advanced air leakage control. These systems will not have a dramatic effect on radon, but will have a beneficial effect on generalized indoor pollutants such as humidity, odors, and household dust.

The Super Good Cents Reference Manual (BPA 1986) describes four general designs for achieving this whole-house and spot ventilation capacity:

1) Integrated Spot and Whole House Design: This system uses one or more of the spot ventilation fans to provide whole house ventilation when necessary. Example: The bath fan is controlled by both a crank timer in the bathroom and a dehumidistat in the living room to provide both spot ventilation needs in the bathroom and the whole house ventilation needs when called for by the dehumidistat in the living room. Fresh air inlets in the bedrooms and undercut doors provide the necessary air circulation of fresh air through the house to the bath fan (Figure M.2).

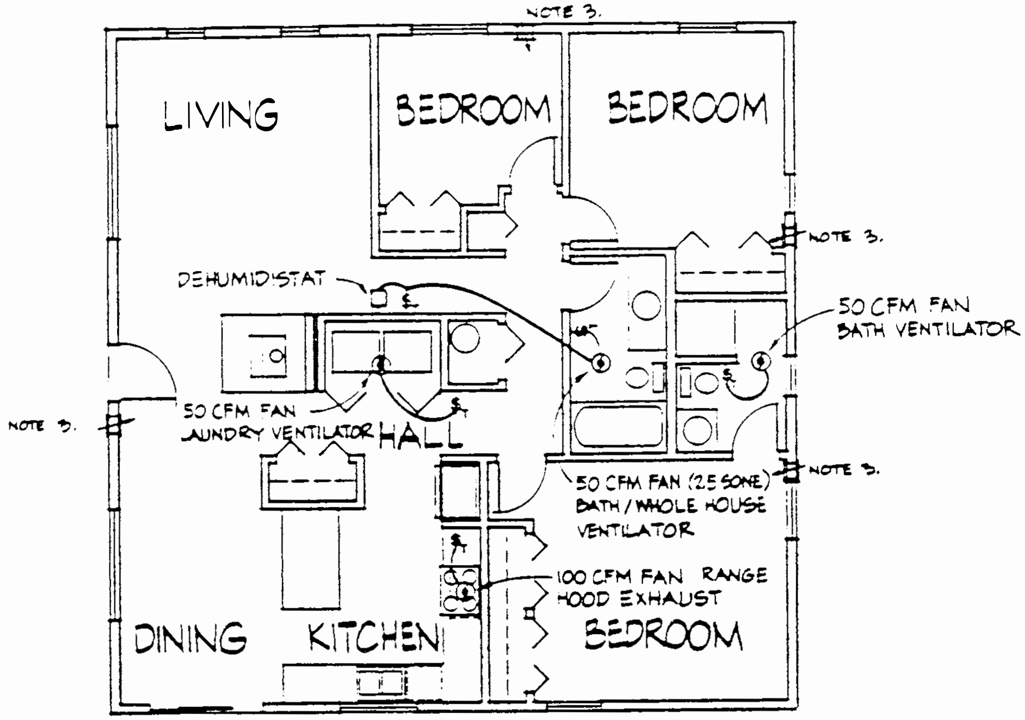
2) Ducted Central Exhaust Design: This system uses a single large multi-speed exhaust fan ducted to bedrooms, baths, kitchen and living areas to provide both whole-house and spot ventilation. Example: A large 200 cfm fan located in the attic has exhaust ducts connected to

each bedroom, bathroom and the kitchen. The fan is controlled to provide a high speed, high flow exhaust when needed for spot ventilation in the kitchen or bathrooms. The fan also operates at a lower flow rate when controlled to provide whole house ventilation (Figure M.3).

3) Discrete Spot and Whole-House Design: This system uses separate fans and control systems to provide spot and whole house ventilation. Example: The system consists of standard bath fans controlled by crank timers, a kitchen range hood, and a single 50 cfm exhaust fan located in a central hallway near the bedrooms connected to a dehumidistat in the living room (Figure M.4).

