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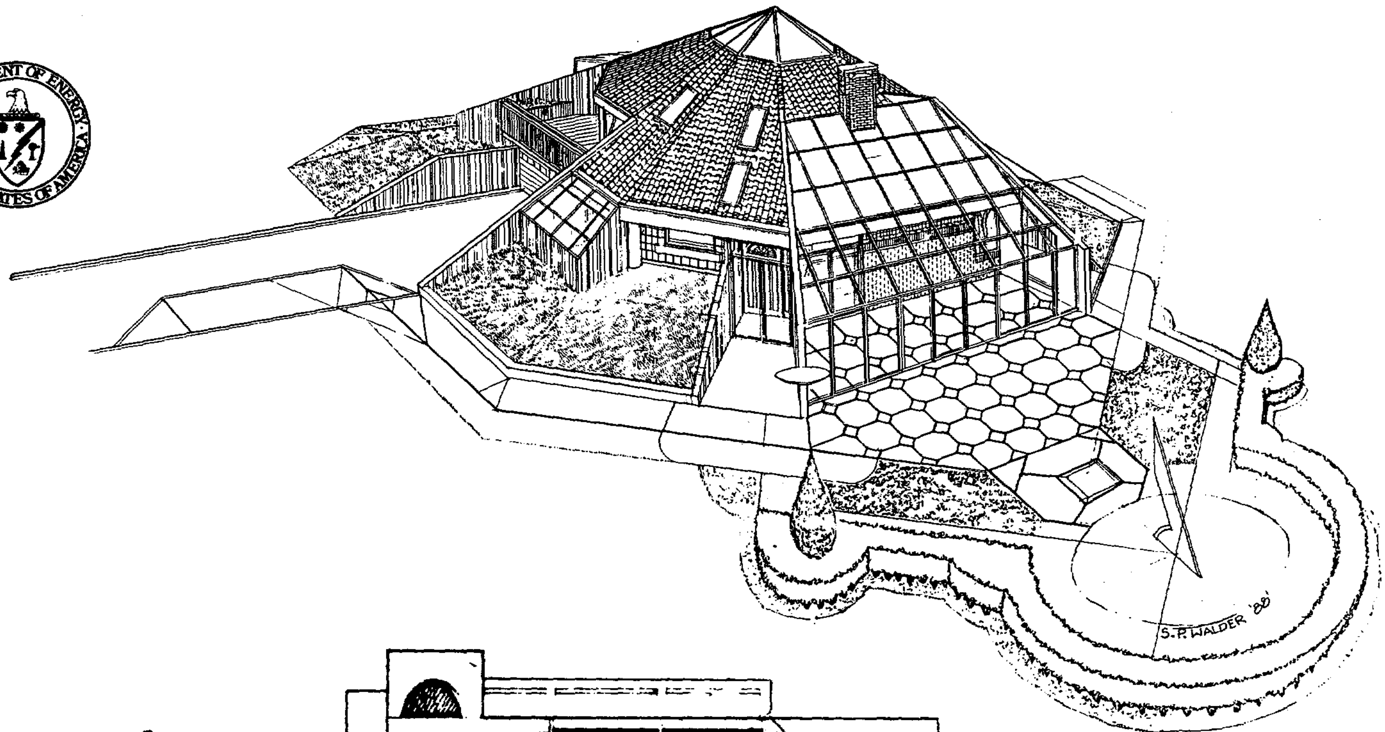
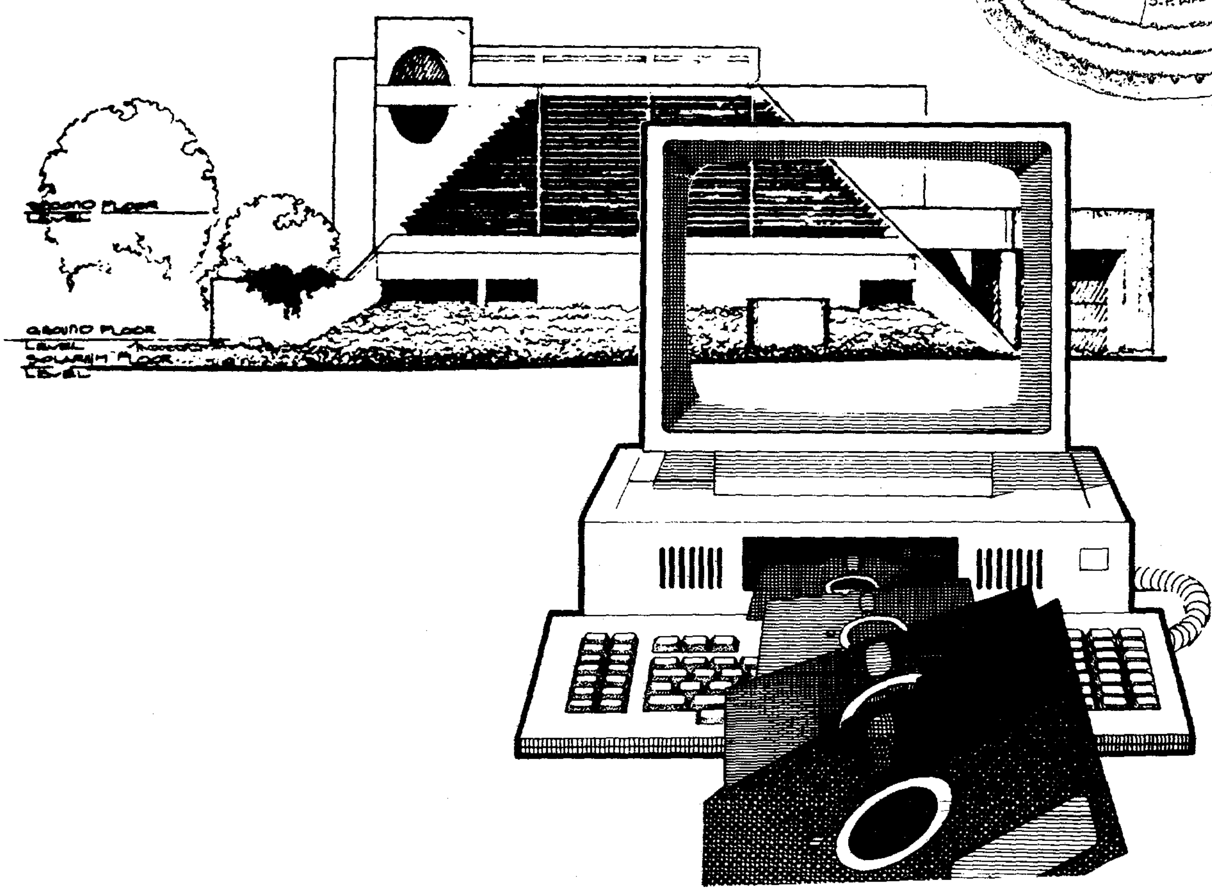
Environmental Assessment

In Support of Proposed Interim Energy Conservation Voluntary Performance Standards for New Non-Federal Residential Buildings

September 1989





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PREFACE

The Energy Conservation for New Buildings Act of 1976, as amended, 42 U.S.C Section 6831 et. seq. requires the U.S. Department of Energy (DOE) to issue energy conservation standards for the design of new residential and commercial buildings. The standards will be mandatory only for the design of new federal buildings and will serve as voluntary guidelines for the design of new non-federal buildings.

The original recommendations for the non-federal residential standards were produced by the American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) Special Projects Committee No. 53 under contract to Pacific Northwest Laboratory (PNL). Those recommendations were published in four volumes entitled Recommendations for Energy Conservation Standards for New Residential Buildings. DOE modified the original recommendations to accommodate an optional, more flexible economic analysis procedure. DOE also directed PNL to produce additional technical documentation for the software that embodies the standards and to assess the economic and environmental effects of the standards.

The final standards are documented in seven publications in support of the Proposed Interim Energy Conservation Voluntary Performance Standards for New Non-Federal Residential Buildings:

- ARES 1.2 User's Guide (Automated Residential Energy Standard) - Explains the use of the ARES program to develop location-specific energy conservation requirements.

- Technical Support Documentation for the Automated Residential Energy Standard (ARES) - Explains the data and algorithms used by the ARES program to optimize energy-related features of new residences.

- Background to the Development Process for the Automated Residential Energy Standard (ARES) - Explains the background and philosophy of the standard development process.

- Technical Support Documentation for the Automated Residential Energy Standard (ARES) Data Base - Documents the assumptions and procedures used to develop the residential energy consumption data base in ARES.

- Description of the Testing Process for the Automated Residential Energy Standard (ARES) - Describes the process used by the development committee to initially test the ARES computer program.

- Economic Analysis - Describes an assessment of the likely impacts of the new standards on the nation's economy.

- Environmental Assessment - Describes an assessment of the likely impacts of the new standards on new home habitability, on institutions associated with residential construction, and on the economy in general.

SUMMARY

Under Title III of the Energy Conservation and Production Act (the Act) (Pub. L. 94-385), as amended, the Secretary of Energy is responsible for developing performance standards for all new residential and commercial buildings. For the federal sector, the standards set mandatory performance levels for the design of federal buildings. For the private sector, the standards are voluntary and serve as guidelines, providing technical information and examples of energy-efficient design practices. The DOE has developed two standards for residential construction. The federal standard (FEDRES) contains mandatory requirements for new construction by federal agencies; the second standard (VOLRES) provides a voluntary guide for private sector construction. This Environmental Assessment (EA) addresses only the latter voluntary standard.

The U.S. Department of Energy (DOE) prepared this EA to explore the possible environmental effects of the proposed voluntary standard on residential buildings constructed for the private sector. This assessment was done as part of DOE's responsibility under the National Environmental Policy Act of 1969, as amended (Pub. L. 91-190, January 1, 1970), and the implementing regulations of the Council on Environmental Quality (CEQ) (40 CFR Parts 1500-1508). Because the proposed standard is voluntary in nature and is intended to serve as a guideline for the private sector, the DOE prepared an EA to address impacts if the voluntary standard is adopted as a mandatory code by state or local jurisdictions. The latter assumption forms the basis for the impacts assessed in this report.

The scope of this assessment is limited to the possible environmental effects on the private sector of the proposed voluntary standard. The economic and socioeconomic impacts of the proposed voluntary residential standard have been analyzed in a separate document (Economic Analysis - In Support of Proposed Interim Energy Conservation Voluntary Performance Standards for New Non-Federal Residential Buildings), and are summarized in this EA.

The EA examines the consequences of the proposed voluntary standard, i.e., the impacts attributable to differences between the design of the baseline residential units and units designed to the voluntary standard. This

assessment emphasizes the possible alterations to the indoor air quality of a residence, and by reference, the estimated effects on the life-cycle cost and energy use of new residential buildings.