4) Forced Air Heating/Cooling System Integrated Design: In this system spot ventilation is provided through bath and kitchen exhaust fans but whole-house ventilation and makeup air are provided through integration with the forced air heating/cooling system. Example: The bath fan is connected to a dehumidistat in the living room to provide whole-house exhaust in a house with a forced air heating/cooling system. The forced air system fan has a low speed setting that is controlled to come on when the dehumidistat calls for the bath fan to run. A motorized damper is controlled by the dehumidistat to open a duct that provides the necessary amount of makeup air into the return air plenum at the forced air heating/cooling system. When the bath fan is turned on by the dehumidistat, the forced air heating/cooling system fan is turned on at low speed and the motorized damper opens to allow fresh air to be pulled into the circulating air in the heating/cooling system, thus providing fresh air throughout the house (Figure M.5).

Figure M.2. Integrated Spot and Whole House System



LEGEND:

S_T TIME SWITCH (SPRING WOUND)

⊙ FAN MOTOR

FRESH AIR INLET

☐ CONTROLLER

NOTES:

1. WHOLE HOUSE FAN/BATH VENTILATOR (2.5 SONE) CONTROLLED BY SWITCH IN BATH, CENTRAL SWITCH, AND BY DEHUMIDISTAT.
2. UNDERCUT BEDROOM AND BATH DOORS TO ALLOW FRESH AIR CIRCULATION THROUGH HOUSE.
3. PROVIDE FRESH AIR INLETS (10 CFM, MIN.) AS FOLLOWS:

1. @ EACH BEDROOM	3 x 10 = 30 CFM
1 @ LIVING AREA	1 x 10 = 10 CFM
TOTAL (MINIMUM)	4 x 10 = 40 CFM

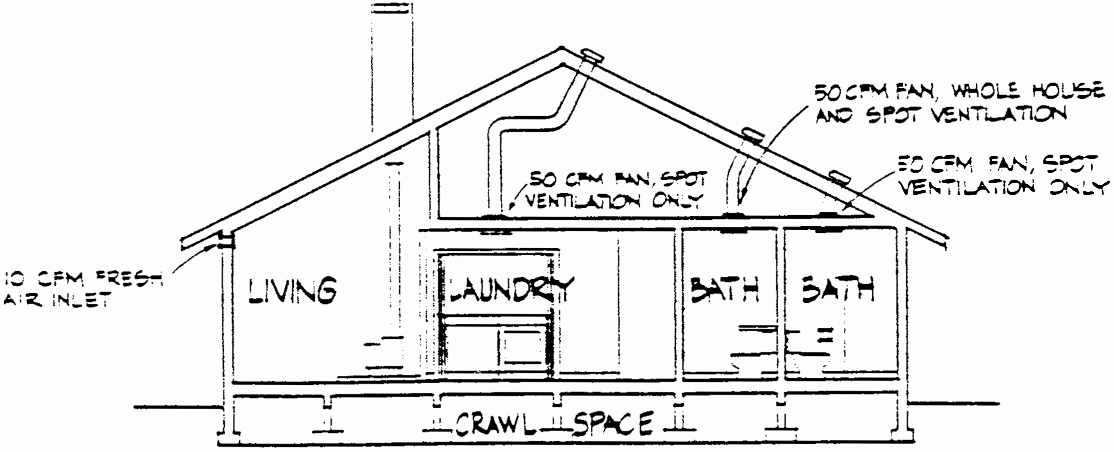
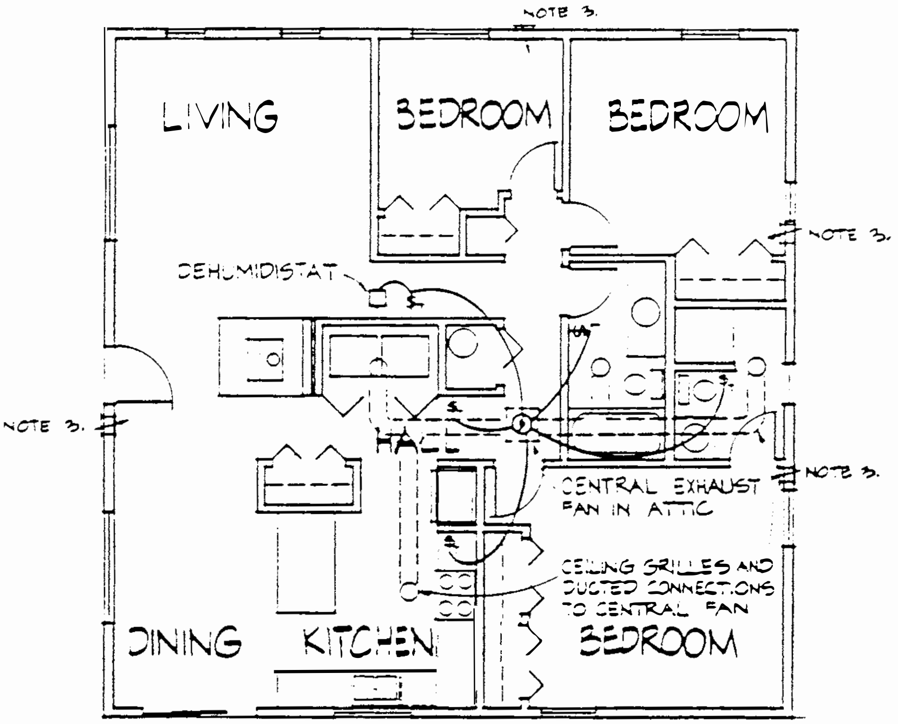


Figure M.3. Ducted Central Exhaust System



LEGEND:

S. TIME SWITCH (SPRING WOUND)

⊙ FAN MOTOR

CEILING GRILLE AND DUCT

FRESH AIR INLET

CONTROLLER

NOTES:

1. CENTRAL EXHAUST FAN IN ATTIC CONTROLLED BY CENTRAL SWITCH, SWITCHES IN KITCHEN, LAUNDRY, BATHS, AND BY DEHUMIDISTAT.

2. UNDERCUT BEDROOM AND BATH DOORS TO ALLOW FRESH AIR CIRCULATION THROUGH HOUSE

3. PROVIDE FRESH AIR INLETS (10 CFM, MIN.) AS FOLLOWS:
1 @ EACH BEDROOM 3x10 = 30 CFM
1 @ LIVING AREA 1x10 = 10 CFM
TOTAL (MINIMUM) 4x10 = 40 CFM

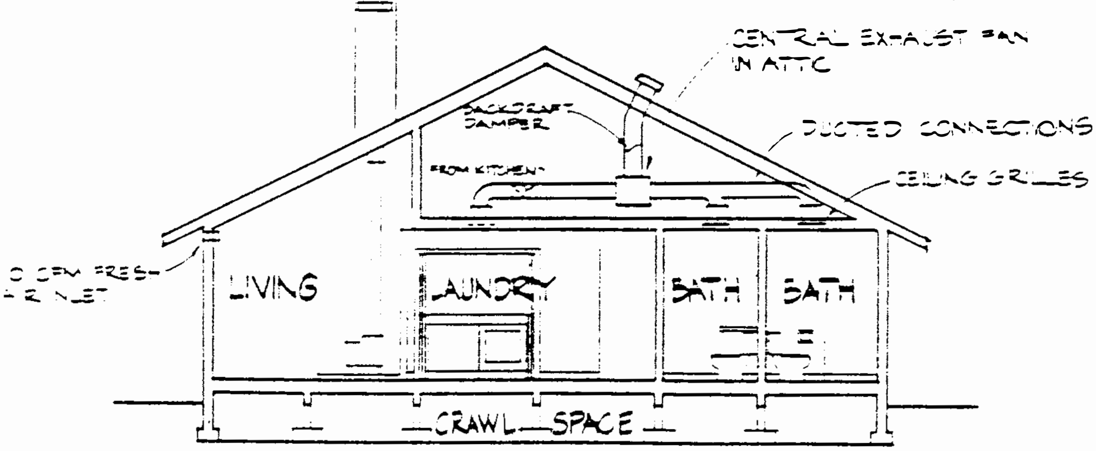
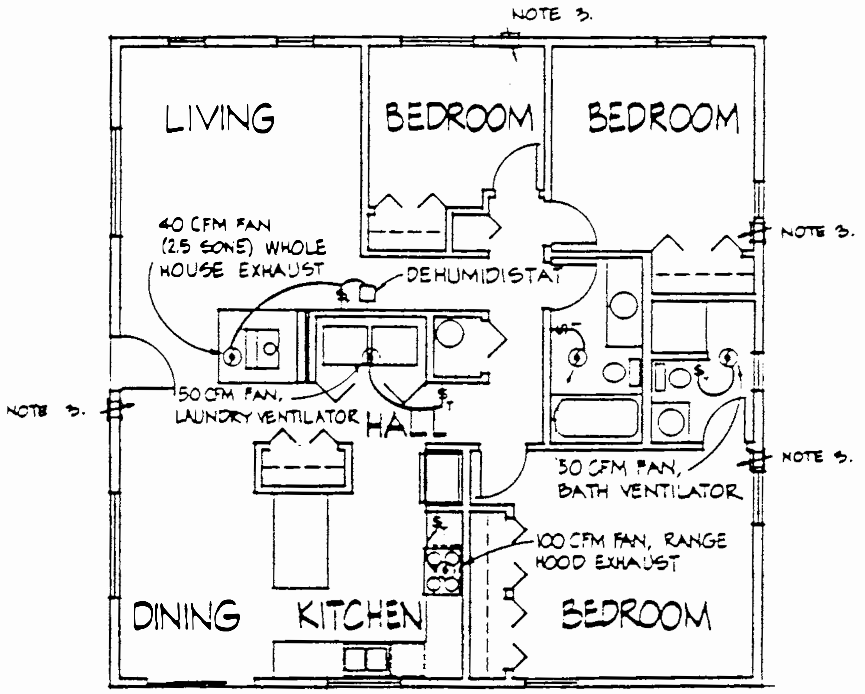