This EA indicates that the impact of the voluntary standard on building habitability, the outdoor environment, the economy, and institutions would not be significant. Specific results are summarized below.

HABITABILITY

In this assessment, habitability is expressed in terms of changes in various indoor air pollutant concentrations and the concomitant health and safety impacts to occupants as a result of building design changes required by the proposed voluntary standard. No significant effects on building habitability were found.

Various pollutants are released continuously or intermittently within residential buildings. An indoor air quality computation model that uses specific pollution emission values (release rates) for selected materials was used to calculate pollutant concentration levels in the case-study residences, based on baseline conditions and on the proposed standard. Incremental pollutant concentrations were calculated for particulate matter, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), radon and formaldehyde. The potential impact on indoor air quality of chemical compounds and microorganisms was assessed qualitatively because the quantitative detail necessary for simulation modeling is not available.

Particulate Matter

Implementation of the proposed voluntary standard is expected to have no effect on the level of particulate matter in residences.

Carbon Monoxide

Currently, estimated indoor concentrations of carbon monoxide (CO) from cooking and smoking are well below levels associated with health risk. The proposed voluntary standard would have no effect on CO concentrations.

Carbon Dioxide

Residential units designed under the proposed voluntary standard are expected to maintain low concentration levels of carbon dioxide (CO_2). The health risk from indoor CO_2 concentrations would not change.

Nitrogen Dioxide

Release of nitrogen dioxide (NO_2) in residential indoor environments is small. The simulated concentrations of NO_2 for the proposed voluntary standard residential units are the same as for baseline residential units.

Radon

Estimated values for indoor air concentrations of radon in residential units, would be the same for the baseline and the proposed voluntary standard residential units.

Formaldehyde

The proposed voluntary standard reduces the level of formaldehyde in some locations and increases concentrations at other locations. Although the magnitude of the change is small, increases could affect certain individuals who have a very low threshold of sensitivity to formaldehyde. A worst case scenario (minimum allowable infiltration rate) results in larger increases of this pollutant, but resulting concentrations are still below levels that would cause health effects in most individuals.

Chemical Compounds

A large number of chemical pollutants have been identified in indoor residential air. Many of these chemical compounds are either odorous, irritants, or suspected carcinogens. However, the proposed voluntary standard is not expected to measurably increase or decrease health risks due to chemical pollutants in residential indoor air.

Microorganisms

Under certain conditions, microorganisms can become indoor air pollutants with a potential health risk. The most severe problems resulting from such pollutants occur when organisms grow on a damp surface or on stagnant water collected on horizontal surfaces. The proposed voluntary standard is not expected to affect existing levels of microorganisms in residential structures.

OUTDOOR ENVIRONMENTAL IMPACTS

On a national basis, there would be a net improvement in outdoor environmental quality from reduced fossil fuel usage. The voluntary standard reduces estimated insulation levels in some locations that were studied, and increases them in other sites. As a result, the net impact on insulation production is not likely to affect the general magnitude of airborne pollutants from its production.

ECONOMIC IMPACTS

The economic analysis of the proposed voluntary standard for new residential buildings concludes that there are no significant adverse effects to society from adopting the VOLRES standard. The voluntary standard will result in a positive net flow of benefits from energy savings that more than offsets higher capital construction and other costs, when compared to current practice. This conclusion was reached by comparing the life-cycle costs of prototypes constructed to current practice or codes and those of units that meet the proposed voluntary standard.

The national net (economic) effect of the voluntary standard, assuming its immediate and full penetration, ranges from nearly $930 million in net benefits for 1988 construction to $1,035 million for 1992 construction. This effect is based on the net present value of energy savings and capital costs using a time frame of 15 years. For construction in 1992, the year with the largest net effect, the capital costs of compliance to the voluntary standard are $1.2 billion. The net present value of energy savings accrued over the 15-year time frame for buildings constructed in 1992 is nearly $2.2 billion. The difference represents a net benefit of $1.0 billion.

Because the standard is voluntary, the net benefits were also calculated assuming that penetration of the proposed standard was staged over a five-year period (1988-1992). In this scenario, full penetration of the voluntary standard does not occur until 1992. The national net effect of the voluntary standard ranges from nearly $186 million in net benefit for construction in 1988 to $1,035 million for construction in 1992.

The voluntary standard also creates a net benefit for individual regions. Assuming full penetration of the voluntary standard, the Northeast receives the greatest annual benefit until 1993, when the net benefits in the South overtake those of the Northeast. The net benefit to the Northeast increases from $336 million for 1988 construction to $384 billion in 1992, after which the net benefit drops steadily until the 2001-2005 construction period, when it reaches $220 million. The net benefit to the West is the smallest of all regional benefits over the study period. Changes in the relative share of net costs and benefits are attributable to forecasted trends in the regional distribution of new housing.

The total economic impact of the voluntary standard, as measured in the gross value of industry output and employment, were estimated using the U.S. Input-Output table. For the purposes of this analysis, the effects of the energy savings have been assumed to occur in the year of construction, when in reality, the energy savings occur over a fifteen-year time period. In 1992, the construction year with the greatest indirect impacts, the combined effect of changes in output results in a net loss of approximately $2.5 billion in output due to construction. This net decrease in output results from a $2.2 billion increase in output resulting from increased capital expenditures for construction and the $4.7 billion decrease in output resulting from lower energy expenditures. Even when all of the output effects of changes in energy costs over fifteen years are assumed to occur in the initial year of construction, the output change represents only 0.05 percent of the total U.S. Gross National Product. This is not considered significant.

The net loss of 10,800 jobs associated with 1991 construction represents the greatest total effect on employment. This figure is composed of an increase of nearly 31,800 jobs due to increased construction costs and a loss of over 42,600 jobs from decreased energy expenditures. This estimate of employment effects, probably an overestimate, represents less than 0.01 percent of total U. S. employment, a figure not considered significant.

IMPACTS ON INSTITUTIONS

The proposed voluntary standard is intended to be a guideline for construction of residential buildings in the private sector. Because it is not a binding standard, there are no institutional impacts that directly result from its issuance by the DOE. However, the effects of adopting the proposed standard as a mandatory code by states and local code entities could impact institutions. Because of the widespread existence of mandatory state energy codes that stipulate minimum **energy conservation measure (ECM)** levels for new residences, adoption (as opposed to implementation) of VOLRES as a mandatory standard to update existing codes is unlikely to adversely impact state and local institutions. However, it is possible that adoption of the proposed voluntary standard would be accompanied by some political controversy, because there are numerous interest groups that would be affected by code modification.

While the large number of user-modifiable parameters in the proposed voluntary standard make it very flexible, this feature also increases the possibility that if the standard is adopted as a code, it may contain a number of politically negotiated parameters. Adoption of a fuel-specific code such as the VOLRES standard may also cause some political and institutional impacts in states where energy codes are presently fuel-blind. In a given locale, the voluntary standards produced (by the **ARES** computer program) for different fuels usually do not have identical ECM requirements or associated construction costs. This feature may result in a certain degree of change in the local market share held by a given fuel.

Enforcement of the voluntary standard as part of local building codes could require different procedures than those typically used for current energy codes in most states. Code enforcement officials may also need additional training and/or equipment (computers). However, the nature and extent of enforcement-related impacts would depend on the features of the proposed voluntary standard as adopted by state or local governments, as well as the compliance paths that are permitted.

CONTENTS

TABLES

1.0 INTRODUCTION

The objective of this environmental assessment (EA) is to identify the potential environmental impacts that could result from the proposed voluntary residential standard (VOLRES) on private sector construction of new residential buildings. In this section, the scope, objectives, and approach of this EA are presented.

1.1 BACKGROUND

The proposed voluntary standard for new residential buildings has undergone considerable revision since its inception in 1977. This section provides a brief legislative history of the standard and then describes the original and present proposals.

1.1.1 Legislative Background

As originally enacted, Title III of the Energy Conservation and Production Act, Pub. L. No. 94-385, 90 Stat. 1144 et seq., required action to develop, promulgate, implement and enforce compliance with performance standards to improve energy efficiency of all new buildings in the nation. The regulatory nature of this action was modified by the Energy Conservation Standards for New Buildings Act of 1976, as amended, (ACT) 42 U.S.C. 6831 et. seq. Responsibility for this action was transferred to the U. S. Department of Energy (DOE) on August 4, 1977, with the passage of Section 304(a), 42 U.S.C. Sec. 7154, of the Department of Energy Organization Act, Pub. L. 95-91.

In November 1979, DOE published proposed performance standards in the Federal Register, 44 FR 68120, et seq. The standards, expressed as maximum energy consumption levels (Btu per square foot per year), were very controversial, generating over 1800 comments. Many commenters expressed concern that the proposed standards were not technically practicable or economically achievable. Furthermore, many commenters stated that the proposed standards placed too great a reliance upon the use of a complex computer program which many commenters said they neither understood nor could afford to use.

Less than a year after the publication of the proposed standard, the Act was again amended by Section 326 of the Housing and Community Development Act of 1980, Pub. L. No. 96-399 (October 8, 1980). This amendment required that DOE promulgate interim standards and extended the promulgation date of the final standard to April 1, 1983. In addition, the Act required that demonstration projects be conducted in at least two geographical areas.

In August 1981, Congress again amended the Act and deferred the appropriation for the program from the 1981 fiscal year to the 1982 fiscal year. Subtitle D of Title 10 of the Omnibus Reconciliation Act of 1981, Pub. L. No. 97-35, amended the Act to create the term "voluntary performance standard," eliminated the provision for a possible statutory sanction for noncompliance, and added a provision that, except for federal buildings, "voluntary standards will be developed solely as guidelines to provide technical assistance for the design and construction of energy efficient buildings."

1.1.2 Summary of the Original Proposal

The most significant aspect of the proposed Building Energy Performance Standards (BEPS), issued in 1979, was that they were a performance standard that set energy limits for the building as a whole. BEPS attempted to combine energy use of, and permit trade-offs for specific energy-using systems such as heating, cooling or domestic hot water. The proposed standards consisted of three requirements. First, energy budget levels would be set; second, they would be applied to a specific building design to obtain an annual rate of consumption; and third, the estimated general rate of energy consumption would be calculated using a method established by DOE. The whole process required the use of a computer simulation to demonstrate that the designed energy consumption of a new building did not exceed the energy level specified for a residential building of its type in its applicable climate area. The BEPS was based on life-cycle cost analyses and defined different residential building types (multi-family high-rise, multi-family low-rise, single-family attached and single-family detached) as well as a procedure to select an appropriate climate zone from 78 Standard Metropolitan Statistical Areas (SMSA).

DOE recognized that many aids, such as model codes or building energy simulation software, would be needed to reduce compliance complexities. It also acknowledged that tools needed to be in formats familiar to members of the building industry. These compliance assistance tools were in the process of being developed by DOE when the implementation sections of the statutes were repealed by the Omnibus Budget Reconciliation Act. The entire package of compliance assistance tools was never completed, but a slide rule and A Guide to Designing and Constructing Energy Efficient Homes was issued in 1983.

1.1.3 The Present Proposal

In response to the revised legislation and to comments made on the proposed BEPS, DOE is now reproposing voluntary performance standards for the non-federal (private) sector. Because of the difference in the economics and process of Federal design and construction of residential buildings, DOE is issuing separate standards for the federal and private sector. Mandatory standards for new federal residential building had been developed previously and are soon to be issued by DOE.

The proposed voluntary standard is for private sector construction and for federally-subsidized private housing only. As such, DOE would not be regulating private sector construction, but rather issuing guidelines to provide technical assistance for the designs and construction of energy-efficient buildings. The proposal represents a significant federal effort to help the private sector develop energy conservation standards without regulatory intrusion. To develop the proposed voluntary standard DOE has worked closely with a special projects committee from the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE). The research project jointly undertaken by DOE and ASHRAE culminated in the proposed interim voluntary standard.

The proposed voluntary standard is presented in the format commonly used by the private sector standards-setting organization rather than as a federal regulation. For example, the proposal contains extensive explanatory material not normally included in federal standards. By submitting the proposed interim standards in a form that is likely to be better understood and more readily used in the private sector, DOE hopes to improve the standard's transferability.

As defined by the Act, the proposed voluntary standard serves as a guideline for the design of new residences; it does not apply to the operation, maintenance or energy consumption of a building once it is built. The proposed voluntary standard operates by setting an energy cost goal for a building (i.e., a quantified target for energy cost at the design stage) and a method to calculate whether the design meets that goal. Through the use of the software ARES (Automated Residential Energy Standard) which supports the proposed voluntary standard, users can also create "packages" of energy conservation components that meet the energy consumption goal. Additional details on the proposed standard are provided in Section 2.1.

1.2 SCOPE AND OBJECTIVES OF THE ASSESSMENT

The proposed voluntary residential building standard sets minimum performance levels to be applied during the design of private sector residential buildings. The proposed voluntary standard is not expected to result in radical changes in residential building design. This assessment addresses the incremental environmental impacts attributable to the changes that result from application of the proposed performance standard. Those impacts were determined by comparing case-study residential prototypes designed first with current energy conservation measure (ECM) levels (the baseline) with prototype units that meet the proposed standard. Various quantified and unquantified environmental consequences attributable to increasing energy conservation in residential buildings are discussed in this report. Emphasis is placed on incremental changes associated with the ECMs required to meet the VOLRES standard instead of current codes or practices, insofar as they can be identified.

1.3 APPROACH USED IN THE ASSESSMENT

In this study, potential impacts were examined by modeling three types of residential buildings in ten locations across the United States, first to meet baseline ECM levels, then to ECM levels required by VOLRES standard. Although the prototypes studied do not include all potential ECM combinations that would meet either current codes or the proposed voluntary standard, they provide enough diversity to constitute a defensible analytical base. The prototypes include the most common housing types, foundations, and space-conditioning systems used in current residential construction. The ten locations were selected to provide a wide range of climatic conditions in which to estimate the effect of the proposed voluntary standard.

Impacts to the indoor environment, which were found to be negligible, are expressed only in the form of incremental changes to a single home. The economic costs and benefits of widespread adoption of the proposed voluntary standard by state and local code enforcement entities could be more substantial. These affect not only individual consumers but the society as a whole. As a result, an effort was made to estimate aggregate economic impacts, using two scenarios for the rate of adoption of the proposed voluntary standard. The results of the economic analysis have been summarized in this document. For a more extensive discussion of the approach used and results obtained in the economic analysis, see Marsh and Roop (1988).

Section 2 of this EA describes the proposed voluntary standard and the major alternative considered in the environmental assessment. Section 3 provides details on the general approach used in the assessment, followed by estimates of specific indoor air quality changes, a discussion of the human health impacts of indoor air pollution, probable outdoor environmental impacts, a summary of estimated socioeconomic impacts, and institutional impacts. In general, these specific discussions include background information, the analytic methodology used, and the conclusions. Appendix A contains detailed descriptions of the assumptions used to generate the configurations of the case-study prototype residences under the proposed voluntary standard. Appendix B provides information on the current required/accepted levels of efficiency found in housing constructed today. The method used to create the baseline prototype residences is also described in Appendix B. Appendix C provides a detailed description of the indoor air quality model used to compute pollutant concentrations. Finally, Appendix D documents the information used to evaluate human health impacts.

2.0 DESCRIPTION OF THE PROPOSED STANDARD AND ALTERNATIVES

This section provides information on the proposed voluntary residential energy standard (VOLRES) and the no-action alternative considered in this assessment. Although the development of the proposed voluntary standard was mandated by legislation, adoption of the standard by the private sector is voluntary.

Neither the DOE nor any branch of the federal government would be directly involved in implementation of either the voluntary standard as a building code or the no-action alternative, defined as a continuation of current practices and existing energy codes. Adoption of the VOLRES standard to replace or update existing energy codes or building practices would be a voluntary action on the part of state, local governments or organizations that sponsor model building codes, such as the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) or the Council of American Building Officials (CABO).

2.1 THE PROPOSED STANDARD

The VOLRES standard has been developed and proposed by the DOE in response to legislation requiring the Secretary of Energy to promulgate voluntary energy performance standards that are designed to achieve the maximum practicable improvements in energy efficiency in new residential buildings and to encourage the use of non-depletable energy sources. In response to this legislative mandate, this voluntary standard sets forth requirements for the design of new residential buildings that would represent the most cost-effective combination of energy conservation options. This voluntary standard should lead to residential building designs that produce the maximum practicable energy savings given the criterion of economic cost-effectiveness.

This voluntary standard relies on minimizing life-cycle costs using estimated energy consumption data, construction cost data, climate data, and appropriate consumer financial parameters. The VOLRES standard is implemented through a computer program documented in <u>ARES 1.2 User's Guide (Automated Residential Energy Standard) - In Support of Proposed Interim Energy</u>

Conservation Voluntary Performance Standards for New Non-Federal Residential Buildings.

The proposed voluntary standard sets forth recommended requirements for the energy-affecting construction components of residential buildings, including insulation levels, windows (amount, glazing layers, sash type), infiltration control measures, space conditioning equipment, and domestic hot-water conditioning equipment. The VOLRES standard includes separate requirements for each of three generic housing types: 1) single family detached housing, 2) multifamily attached housing, and 3) manufactured housing. Within each housing type, separate requirements are set forth for each of five space-conditioning equipment combinations: 1)natural gas heat with electric cooling, 2) oil heat with electric cooling, 3) liquid propane gas (LPG) heat with electric cooling, 4) electric resistance heat with electric cooling, and 5) electric heat-pump heating and cooling.

The voluntary standard requires that residential housing be constructed to minimize overall costs to the homeowner over the assumed life of the home. The monetary factors included in the assessment of these life-cycle costs are initial construction costs, operation and maintenance costs, energy costs, tax effects, and resale value of the home, all of which are discounted to adjust for inflation and lost-opportunity costs. A house complies with the voluntary standard if its annual space-conditioning energy cost is shown to be less than or equal to that of a similar house constructed to achieve minimum overall life-cycle costs to the homeowner, given local construction costs, fuel prices, and economic conditions.

The proposed voluntary standard includes minimum recommendations for infiltration control measures, but it allows stricter measures to be implemented at the user's option if necessary to meet the energy-cost budget. The minimum recommendations reflect current building practices, such that air exchange rates (assumed to average approximately 0.5 air changes per hour) and indoor air quality are not adversely affected by the standard. The optional tighter measures are specified such that air exchange rates do not fall below 0.35 air changes per hour, the threshold below which forced ventilation would be required to maintain acceptable air quality.[a] The tighter measures are never required, but are offered as an option to allow users to select less stringent component efficiencies (eg., lower R-values for insulation).

2.1.1 The Automated Residential Energy Standard Computer Software

Procedures that automate the development of specific criteria to comply with this voluntary standard are embodied in a computer program, Automated Residential Energy Standard (ARES). This program maintains data bases of estimated residential energy consumption for a variety of locations, of construction costs, of economic and financial parameters, and of typical building characteristics. Using these data, ARES identifies for each locality the combination of energy conservation measures that results in the minimum overall life-cycle costs to the homeowner. The annual energy costs of the optimal house constitute the target energy costs required by the voluntary standard. ARES then provides an initial set of prescriptive requirements (a package) that meets this energy budget, and a point system designed to allow evaluation of specific building designs against the prescriptive target. The user can also generate "alternative [prescriptive] packages" by changing one or more of the minimum requirements of the initial package.

The ARES program is designed to be used by code officials responsible for establishing energy codes in specific jurisdictions. The user can modify the various economic, financial, and climatic inputs to ARES to tailor the resulting voluntary standard to specific localities. The program also provides alternative compliance materials in the form of a flexible point system or an energy cost target (see below).

The Energy Data Base

The ARES energy data base contains annual heating and cooling loads for residential housing built to any common level of thermal integrity in any of 886 locations throughout the United States. The energy data are derived from parametric computer simulations of residential energy performance. The development and format of these data are documented in a draft report to be

(a) These estimated air exchange rates do not include the effects of occupants, which increase infiltration slightly.

published by the DOE entitled Technical Documentation for a Residential Energy Use Data Base Developed In Support of ASHRAE Special Project 53.

The Cost Data Base

The ARES cost data base contains 1986 construction costs for all common ceiling, wall, crawlspace and basement insulation levels; window types; and HVAC equipment efficiencies. Twelve sets of cost data are included representing 11 regions of the United States and the national average. Table 2.1 lists the states included in each region.

When using ARES, local jurisdictions may choose the most appropriate regional data base. The selected data base may also be altered if necessary to reflect local conditions by changing construction costs and/or adding or deleting component levels as appropriate.

The Life-Cycle Cost Optimization

The life-cycle cost calculations required by the proposed voluntary standard reflect the value of energy conservation measures to a typical homeowner. The life-cycle cost is defined as the sum of the net present values of the following cash flows over a seven-year time period:

- down payment on loan
- loan fees and other closing costs
- up-front interest charges (points) on loan
- tax deductions on points
- mortgage payments over the period of analysis
- tax deductions on mortgage interest over the period of analysis
- space conditioning energy costs over the period of analysis
- non-fuel operation and maintenance costs over the period of analysis
- resale value of home at the end of the period of analysis.

Only the portion of loan, tax, etc. costs attributable to the ECMS are important in the life-cycle cost calculations.