Figure M.4. Discrete Spot/Whole House System



LEGEND:

S_T TIME SWITCH (SPRING WOUND)

⊘ FAN MOTOR

╪ FRESH AIR INLET

☐ CONTROLLER

NOTES:

1. WHOLE HOUSE FAN (2.5 SONE) CONTROLLED BY CENTRAL SWITCH AND BY DEHUMIDISTAT. KITCHEN, LAUNDRY, AND BATH VENTILATORS CONTROLLED BY INDIVIDUAL SWITCHES.
2. UNDERCUT BEDROOM AND BATH DOORS TO ALLOW FRESH AIR CIRCULATION THROUGH HOUSE.
3. PROVIDE FRESH AIR INLETS (10 CFM, MIN.) AS FOLLOWS:

1 @ EACH BEDROOM	3 x 10 = 30 CFM
1 @ LIVING AREA	1 x 10 = 10 CFM
TOTAL (MINIMUM)	4 x 10 = 40 CFM

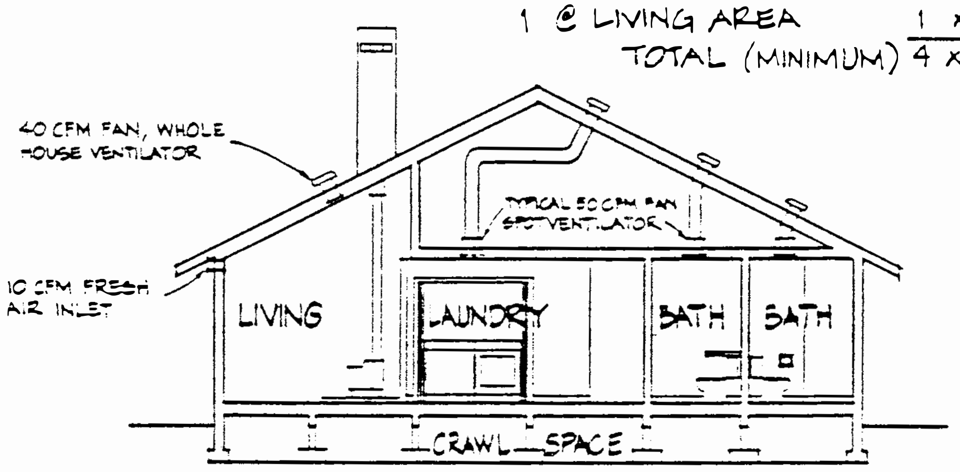
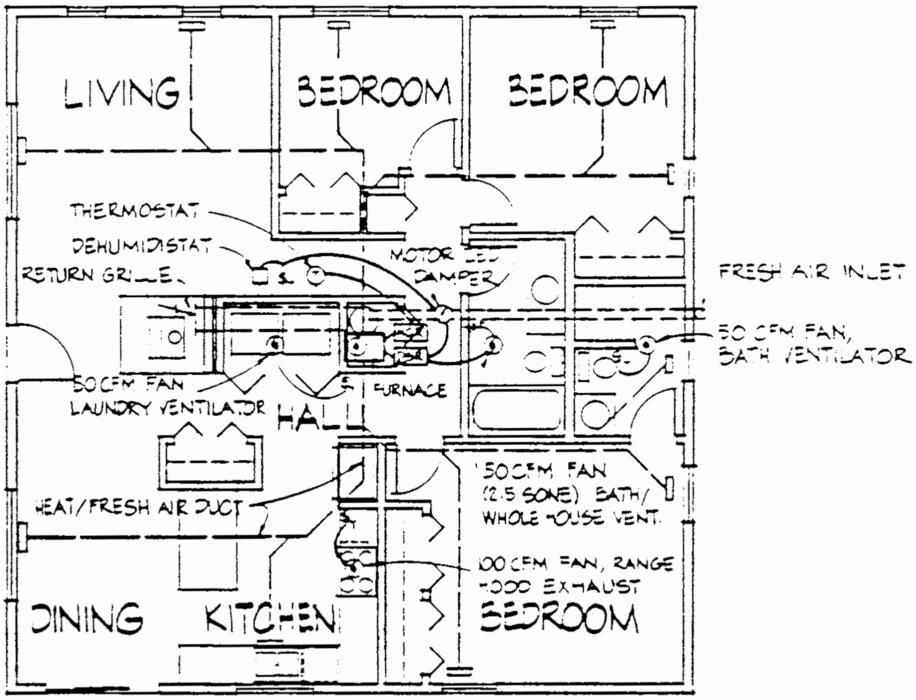