The 7-year period used in the life-cycle analysis reflects the median turnover period of home ownership and mortgages. All cash flows are discounted at a user-modifiable alternative investment rate. Mortgage payments and interest fractions (i.e., the fraction of each mortgage payment that reflects the

Table 2.1. Construction Cost Databases in ARES

Region	States in Region
National Average	All
New England	CN, MA, ME, NH, RI, VT
Mid-Atlantic	DC, DE, MD, NJ, NY, PA
Mid-South	GA, NC, SC, VA, WV
Florida	FL
South Central	AL, AR, KY, LA, MS, OK, TN, TX
Central	IA, KS, MO, NB
North Central	IL, IN, MI, MN, ND, OH, SD, WI
Mountain	CO, NV, UT, WY
Southwest	AZ, NM
Pacific Southwest	AK, CA, HI
Pacific Northwest	ID, MT, OR, WA

interest) are based on common financial calculations and current economic parameters that must be supplied by the user. The resale value of the home is assumed to be identical to its initial cost in current dollars at the end of the period of analysis. Thus the real value of the home's ECMS is assumed to decline at the rate of inflation.

The ARES program identifies the hypothetical house with the minimum life-cycle cost via an exhaustive search of all combinations of insulation levels, equipment efficiencies, and window types available in the cost data base. In concept, the energy and construction costs of houses built to every combination of conservation options are calculated and compared. The combination with the lowest overall life-cycle cost is used as the basis for the energy cost budget. However, several constraints are applied during the optimization. First, the optimization assumes that the window area of the house is equally distributed on the four cardinal orientations. Though this seldom matches the construction of a particular house, it represents the average condition of large numbers of residences. Second, the optimal levels of ceiling insulation, wall insulation, windows, and equipment efficiencies are forced to be the same regardless of the foundation type. This is accomplished by identifying a prevalent foundation type for each location and optimizing a prototypical house with that foundation. Once the upper envelope conservation levels are established, the foundation insulation levels for each additional foundation type are optimized assuming the same upper envelope is installed. Thus, each foundation type results in a unique energy cost budget.

Prescriptive Package Compliance Alternative

The ARES program provides prescriptive packages of options that will meet the energy cost budget associated with the optimal combination of components identified by the life-cycle cost optimization. One prescriptive package is created for each of the 5 fuel/equipment combinations. However, each prescriptive package differs from its original optimal combination of options (that produced the energy budget) due to a constraint applied in the program. The prescriptive packages assume that windows are equally distributed on the east and west faces of the house, rather than on all four faces as is done in the original optimization. This constrained configuration is intended to approximate the worst possible orientation scenario, so that virtually any house, regardless of its window placement, would have energy performance at least as good. The purpose is to minimize the possibility that a house allowable under the prescriptive compliance path would not be allowable under the points compliance path (described below). Given this constraint, ARES identifies the combination of options that meets the energy cost budget with the minimum construction cost.

In addition to the five voluntary standard prescriptive packages, the user of the program (state or local governments or building code officials) may develop additional packages to satisfy local preferences. This is accomplished by applying specific constraints, such as a fixed-wall insulation level, or window-to-floor area ratio, then allowing ARES to identify the other components of the house that result in acceptable energy use at a minimum construction cost. This allows code officials to create simple compliance approaches for technologies and preferences common to their localities.

Point System Compliance Alternative

The point system printed by ARES is designed to allow builders to deviate from the prescriptive packages identified by the cost optimization while maintaining thermal integrity. Various levels of conservation options are assigned "points," which are tabulated in the compliance materials printed by the program. The points are directly proportional to the annual energy costs of the home, providing builders the capability to evaluate the energy cost impacts of various construction options. Options that may be evaluated by the point system include various insulation levels, equipment efficiencies, and various window parameters, including number of glazings, solar transmittance, and orientation.

Performance Compliance Alternative

The proposed voluntary standard allows construction of any house that has annual energy costs less than or equal to those of the optimal house. To accommodate new and innovative technologies, the standard provides the option of evaluating the energy performance of a design against that of a similar house that complies with the prescriptive requirements. An energy analysis must be conducted for both the design house and the target house using a calculation technique appropriate for the technologies involved. Typically, this requires use of a computer simulation tool.

2.2 NO-ACTION ALTERNATIVE: CONTINUED USE OF CURRENT ENERGY CODES AND ENERGY-RELATED BUILDING PRACTICES

As noted above, the proposed voluntary standard is a recommended level of energy efficiency for residential building components, the adoption and implementation of which in the private sector is voluntary. For the purpose of this assessment of potential impacts of the voluntary standard's implementation, the no-action alternative consists of the continued application of the energy codes and building practices that are currently in use.

At the present time, thirty-three states have adopted mandatory energy efficiency codes for residential buildings. Most other states have adopted model energy codes which are enforced at the discretion of local governments.

Most of these mandatory and model codes are based on several prominent standards that were developed in the late 1970s and early 1980s by organizations such as ASHRAE, the Council of American Building Officials (CABO), and Building Officials and Code Administrators International, Inc. (BOCA). These parent standards tend to be technically compatible, with minimum requirements usually expressed as maximum allowable overall thermal transmittance values (U_o) for major envelope components and minimum values of allowable thermal resistance (R) for perimeter insulation of slabs-on-grade (NCSBCS 1985). Criteria are expressed as or drawn from graphs based on annual heating degree days (HDD).

Most states with mandatory codes have made some modifications to the parent standards in their adoption process. Since HDD can vary widely in a given state, one common approach is to establish several state code levels for a limited number of climatic zones that span the state's HDD range. This approach helps avoid the problems of enforcing a code that could fluctuate substantially due to the presence of numerous microclimates. Other modifications may also be adopted, such as prescribing envelope performance on the basis of the heating and cooling appliances (and their efficiencies) selected for a new home. State energy codes are reviewed and updated from time to time. Most states have updated their code at least once since initial adoption (NCSBCS 1985).

Several states (including California, Florida, Hawaii, Louisiana, Nevada, North Carolina, Washington, Oregon and Alaska) have developed their own codes rather than adopting modified versions of the parent standards (although there frequently is a perceptible relationship to the latter). Some of these codes have sophisticated compliance mechanisms using computer software (eg., California's CALPAS program); almost all have a variety of paths to compliance so as not to limit design of and construction techniques for new homes.

2.2.1 Base Case Energy Efficiency Requirements

Estimation of the potential impacts of the VOLRES standard was based on a limited number of case studies, since the inherent flexibility of the voluntary standard permits an almost limitless variety of component packages (see Section 3.2, General Methodology). For each location included as a case study, the corresponding baseline (existing) code or level of current building practices was also determined. The following discussion provides some information on how the base efficiency levels were developed.

State energy codes are often expressed as performance levels for individual envelope and space-conditioning components. Quite frequently, the efficiency of the wall components (opaque areas, windows, and doors) is expressed as a single U_0 value, to permit trade-offs among levels of insulation, window area and treatment, etc. However, life-cycle cost calculations for the base codes and comparison with the proposed voluntary standard required separate efficiency values for each component.

In addition, home builders in states without mandatory codes often opt for component performance levels that exceed model codes, due to the influence of consumer demand, utility incentive programs, or other factors. (This also occurs in mandatory code states.) The opposite case also occurs, where prevailing efficiency levels fall below the recommended minimums of a non-mandatory standard.

Therefore, the base code for each location was not determined by examining code regulations, but by obtaining information about the most prevalent ECMs currently installed by builders in that location. A telephone survey employing open-ended questions was used to acquire this information. Respondents included code enforcement officials at the state and local level; prominent local builders, developers and designers; utility staff and other knowledgeable persons. Three to four sources of information were sought for each location; more were used if it was difficult to obtain a consensus about typical construction practices.

Baseline ECM levels for manufactured homes were obtained in a similar manner, but the source was a telephone survey of over 80 manufacturers conducted by Pacific Northwest Laboratory (PNL) in the fall of 1987 (Nesse et al. 1987). Levels installed by the surveyed manufacturers often exceeded those required to meet the Department of Housing and Urban Development (HUD) Manufactured Homes Construction and Safety Standards (MHCSS), a pre-emptive national minimum required for this type of housing. Where this was the case, current practice rather than MHCSS was used to represent the base case for this type of housing.

3.0 ANALYSIS OF POTENTIAL IMPACTS

This chapter presents an assessment of the potential impacts of adopting the proposed voluntary energy efficiency standard (VOLRES) for new residential buildings. The voluntary standard produces recommended levels of energy conservation measures (ECMs) for the envelope and space conditioning components of new homes. If the ECMs currently in use are changed to those recommended in VOLRES, the difference in materials, energy use and cost could trigger certain environmental and socio-economic impacts. In some instances, the impacts can be estimated in quantified terms. Other impacts, however, are difficult to quantify because of lack of data, so comparisons are in qualitative terms.

3.1 FOCUS OF THE ASSESSMENT

The proposed voluntary standard recommends combinations of ECMs that minimize the life-cycle cost of a residence. Use of the recommended ECMs could affect building habitability (the indoor environment), the outdoor environment, the nation's economy, and the institutional processes associated with residential construction. Changes in the habitability of residential buildings include potential impacts on indoor air quality and the related human health impacts. Both are discussed in Section 3.3. The outdoor environment is affected by changes in the energy consumption of residential buildings and by possible slight changes in the various process waste streams from insulation manufacturing. These potential impacts are discussed in Section 3.4. Economic and social impacts stemming from adopting the proposed standard have been examined in a separate report Economic Analysis - In Support of Proposed Interim Energy Conservation Voluntary Performance Standards for New Non-Federal Residential Buildings, and are summarized in this report in Section 3.5. Adopting the proposed voluntary standard as a mandatory energy code could also lead to certain institutional impacts for state and local agencies that regulate building practices. Federal agencies, however, are not likely to be impacted. The nature and extent of such institutional impacts are somewhat conjectural, so discussion of these impacts in Section 3.6 is quite limited.

This report does not address potential changes in aesthetic qualities of residential buildings, because those are design choices that are not dictated by VOLRES, which is a performance standard.

3.2 GENERAL METHODOLOGY

The proposed VOLRES standard is a highly flexible approach to specifying requirements for the energy-efficient design of residential buildings. As a performance standard based on minimized life-cycle costs, its flexibility is enhanced by the use of local climatic conditions in combination with local fuel prices and local construction costs. Economic parameters used in the life-cycle cost calculations (e.g., interest rates) may also be adjusted by the user to reflect local circumstances or regulatory positions. The net result is a standard that can easily be tailored to local conditions.

As noted in Section 2, the proposed voluntary standard is generated by a menu-driven computer program (ARES). The software employs an interactive format that permits the user to select various settings, options and restrictions. Some input files (e.g., ECM costs, ECM levels to be considered and economic variables) can also be modified (edited) by the user. Varying selections in the menus or changing inputs will also modify the VOLRES package and point system that results in minimum life-cycle cost. For example, changing important economic parameters, such as the discount rate, or building characteristics, such as the percentage of window area facing south, can result in specification of a different heating appliance efficiency, wall insulation level, or window glazing. The corresponding energy target and point system would also change.

Because of this flexibility, analysis of the VOLRES standard is based on a set of case studies. The case studies consist of prototype buildings hypothetically located in ten locations across the United States. Each prototype building in each location was equipped with ECMs that were generated by specific settings in ARES. The assessment was constrained by limiting the locations and fuel/appliance combinations to be studied. This process provided a number of hypothetical building configurations that meet the proposed voluntary standard, and their associated costs and energy usages under VOLRES. The results were compared to the components, energy use and costs of identical buildings that would meet the codes or current building practices in the same locations. The differences (deltas) were assumed to approximate the potential changes resulting from the use of the voluntary standard.

The settings and assumptions that were used to develop VOLRES packages for the case studies are summarized below. Greater detail on these factors can be found in Appendix A and in the report on the economic analysis that accompanies this assessment (Marsh et al. 1988). The economic report also includes results of sensitivity studies that were conducted to examine the possible range of changes in the cost and energy use characteristics that would be induced if several of these assumptions and settings were modified.

Case Study Locations. Ten cities distributed across the continental United States were selected as locations where VOLRES would be compared to existing energy efficiency-related building practices and requirements. These locations (see Table 3.1) represent a range of heating and cooling degree day values that span the predominant climatic conditions in the United States.

Building Prototypes. Residential structures are represented as generic prototypes in ARES (single family and multi-family site-built homes, and single-wide manufactured/mobile homes). Table A.1 in Appendix A lists the prototypes used in ARES and the foundation options which were studied in this analysis. Table A.2 in the same appendix provides the dimensions of the relevant components, by prototype.

Fuels. The voluntary standards generated by the ARES software are specific to fuel/heating appliance combinations selected by the user. In this analysis, VOLRES standards were created for the two predominant heating fuels in each location studied. However, ARES creates separate voluntary standards for electric forced air and electric heat pump appliances, so where this heat

TABLE 3.1. Locations and Fuels Examined in the Assessment

Location	Single and Multi-Family Gas	Single and Multi-Family Electricity	Single and Multi-Family HP	Single and Multi-Family Oil	Manufactured Homes Gas	Manufactured Homes Electricity	Manufactured Homes LPG	Manufactured Homes Oil
Atlanta	x	x	x		x	x	x	
Denver	x	x	x		x	x	x	
Fort Worth	x	x	x		x	x	x	
Minneapolis	x	x	x		x	x	x	
Pasadena	x	x	x		x	x	x	
Phoenix	x	x	x		x	x	x	
Seattle	x	x	x		x	x	x	
Tampa	x	x	x		x	x	x	
Albany[a]	x	x	x	x	x	x	x	x
Providence[a]	x	x	x	x	x	x	x	x

(a) Multi-family residences in these locations are frequently heated with electricity, so that prototype was modeled with all four fuels.

source was used, both electricity standards were analyzed. Table 3.1 above shows the fuels selected for each case-study location. Prices used for selected fuels were current (1986) location-specific per-unit costs obtained from published sources (see Appendix A).

Construction Costs. The ARES program contains data bases with average construction costs (1986 dollars) for twelve regions covering the continental United States. These costs are default values that can be modified by individual users of the software. For the purpose of this study, no changes were made to the default values.

Economic Parameters. The ARES program contains a file listing the economic parameters that guide its component life-cycle cost calculations. In conjunction with its other files and programming, the software generates a package of components and a point system that represent minimized building life-cycle cost in the selected location (see Section 2.1). For the purposes of this assessment, the default values for the economic parameters (listed in Table 3.4) were used.

Heating Appliance Efficiencies. The ARES program does not permit consideration of appliance efficiencies below the mandatory minimum efficiencies established in the National Appliance Energy Conservation Act (NAECA) of 1987 (42 USC 6201). However, ARES can select efficiencies higher than the NAECA minimum criteria for new space-conditioning equipment as it creates the proposed standard. In the building configurations created for the proposed voluntary standard, ARES occasionally selected these higher efficiencies. The NAECA minimum criteria were used, however, in developing comparative life-cycle costs of current codes and construction practices for the economic impact analysis.

Windows. Users of VOLRES can choose the amount of fenestration (window-to-floor-area ratio), the percent facing south (except in manufactured housing), and the types of glazing that are to be considered in creating the voluntary standard. Changing any of these items can result in modifications in other component requirements. The settings used to develop the VOLRES standard for each case study are provided in Appendix A.

These settings were used in ARES to create ECM packages that meet the requirements of the voluntary standard in the case study locations for each housing prototype. Tables A.5 through A.7 in Appendix A list the resulting proposed voluntary standard package for each prototype in each site. The tables also show the component levels estimated for the baseline (current energy code and/or building practices) in each location.

The potential impacts of the incremental changes to energy-related building components are discussed in the remaining portions of this chapter. Impacts to the indoor and outdoor environment are largely the result of modifications to the amount of insulation and framing in the building envelope. Economic impacts derive from the changes in the costs to produce, purchase, heat, and cool homes constructed to meet VOLRES. These latter impacts are summarized in this chapter and more fully discussed in the economic analysis.

3.3 HABITABILITY IMPACTS

The following section examines the potential for changes in the habitability (indoor environment) of residential units when ECM levels are changed to meet the proposed voluntary standard. The discussion focuses on the projected impact on indoor air quality (IAQ) and related impacts on the health of the occupants.

3.3.1 Approach to Indoor Air Quality Analysis

The indoor air-quality (IAQ) analysis is based on a computer simulation of the generation, buildup, and dissipation of various pollutants in occupied residential buildings. A constant natural ventilation rate was assumed for all prototypes in all locations for both the base code and the proposed voluntary standard simulations. The rate used was 0.52 air changes per hour (ACH), which is representative of typical rates for current new residential construction (BPA 1988, Grimsrud et al. 1982). (For more information on fresh air ventilation see Appendix C, Section C.2.2.1.) In ARES, this rate is the result of selecting the "Normal" Infiltration (Construction) Package (see Section 2.1). Therefore, the IAQ computer simulation detected only those changes that resulted from certain envelope modifications (those that altered the insulation mass in the prototype homes). Formaldehyde, which is emitted by insulation materials, was the only (measured) pollutant for which the estimated concentration changed. Because the air exchange rate was held constant, levels of indoor air pollutants that emanate from sources other than building materials (e.g., radon) were not affected by changes that allowed the building prototypes to meet the proposed standard rather than current energy codes or building practices.

A slightly different approach was used in order to test a "worst case" impact of the voluntary standard. In the worst case scenario, the baseline homes were assumed to have "normal" infiltration, while the VOLRES homes were modeled with "tight" infiltration construction. This test was carried out only for study homes in Ft. Worth, the location where use of the proposed standard resulted in the greatest increase in insulation materials in the initial comparison. A description of this test and the results are presented in Section 3.3.3.1.

Because of the complex nature of indoor air quality studies, only the major aspects of the approach to the analysis are presented in this section. More detailed information may be found in Appendix C.

Studies of IAQ and related human health impacts are a relatively recent development, and some aspects of both the behavior of known pollutants and human epidemiological responses are not clearly understood or documented. For example, recent reviews indicate that, for many pollutants, there is no consistent link between outdoor ambient and indoor concentration levels; indoor pollutant levels often exceed outdoor levels (Yocum 1982; Walsh, Dudney and Copenhaver 1984). However, by considering both indoor and outdoor pollutant source relationships, the magnitude of monitored indoor values can be explained (Wadden and Scheff 1983). These relationships provide the basis for predicting incremental changes in IAQ. The approach used in the analysis of the proposed voluntary standard was designed to estimate the expected concentrations of selected indoor air pollutants. Although any residential unit could have IAQ problems due to the presence of a wide variety of substances and/or activities (particularly if accompanied by an inadequate fresh air supply or unusual indoor pollutant release rates), this analysis focuses on changes to the normal range of pollutant emissions found in residences. (See Table C.3 in Appendix C for a concise listing of the ranges used in the air quality analysis.)

The predicted pollutant levels under the baseline and proposed voluntary standard were derived by using a computer simulation approach that has been used and accepted by many IAQ experts (e.g., Miksch, Hollowell and Schmidt 1982; Molhave 1982). Pollutant concentrations estimated by this method have corresponded reasonably well with monitored pollutant concentrations.

Incremental changes to indoor air-pollutant concentrations were estimated by computing concentration values for both the case study prototype homes configured to meet existing energy codes, and for identical homes that meet the proposed voluntary standard in each location. The primary focus of this assessment is on those pollutants that have suspected adverse effects on human health (particulate matter, CO, CO_2, NO_2 radon, and formaldehyde). A number of studies have been made (see Table C.1 in Appendix C) of the release rates of these pollutants from various building materials. The emission rates used in the IAQ modeling effort were derived from this literature. Most quantitative

IAQ research to date has been focused on the pollutants listed above. Therefore, while other pollutants are present inside buildings, no attempt was made to model their expected concentrations.

The IAQ model computed the long-term, steady-state concentrations for the six pollutants of interest. Average outdoor pollutant concentrations (from the air and underlying soils) are normally treated as background levels to which internally-generated pollutant emissions are added. For this analysis, the concentration of outdoor pollutants was considered to be invariable from the base case to the proposed voluntary standard, and therefore was set to zero. Concentrations for each pollutant were computed for three release rates: low (defined as lowest expected emission rate), medium (a typical rate), and high (a maximum emission rate). Together these numbers span the expected range of emission rates for pollutants from sources expected to be found in the case-study residences.

3.3.2 Determinants of Indoor Air Quality and Assumptions or Analysis Used

Although it is known that indoor air quality depends mainly on factors such as the building design, materials, contents, usage, and envelope tightness, the relationship among those factors can be complex. Changes in building energy standards typically affect the concentration of indoor pollutants in two major ways. First, a new standard can increase or decrease the air exchange rate between indoor and outdoor air by specifying allowable equivalent leakage areas. If this change results in an increase in the indoor/outdoor air change rate, indoor-generated pollutant concentrations are reduced. However, if the primary source of a pollutant is outside the building envelope, its indoor levels may <u>increase</u> with a higher fresh air exchange rate.

Second, a new standard could alter the internal sources of indoor pollutants by changing the type and/or amount of various building materials used. Various pollutants are released within the residential building continuously or intermittently. These pollutants can originate from furnishings within a building (e.g., carpets or furniture), from building materials (e.g., insulation or particle board), or from indoor activities of building occupants (e.g., smoking, use of household products or cooking).

As noted in Section 3.3.1, the IAQ analysis was simplified by making two assumptions about building-derived pollutants. First, the only differences in building materials between the base code and the proposed standard residence were changes in insulation levels (and framing)[a] in envelope components. Second, the air change rate of the base code and proposed voluntary standard design was assumed to be identical at 0.52 ACH.