Figure M.5. Whole House Ventilation Integrated with Central Forced Air



LEGEND:

- S TIME SWITCH (SPRING WOUND)
- ⊙ FAN MOTOR
- MOTORIZED DAMPER
- --- OVERHEAD DUCT
- —⌷ UNDERFLOOR DUCT AND REGISTER
- ☐ CONTROLLER

NOTES:

1. WHOLE HOUSE FAN/BATH VENTILATOR (2.5 SONE) CONTROLLED BY SWITCH IN BATH, BY DEHUMIDISTAT OR BY CENTRAL SWITCH VIA 24 VOLT RELAY [DSR]. FRESH AIR SUPPLY DAMPER IS CONTROLLED BY CENTRAL SWITCH OR DEHUMIDISTAT. FURNACE FAN DISTRIBUTES FRESH AIR — CONTROLLED BY 24 VOLT RELAY [DSR] OR BY TSTAT VIA 24 VOLT RELAY [HCR].
2. UNDERCUT BEDROOM AND BATH DOORS TO ALLOW FRESH AIR CIRCULATION THROUGH HOUSE.

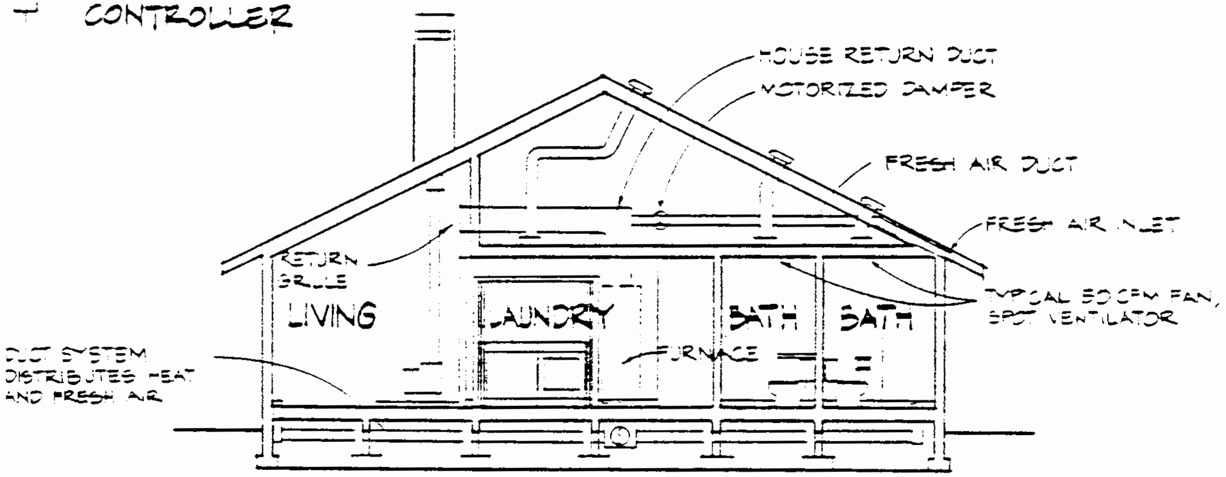


Table M.3. Summary of Radon Reduction Techniques (EPA 1986)

Method	Principle of Operation	House Types Applicable	Estimated Annual Avg. Concentration Reduction, %	Confidence in Effectiveness	Operating Conditions and Applicability	Estimated Installation and Annual Operating costs	Sources of Information
Natural ventilation	Air exchange causing replacement and dilution of indoor air with outdoor air by uniformly opening windows and vents	All[a]	90[b]	Moderate	Open windows and air vents uniformly around house Air exchange rates up to 2 ach may be attained May require energy and comfort penalties and/or loss of living space use	No installation cost Operating costs for additional heating are estimated to range up to a 3.4-fold increase from normal (0.25 ach) ventilation conditions[c]	Be84, ASHRAE85, DOC82
Forced air ventilation	Air exchange causing replacement and dilution of indoor air with outdoor air by the use of fans located in windows or vent openings	All	90[b]	Moderate	Continuous operation of a central fan with fresh air makeup, window fans, or local exhaust fans Forced air ventilation can be used to increase air exchange rates rates up to 2 ach May require energy and comfort penalties and/or loss of living space use	Installation costs range up to $150 Operating costs range up to $100 for fan energy and up to a 3.4-fold increase in normal (0.25 ach) heating energy costs[c]	Be84, Go83, ASHRAE85, DOC82
Forced air ventilation with heat recovery	Air exchange causing replacement and dilution of indoor air with outdoor air by the use of a fan powered ventilation system	All	96[d]	Moderate to high	Continuous operation of units rated at 25-240 cubic feet per minute (cfm) Air exchange increased from 0.25 to 2 ach In cold climates units can recover up to 70% of heat that would be lost through house ventilation without heat recovery	Installation costs range from $400 to $1500 for 25-240 cfm units Operating costs range up to $100 for fan energy plus up to 1.4-fold increase in heating costs assuming a 70% efficient heat recovery[c]	Be84, CR86, NYSERDA85, Na81, We86b
Active avoidance of house depressurization	Provide clean makeup air to household appliances which exhaust or consume indoor air	All	0-10[e]	Moderate[f]	Provide outside makeup air to appliances such as furnaces, fireplaces, clothes dryers, and room exhaust fans	Installation costs of small dampered duct work should be minimal Operating benefits may result from using outdoor air for combustion sources	Na85

Table M.3. (Cont.)

Method	Principle of Operation	House Types Applicable	Estimated Annual Avg. Concentration Reduction, %	Confidence in Effectiveness	Operating Conditions and Applicability	Estimated Installation and Annual Operating costs	Sources of Information
Sealing major radon sources	Use gas-proof barriers to close off and exhaust ventilate sources of soil-gas-borne radon	All	Local exhaust of the source may produce significant house-wide reductions	Extremely case specific	Areas of major soil-gas entry such as cold rooms, exposed earth, sumps, or basement drains may be sealed and ventilated by exhausting collected air to the outside	Most jobs could be accomplished for less than $100 Operating costs for a small fan would be minimal	Sc85b, Na85, NYSERDA85
Sealing radon entry routes	Use gas-proof sealants to prevent soil-gas-borne radon entry	All	30-90	Extremely case Specific	All noticeable interior cracks, cold joints, openings around services, and pores in basement walls and floors should be sealed with appropriate materials	Installation costs range between $300 and $500	NYSERDA85, Sc83
Drain tile soil ventilation	Continuously collect, dilute, and exhaust soil-gas-borne radon from the footing perimeter of houses	BB PCB S	Up to 98	Moderate[9]	Continuous collection of soil-gas-borne radon using a 160 cfm fan to exhaust a perimeter drain tile Applicable to houses with a complete perimeter footing level drain tile system and with no interior block walls resting on sub-slab footings	Installation cost is $1200 by contractor Operating costs are $15 for fan energy and up to $125 for supplemental heating	He86
Active ventilation of hollow-block basement walls	Continually collect, dilute, and exhaust soil-gas-borne radon from hollow-block basement walls	BB	Up to 99 +	Moderate to high	Continuous collection of soil-gas-borne radon using one 250 cfm fan to exhaust all hollow-block perimeter basement walls Baseboard wall collection and exhaust system used in houses with French (channel) drains	Installation costs for a single suction and exhaust point system is $2500 (contractor installed in unfinished basement) Installation cost for a baseboard wall collection system is $5000 (contractor installed in unfinished basement) Operating costs are $15 for fan energy and up to $125 for supplemental heating	He86