The location-dependent envelope changes attributable to the proposed voluntary standard were provided in Table A.5 through A.7. That table also indicates the changes in insulation thickness between the baseline and proposed standard for all prototypes (and their variations) at each of the ten locations. The insulation mass associated with the thickness values displayed in this table were used to estimate changes in the levels of formaldehyde in prototype residences.

Several other assumptions were needed to model the behavior of the other pollutants considered in this analysis. Radon levels were modeled using a typical range of background values rather than attempting to determine levels specific to the locations studied in this analysis. Section C.2.3.5 in Appendix C provides a more detailed discussion of the sources and causes of variability in the levels of this pollutant.

Combustion pollutants (CO, CO_2, NO_2 and particulate matter), are primarily related to activities within the residential unit. Emission rates of these pollutants are not affected, therefore, by the design or building material used. Within a residential building, cigarette smoking and use of stoves and ovens are the main sources of combustion products. On a mass basis, airborne particles, CO_2, CO, and formaldehyde are the major components of sidestream cigarette smoke (i.e., from the burning tip) (Girman et al. 1982). Many other

(a) When the proposed standard specifies wall insulation efficiencies of R-19 or higher, ARES assumes that 2" x 6" (rather than 2" x 4") framing will be used to accommodate the thicker fiberglas batts needed. Higher levels may also require the addition of rigid insulation (e.g., polystyrene boards) beneath the exterior treatment.

organic and inorganic combustion products have also been identified [National Research Council (NRC) 1981a], but indoor concentrations of these pollutants were not estimated in this assessment.

Because of the nature of the sources of pollutants produced by combustion, the following assumptions were made to determine the source terms for combustion pollutants:

- The typical smoker smokes an average of 2 cigarettes per hour or 31 cigarettes over the course of 16 waking hours a day (NRC 1981a).
- The number of smokers in a residence was 0 (minimum value), 1 (middle or typical value), and 2 (maximum value).
- If one occupant smokes, that occupant is in the residence 80% of his/her waking hours and smokes 25 cigarettes indoors. The second smoking occupant is in the residential unit 40% of his/her waking hours and smokes an additional 12 cigarettes indoors.
- Gas stove range-top burners are used an average of 2 h per day. Gas ovens are used an average 1 h per day.
- Gas furnaces and hot water heaters are vented directly to the outdoors.

3.3.3 Results of Indoor Air Quality Simulations

The discussion of the results of the IAQ simulations begins with a brief review of the character of each pollutant, followed by information on its associated health impacts. The indoor concentrations computed for each of the three residential units are then presented. Each subsection ends with findings of IAQ impacts based on the estimated values of indoor pollutant concentrations. The incremental changes in pollutant concentrations upon which the findings are based are presented in a series of tables (one for each location).

Due to the assumptions outlined previously, no changes in the concentrations of pollutants emanating from sources _other_ than the building materials affected by the voluntary standard would be expected to occur. Slight changes could occur, however, if the VOLRES standard were developed under tight construction requirements, and the baseline case uses the normal construction approach. These worst case results are discussed below.

3.3.3.1 Worst-Case Assumptions

The worst-case assumptions were tested by simulating the change in the prototype of a single-family, electrically heated house with a crawl space located in Fort Worth, Texas. This particular case was used as a test of the worst-case assumptions because it produced one of the largest incremental increases in insulation material and consequently of formaldehyde levels, of all of those modeled in the initial comparison. To model the worst case, the infiltration in the proposed voluntary standard version of the prototype home was reduced to 0.40 ACH ("tight construction"). Pollutant levels were then simulated in the IAQ model. The air change rate in the baseline home remained at 0.52 ACH ("normal construction"). The results for the six pollutants of interest are summarized in Table 3.2. The decrease in the air change rate in the prototype that meets the proposed standard triggered slight increases in the concentrations of radon and combusted pollutants.

Estimated formaldehyde concentrations increase appreciably, however, in the worst case (normal baseline to tight standard prototypes). This increase is a result of both the decrease in natural infiltration and the increase in the mass of insulation materials in the proposed standard prototype. Nevertheless, the resulting levels are still below the threshold of sensitivity for most individuals.

TABLE 3.2. Summary of Incremental Changes in Indoor Air Quality for the Worst-Case Assumptions (Single-Family Residences)

Pollutant (Units)	Low	Typical	High
Radon (pCi/l)	0.009	0.031	0.891
Particulates (μg/m3)	0.000	0.028	0.041
CO (mg/m3)	0.000	0.223	0.328
CO_2 (mg/m3)	265.4	265.6	265.7
NOx ()g/m3)	0.0000	0.0001	0.0003
Formaldehyde (μg/m3)	21.7	60.4	170.1

Combustion pollutant increases are directly related to the change in ACH. Although the model predicted slight increases in the radon and formaldehyde concentrations due to decreased infiltration, the actual change is dependent on other factors besides infiltration that are less understood and more difficult to predict. The discussion of pollutant behavior in the expected case (i.e., no change in ACH) in Section 3.3.3.2 provides some perspective on the values shown in Table 3.2.

3.3.3.2 Particulate Matter

The discussion of particulates is limited to suspended particulates created by combustion. Although varying amounts of dust may be present in residential structures as a result of physical activity in the building, these particulates generally are large enough to remain suspended only temporarily before they are mechanically filtered out by central ventilation filters. Regardless of the source of suspended particulates in a building, either the total suspended particulate (TSP) levels can be examined in an analysis such as this, or only the respirable suspended particulate (RSP) portion. This report focuses on RSP levels by assuming that particles larger than 3.5 micrometers (μm) are present only on a very short-term basis in most structures before they settle out of the air or are filtered out.

Emission rates of RSPs from tobacco smoking are estimated to be 10.8 milligrams (mg) per cigarette smoked (Girman et al. 1982), or about 335 mg of RSP per smoker per day. For this analysis, the emission rate of RSP uses an average rate of RSP from each cigarette smoked and assumes the previously specified number of occupancy hours per day and a smoker population of 0, 1, or 2 (low, medium, or high).

Health Impacts. The health impacts caused by particulate matter depend to some extent on the sensitivity of the exposed individual. Studies based on low levels of particulate matter suggest that children, asthmatics, smokers, obligatory mouth breathers, and persons with pneumoconiosis or influenza may be at higher risk to deteriorating respiratory functions. Children may also show symptomatic irritation. A study by Lawther, Waller and Henderson (1970) showed likely short-term aggravation of bronchitis at 250 to 500 $\mu g/m^3$ measured by the British Smoke (BS) method. Lunn, Knowelden and Handyside (1967) showed that decreased lung function and increased acute respiratory disease in children may occur from long-term exposure to particulate matter below 230 $\mu g/m^3$ of BS. Bouhuys, Beck and Schoenberg (1978) showed that decreased lung function in adults may occur at long-term particulate levels as low as 130 to 180 $\mu g/m^3$ of TSP, and Bouhuys, Beck and Schoenberg (1978) and Ferris et al. (1973) showed that some risk of increased respiratory disease and/or symptoms in adults may exist from long-term levels of 110 to 180 $\mu g/m$ of TSP. Appendix D provides more information on the health effects of particulate matter and suggests that current studies do not support health risks of consequences below 55 $\mu g/m^3$ of particles capable of penetrating the thoracic regions of the lungs. Thoracic particles (TP) are defined as particle size less than a nominal 10 μm [U.S. Environmental Protection Agency (EPA) 1982].

Expected Impact of the Proposed Voluntary Standard. Tables 3.3a through 3.3j show the incremental changes in concentration levels of particulate matter based on 0, 1, or 2 smokers in the residence and either a gas-fueled cook stove and oven or an electric stove and oven. As the sources for particulate matter are related to occupant behavior, which did not change, the incremental changes as a result of the proposed voluntary standard are zero for all house types and locations when ACH is held constant.

Findings. Implementation of the proposed voluntary standard is expected to have no effect on the levels of particulate matter in residences and no effect on health risks.

Carbon Monoxide

The major sources of carbon monoxide (CO) analyzed in this assessment are gas cooking appliances and occupant smokers. Cooking over a gas burner is expected to release from 200 to 1800 mg of CO per burner-hour (Cole et al. 1983). CO is released at a higher rate from gas ovens [1300 to 3000 mg per oven-hour (NRC 1981a)]. In calculating the CO concentration level for the residential units, a cook stove gas burner is assumed to be used an average of 2 h per day and the oven is assumed to be used 1 h per day. Cigarette smoking is a second source of residential indoor CO. For each cigarette smoked, 105 mg of CO is released from sidestream and mainstream smoke (NRC 1981a). Smokers are

TABLE 3.3a Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Albany

Fuel	Building Type	Foundation Type	Radon			Particulates			CO_2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.4	-1.0	-3.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
OIL		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.4	-1.0	-3.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.4	-1.0	-3.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
OIL		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	3.6	10.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.4	-1.0	-3.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.6	6.8	19.6
OIL		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.4	30.4	87.3
PROPANE		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.6	23.0	66.0
ELECT.		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.9	31.8	91.4

TABLE 3.3b Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Atlanta

Fuel	Building Type	Foundation Type	Radon			Particulates			CO2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	15.8	45.5
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.8	36.9
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.8	36.9
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12.8	34.2	98.2
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12.8	34.2	98.2
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.7	28.6	82.3
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.4	27.9	80.1
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.2	24.6	70.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.2	19.1	54.9
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.9
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.2	19.3	55.4
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.2	19.3	55.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.0	13.3	38.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.9	37.0
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.9
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.9	37.0
OIL		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14.2	38.0	109.2
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.1	18.8	54.1

TABLE 3.3c Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Denver

Fuel	Building Type	Foundation Type	Radon			Particulates			CO_2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.9	10.3	29.5
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.4	14.4	41.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.3	11.5	33.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.9	10.5	30.3
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.1	16.2	46.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.9	21.0	60.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.7	12.7	36.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.0	10.8	31.0
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.1	16.2	46.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.4	14.4	41.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.3	11.5	33.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.9	10.5	30.3
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.7	36.5
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.3	16.9	48.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9	13.0	37.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.9	37.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.7	53.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.8	23.4	67.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.0	13.3	38.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9	13.0	37.4
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.7	53.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.3	16.9	48.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9	13.0	37.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.9	37.0
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.1	-16.2	-46.5
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.1	-16.2	-46.5
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.7	12.6	36.3

TABLE 3.3d Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Fort Worth

Fuel	Building Type	Foundation Type	Radon Low	Radon Med	Radon High	Particulates Low	Particulates Med	Particulates High	CO2 Low	CO2 Med	CO2 High	CO Low	CO Med	CO High	NOx Low	NOx Med	NOx High	Formaldehyde Low	Formaldehyde Med	Formaldehyde High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.6	20.3	58.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	15.5	44.6
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	15.5	44.6
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	15.5	44.6
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.8	26.2	75.4
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.8	26.2	75.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.2	16.5	47.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.0	16.0	46.1
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.7	9.8	28.2
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	7.4	21.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	3.7	10.6
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	2.9	8.4
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.5	22.7	65.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.7	17.9	51.6
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.3	52.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.7	17.9	51.6
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.7	28.7	82.4
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.5	22.7	65.3
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.6	53.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.8	10.0	28.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.0	5.2	15.1
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.1	5.6	16.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.0	5.2	15.1
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.1	-3.0	-8.6
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	3.0	8.6
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.3	22.1	63.7

TABLE 3.3e Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Minneapolis

Fuel	Building Type	Foundation Type	Radon			Particulates			CO2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.5	-6.6	-18.8
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.7	-10.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-1.6	-1.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.7	-10.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5	-3.9	-11.2
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.7	-10.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5	-3.9	-11.2
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7	-7.1	-20.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.7	-4.5	-12.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.3	-12.4
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7	-7.1	-20.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.9	-11.1
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7	-7.1	-20.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.7	-4.5	-12.9
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-8.0	-21.4	-61.6
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	6.0	17.1
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	7.4	21.2

TABLE 3.3f Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Pasadena

Fuel	Building Type	Foundation Type	Radon			Particulates			CO_2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.7	15.1	43.4
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1	10.9	31.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	15.7	45.1
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.7	15.1	43.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.6	53.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.9	18.3	52.7
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	15.7	45.1
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1	10.9	31.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	18.1	52.0
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5	-4.0	-11.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	3.2	9.1
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	3.2	9.1
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.1	13.5	38.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.1	13.5	38.8
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.1	16.2	46.6
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.0	15.9	45.7
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5	-4.0	-11.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	3.2	9.1
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	3.2	9.1
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.2	8.6	24.7
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	15.4	44.2
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13.0	34.5	99.3

TABLE 3.3g Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Phoenix

Fuel	Building Type	Foundation Type	Radon			Particulates			CO2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.6	-17.5	-50.3
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.8	-18.1	-52.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.6	-17.6	-50.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.8	-18.1	-52.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.0	10.7	30.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.2	11.3	32.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9	5.2	14.9
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	4.4	12.7
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.4	-6.3	-18.1
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.8	-12.8	-36.9
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.6	-12.3	-35.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.8	-12.8	-36.9
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.5	-1.4
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.0	-5.2	-15.1
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.8	-4.9	-14.2
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.0	-5.2	-15.1
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.0	10.7	30.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.6	4.2	12.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.6	1.8
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.3	16.9	48.5
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.7	36.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9	13.0	37.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.7	36.5
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.8	-2.3	-6.5
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.4	14.5	41.7
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.3	22.1	63.7

TABLE 3.3h Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Providence

Fuel	Building Type	Foundation Type	Radon			Particulates			CO2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.2	24.6	70.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.2	24.6	70.8
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.6	53.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.9	18.3	52.7
OIL		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.2	24.6	70.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.7	53.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.0	18.6	53.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.9	18.3	52.7
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.4	27.7	79.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.1	21.7	62.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.0	21.4	61.6
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.0	21.3	61.2
OIL		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.4	27.7	79.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.1	21.7	62.4
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.2	21.8	62.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.0	21.4	61.6
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1	10.9	31.2
OIL		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.6	7.0	20.2
PROPANE		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.8	26.2	75.3
ELECT.		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14.5	38.6	110.9

TABLE 3.3i Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Seattle

Fuel	Building Type	Foundation Type	Radon			Particulates			CO2			CO			NOx			Formaldehyde		
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.2	16.4	47.2
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.8	36.9
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.6	12.3	35.4
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	12.8	36.9
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.7	-10.5
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5	-3.9	-11.2
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.2	13.8	39.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.7	7.3	21.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.7	9.8	28.1
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.9	10.3	29.5
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7	-7.1	-20.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.6	-1.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.9	-11.1
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.5	-4.0	-11.5
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7	-7.1	-20.5
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.7	-7.1	-20.5
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.6	-4.2	-12.0
GAS	Manu-factured	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	3.0	8.6
PROPANE	Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.6	6.8	19.6
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.3	22.1	63.7

TABLE 3.3j Summary of Incremental Changes in Pollutant Levels from the Base Code to the Proposed Voluntary Standard for Tampa

Fuel	Building Type	Foundation Type	Radon Low	Radon Med	Radon High	Particulates Low	Particulates Med	Particulates High	CO2 Low	CO2 Med	CO2 High	CO Low	CO Med	CO High	NOx Low	NOx Med	NOx High	Formaldehyde Low	Formaldehyde Med	Formaldehyde High
GAS	Single-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	11.8	33.8
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	7.6	21.8
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	7.6	21.8
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	7.6	21.8
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.0	-5.2	-15.1
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.0	-5.2	-15.1
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.0	-5.2	-15.1
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2.0	-5.2	-15.1
GAS	Multi-Family	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.0	-15.9	-45.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.0	-15.9	-45.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.0	-15.9	-45.7
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.1	-16.2	-46.6
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.4	-11.7	-33.7
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.0	-15.9	-45.7
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.0	-15.9	-45.7
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.1	-16.2	-46.6
HP		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.0	-10.6	-30.6
		unconditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.0	-10.6	-30.6
		conditioned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.0	-10.6	-30.6
		slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4.1	-11.0	-31.5
GAS	Manu-factured Home	crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.1	-16.2	-46.6
PROPANE		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.4	-3.8	-11.0
ELECT.		crawl space	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0

assumed to smoke 31 cigarettes a day (NRC 1981a). However, not all of an occupant's smoking is done within the residential unit. Assuming one smoker in the residence smoking 80% of his/her nonsleeping time, then an average of 25 cigarettes would be smoked in the residence per day. If two smokers occupy the residence, it is assumed that the second smoker occupies the resident 40% of his/her nonsleeping time and averages 12 cigarettes per day smoked within the residential unit.

Health Impacts. Carbon monoxide is many times more efficient at binding with hemoglobin than oxygen (Meyer 1983). Thus, low concentrations of CO in indoor air can result in substantial carboxyhemoglobin (COHb) concentrations in the blood (see Appendix D). Available information on health risks suggests that persons with angina, peripheral vascular disease, and other types of cardiovascular disease are at the greatest risk from low-levels of CO (Anderson et al. 1973). Current studies do not show significant health risks if CO concentrations are below 10 mg/m as an 8-h average (see Appendix D for details).

Expected Impact of the Proposed Voluntary Standard. Tables 3.3a through 3.3j show the incremental change in computed indoor concentrations of CO for the baseline and for the proposed standard. For all house types and locations, there was no change in indoor levels of CO as a result of the proposed voluntary standard when ACH is assumed to be unchanged.

Findings. The proposed voluntary standard will not have an effect on indoor concentrations of CO.

Carbon Dioxide

Human breathing is a significant source of carbon dioxide (CO_2). Normal respiration produces 8.9 mg/second of CO_2 per person. Other sources include cigarette smoking (80 mg of CO_2 per cigarette), gas stoves (483,000 to 550,000 mg/burner-h), and gas ovens (383,000 to 400,000 mg/burner-h).

Health Impacts. Excessive carbon dioxide triggers increased breathing to maintain the proper exchange of oxygen and CO_2. If inhaled air already contains high levels of CO_2, then the breathing rate has to be increased to purge CO_2 at the rate it is produced (Meyer 1983). The Occupational Safety and Health Administration (OSHA) has a CO_2 standard for the workplace of

9,000 mg/m^3. ASHRAE has a recommended guideline for the nonworkplace of 4,500 mg/m^3 continuous (24-h per day) exposure [Bonneville Power Administration (BPA) 1984]. Japan is the only country to have established an indoor standard for CO_2 applicable to residences. The Japanese standard is 1,800 mg/m^3 for continuous exposure (Walsh 1984).

Expected Impact of the Proposed Voluntary Standard. Table 3.3a through 3.3j show the incremental change in computed concentrations of CO_2 for the baseline and proposed standard units. Indoor concentrations of CO_2 remained unchanged as a result of the proposed voluntary standard when ACH was held constant.

Findings. The proposed voluntary standard will have no affect on indoor concentrations of CO_2.

Nitrogen Dioxide

The sources of nitrogen dioxide (NO_2) addressed in this assessment are gas stoves and ovens and cigarette smoking. Cole et al. (1983) reports that gas range-top burners release NO_2 at a rate of 70 to 120 mg/burner-h of operation. Gas ovens release rates between 80 and 130 mg/oven-h of operation have been noted by Girman et al. (1981). A NO_2 source term for tobacco smoking has also been measured and averages 0.065 mg/cigarette (NRC 1981a).

Health Impacts. The most sensitive populations to low levels of NO_2 are children and persons with asthma, chronic bronchitis, and emphysema (see Appendix D). Other persons who have hay fever or liver or hormonal disorders may also be affected at low levels of NO_2. As noted in Appendix D, trying to separate health effects caused by NO_2 from health effects caused by other pollutants is very difficult because community epidemiology studies do not provide clear evidence of the effects of low levels of NO_2. However, the studies also do not disprove that there is an association between low levels of NO_2 and health risk. Thus, based principally on controlled human exposure studies, the EPA (1982) currently considers that NO_2 concentration levels below 90 μg/m^3 on an annual average can provide adequate protection against harmful health effects from low levels of NO_2 (see Appendix D).

Expected Impact of the Proposed Voluntary Standard. Tables 3.3a through 3.3j show the incremental change in computed concentration of NO_2 based on release of NO_2 from gas cooking appliances and smoking. No changes in NO_2 concentrations will occur as a result of the proposed voluntary standard if ACH is not modified.

Findings. Release of NO_2 from cooking appliances and tobacco smoking is small. The computed concentrations for NO_2 for the proposed standard are unchanged from those computed for the baseline residences. Thus, the proposed voluntary standard would have no effect on annual NO_2 levels in residential structures.

Radon

The greatest single source of radon is soil. Source terms from the soil range from 0.1 to 1 pico curies per square meter of soil per second (pCi/m^2-sec) in the low-radon release areas to 1 to 10 pCi/m^2-sec in high-radon release localities. Radon is also released from the aggregate contained in concrete. Release rates range from 0.02 to 0.06 pCi/m^2-sec for each side of a 0.2-meter-thick wall. A concrete slab on soil will emanate radon both from the concrete aggregate and from the diffusion of the radon from the soil through the pores, cracks, and holes in the concrete. An intact concrete slab without cracks or leaks through pipes will reduce flux from soil beneath it by a factor of about 10 (Bruno 1981); a vented crawl space can further reduce flux. The magnitude of the source term depends on whether the slab is on soil in a high-radon or a low-radon release area. Unfortunately, there is no complete map of where high-radon release areas are located. Attempts to correlate geological surface features with radon release rates have had mixed results.