Table M.3. (Cont.)

Method	Principle of Operation	House Types Applicable	Estimated Annual Avg. Concentration Reduction, %	Confidence in Effectiveness	Operating Conditions and Applicability	Estimated Installation and Annual Operating costs	Sources of Information
Sub-slab soil ventilation	Continually collect and exhaust soil-gas-borne radon from the aggregate or soil under the concrete slab	BB PCB S	80-90, as high as 99 in some cases	Moderate to high	Continuous collection of soil-gas-borne radon using one fan (~ 100 cfm, ≥ 0.4 in.; H_2O suction) to exhaust aggregate or soil under slab For individual suction point approach, roughly one suction point per 500 sq ft of slab area Piping network under slab is another approach, might permit adequate ventilation without power-driven fan	Installation cost for individual suction point approach is about $2000 (contractor installed) Installation costs for retrofit sub-slab piping network would be over $5000 (contractor installed) Operating costs are $15 for fan energy (if used) and up to $125 for supplemental heating	Er84, Br86b, NYSERDA85, Sa84, He86, Sc86

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[a] BB (Block basement) houses with hollow-block (concrete block or cinder block) basement or partial basement, finished or unfinished
PCB (Poured concrete basement) houses with full or partial, finished or unfinished poured-concrete walls
C (Crawl space) houses built on a crawl space
S (Slab, or slab-on-grade) houses built on concrete slabs.

[b] Field studies have validated the calculated effectiveness of fourfold to eightfold increases in air exchange rates to produce up to 90 percent reductions in indoor radon.

[c] Operating costs are ascribed to increases in heating costs based on ventilating at 2 ach the randon source level; as an example, the basement with 1) no supplementary heating or 2) supplementary heating to the comfort range. It is assumed the basement requires 40 percent of the heating load and if not heated would through leakage still increase whole house energy requirements by 20 percent. Operating costs are based on fan sizes needed to produce up to 2 ach of a 30x30x8 ft (7200 cu ft) basement or an eightfold increase in ventilation rate.

[d] Recent radon mitigation studies of 10 inlet/outlet balanced mechanical ventilation systems have reported radon reduction up to 96 percent in basements. These studies indicate air exchange rates were increased from 0.25 to 1.3 ach.

[e] This estimate assumes that depressurizing appliances (i.e., local exhaust fans, clothes dryers, furnaces, and fireplaces) are used no more than 20 percent of the time over a year. This suggests that during the heating season use of furnaces and fireplaces with provision of makeup air may reduce indoor radon levels by up to 50 percent.

[f] Studies indicate that significant entry of soil-gas-borne radon is induced by pressure differences between the soil and indoor environment. Specific radon entry effects of specific pressurization and depressurization are also dependent on source strengths, soil conditions, the completeness of house sealing against radon, and baseline house ventilation rates.

[g] Ongoing studies indicate that where a house's drain tile collection system is complete (i.e., it goes around the whole house perimeter) and the house has no interior hollow-block walls resting on sub-slab footings, high radon entry reduction can be achieved.

TABLE M.4. Effectiveness of Radon Reduction Techniques

Technique	Reduction
Natural Ventilation	90%
Forced Air Ventilation	90%
Forced Air Ventilation With Heat Recovery	96%
Sealing Radon Entry Routes	30-90%
Drain Tile Soil Ventilation	98%
Active Ventilation of Hollow Block Basement Walls	99+%
Sub-Slab Soil Ventilation	80-91%

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