Brick (adobe and red) building material is also a source of gaseous radon. Another major source of indoor radon is water from underground supplies. Radon emission rates from water were selected to cover the expected range to be found in community water systems.

The greatest variability in radon source terms is associated with geological features (water supply and substrate); considerably less variability occurs in the building materials (Sachs, Hernandez and Ring 1982; Abu-Jarad and

Fremlin 1982). Ambient outdoor radon concentrations show considerable variation due to soil and weather factors. A background atmospheric value of 0.25 pico curies per liter (pCi/ℓ) is typical.

Health Impacts. Radon gas and its decay products are present everywhere in concentrations that vary with location, the time of day, and weather conditions. Decay products in the air we breathe can become deposited and retained in the lungs, sometimes contributing to lung cancer. Studies (e.g., Evans 1967, Jorgensen 1973 and Archer 1978) show that uranium miners, who are subjected to elevated levels of radon and radon daughters, have higher rates of lung cancer than the general population.

Because the effects of radon exposure seem to be cumulative, contributions to individual exposures from all sources (e.g., residences, commercial buildings, and outdoor air) must be considered. The severity of an individual's reaction to radon gas exposure will depend on many factors, such as the length of the exposure and the concentration levels. The research data developed from radon daughter epidemiology studies suggest that an absolute threshold exposure for lung cancer induction has not been identified. Thus, for very low levels of exposure, such as those typically associated with indoor air, researchers have not fully agreed on the impact of radiation on human health. More detailed information on radon and its health effects is presented in Appendix D.

Expected Impact of the Proposed Voluntary Standard. Incremental changes in radon concentrations were computed for each of the residences and are presented in Tables 3.3a through 3.3j. The low, medium, and high values are derived from the source-term assumptions discussed above. The design changes related to the proposed voluntary standard do not affect indoor radon concentrations.

Findings. The proposed voluntary standard will not affect indoor radon concentrations.

It is not the intent of this radon evaluation to dismiss the potential hazard of the presence of radon in the indoor environment. However, comparison between the baseline residence constructed according to current practices and the same residence constructed according to the proposed standard using the normal infiltration rate clearly indicates that no change would occur as a result of the proposed standard as long as infiltration rates are not modified. Thus, no change in health risk from indoor radon concentrations would occur. Note that radon release from soil, water, and building materials varies greatly from site to site and should remain a major health concern until tests determine that radon is not present at elevated levels on a given site in a specific building. (Radon concentrations can vary considerably from building to building at the same location.)

Formaldehyde

Formaldehyde is a substance used in the manufacture of many building materials. Insulation, particle board, plywood, wall board, and similar construction materials are all major indoor sources of gaseous formaldehyde. Formaldehyde can also be emitted during combustion processes. Typical emission rates for gas cooking appliances range from 15 mg/burner-h for range-top burners to 25 mg/oven-h for ovens. Formaldehyde is also a component of side-stream cigarette smoke (i.e., smoke released from the burning tip of a cigarette). Typically, about 1 mg of formaldehyde is released for each cigarette smoked (NRC 1981a).

Release rates for formaldehyde vary because many factors are involved. Andersen (1979) found that indoor formaldehyde concentrations in Danish homes are a function of air temperature, humidity, air change rate, ratio of particle board surface area to room volume, and surface coating and type of particle board used. Age has also been identified as a factor in formaldehyde release; about half of the formaldehyde in particle board, for instance, is released over a period of 58 months (NRC 1981b). Ventilation rates, humidity, and the amount of resinous material in a residence seem to be the most important factors that contribute to airborne formaldehyde accumulation. Standards have been established by HUD for manufactured homes limiting permissible amounts of formaldehyde emissions from the plywood and particle board used in these homes. These restrictions are designed to limit indoor formaldehyde concentrations to 0.4 ppm.

Health Impacts. In low concentrations, formaldehyde irritates the eyes and mucous membranes of the nose and throat (NRC 1981b). The severity of the symptoms increases with concentration. Some human beings are much more sensitive to formaldehyde than others. For example, formaldehyde odor is most commonly detected at 1,200 $\mu g/m^3$, but some individuals can detect formaldehyde odor at concentrations of 60 to 70 $\mu g/m^3$. Eye irritation has been reported at formaldehyde concentrations as low as 10 $\mu g/m^3$ (see Appendix D for more details).

The Consumer Product Safety Commission (CPSC) has received numerous complaints about formaldehyde concentrations in residential buildings. The CPSC reports that residential concentrations of 10 to 120 $\mu g/m^3$ have been identified as causing nausea; eye, nose, and throat irritations; headache; vomiting; and stomach cramps (Greisemer et al. 1980). Research information compiled by Gupta, Ulsamer and Preuss (1982) verifies that the human threshold for short-term exposure to low concentrations of formaldehyde varies widely.

The National Academy of Science (NAS) concluded that there is no population threshold for the irritant effects of formaldehyde (NAS 1980). Persons sensitized to formaldehyde and persons with hyperactive airways may respond severely to formaldehyde (NAS 1981). The Academy has estimated that 10% to 12% of the U.S. population may have hyperactive airways, which may make them more susceptible to the irritant effects of formaldehyde (NAS 1981b).

Expected Impact of the Proposed Voluntary Standard. The incremental change in computed indoor concentrations of formaldehyde from levels of insulation specified by the proposed standard are shown in Tables 3.3a through 3.3j. The emission rates displayed are those for new insulation. Formaldehyde emission rates and resulting concentrations would drop as the material ages. With no alteration in ACH between base codes and the proposed voluntary standard, the changes in formaldehyde concentrations are proportional to the increases (or decreases) in the total mass of insulation in the building that would be required to meet the proposed standard.

Findings. Formaldehyde concentrations are expected to increase slightly in some building types in some locations (e.g., single family residences in Atlanta). Although the increases are small (generally less than 30 mg/cubic meter for the typical emission rates), the change could have a negative impact on extremely sensitive individuals with a very low tolerance for airborne formaldehyde.

Chemical Compounds

Measurement studies have shown that a wide variety of chemical contaminants, many of which are organic compounds, are present in residential indoor air. Over 300 chemical compounds have been positively identified in residential air. Several studies have addressed the difficult problem of quantifying the exact concentrations present in indoor air. This assessment has focused on those compounds that have indoor air concentrations greater than outdoor levels. Chemical compounds identified in five studies of residential air are presented in Appendix C. One study indicated that chemical compounds found in indoor residential air generally occur in low concentrations relative to industrial hygiene exposure levels, although as mentioned above, they occur in high concentrations relative to outdoor concentrations (Miksch, Hollowell and Schmidt 1982).

The presence of chemical compounds in residential air results from one or more of the following sources.

- infiltration of outdoor chemicals
- episodic events (i.e., cooking or cleaning)
- natural consequences of indoor living (respiration and perspiration)
- outgassing from household appliances and building materials.

Each of these sources is discussed in Appendix C.

Health Impacts. The chemical compounds found in indoor residential air are treated in this document as one complex class of indoor pollutants emanating from many sources. Moreover, because of the large number of chemical compounds potentially present in residential buildings, comprehensive discussion of each compound is impractical. The health effects of chemical pollutants are relatively uncertain. Molhave (1982) summarizes the number of expected carcinogens, airway irritants, and odorous organic compounds that he was able to detect from 42 commonly used building materials in chamber emission studies. A total of 52 different compounds were identified: 25% were suspected carcinogens, 82% were known or suspected airway irritants, and 30% were odorous compounds (see Appendix C).

Expected Impact of the Proposed Voluntary Standard. Design of residential buildings to meet the proposed voluntary standard should not influence two important sources of chemical pollutants in indoor air: occupant-stimulated episodal events (such as cooking, cleaning etc.), and natural consequences of indoor living (respiration, perspiration). These sources are influenced more by the number of occupants and their living habits than by the air exchange rate. If residents follow the directions on consumer products and provide adequate ventilation while they are using the products indoors, the pollutant concentration levels should be low.

Building materials are thought to be another major source of chemical pollutants (Molhave 1982). Residences designed to meet baseline conditions and residences designed to meet the proposed voluntary standard use the same inventory of building materials, except for the amount of insulation materials. Table 3.4 shows expected chemical rates from new building insulation materials. Where the proposed standard allows for reduced insulation, emissions of formaldehyde from fiberglass would be reduced. Where insulation materials such as polystyrene are used, organic emission sources would increase. Strategies that can mitigate the level of chemical compounds emanating from building materials include "drying out" the building for a specific period of time to reduce emission levels before occupancy and selecting less emissive or harmful materials.

Findings. A large number of chemical pollutants have been identified in indoor residential air. Many of these chemical compounds are either odorous, irritants, or suspected carcinogens. Although many of the chemical compounds found in indoor air come from building materials (emanation rates for which decline with age), many others are related to occupants and their activities. From the information used in this study, it is evident that chemical compounds can pose health risks to residential occupants in either short-term episodal or long-term acute concentrations. As with other indoor air pollutants discussed above, the sensitivities of individuals to these indoor chemical pollutants

TABLE 3.4. Organic Emissions from New Building Insulation Materials

Material	Description	Organic[a] Emission (mg/m^2-hr)	Formaldehyde[b] Emission (mg/m^2-hr)
Fiberglass	Fiberboard, 0.5"	0.017	NM[c]
Fiberglass	Batt, 3.0"	NM	0.02 to 0.17
Mineral Wool	Insulation Batt	0.012	NM
Organic	Woodfiber Board	0.120	NM
Foam	Polystyrene	1.4	NM
Foam	Polyurethane	0.12	NM

(a) Taken from Molhave (1982).
(b) Comparable form of emission computed from 0.34 to 2.3 μg/g-day emission rate given by Gupta, Ulsamer and Preuss (1982).
(c) NM = not measured.

will vary widely. The proposed voluntary standard is not, however, expected to measurably increase or decrease health risks due to chemical pollutants in residential indoor air.

Microorganisms

Microorganisms are indoor air pollutants with potential health risks under selected conditions. Thus, airborne microorganisms are recognized as factors to be considered in indoor environments. A broad array of algae, bacteria, fungi, protozoa, mites, and viruses are present. They are capable of provoking toxicity, infection, and allergenic responses. Some level of microorganisms on the human body and in the indoor environment is normal. Human response to microorganisms depends on the ability of the microorganism to produce disease and on the "immunity" of the individual, which can vary from person to person. Thus, the allergenic response, toxic reaction, infection, and dermal or mucous membrane irritations from exposure to microorganisms depend on the type of microorganism, its concentration, and the susceptibility of the exposed individual.

Most severe pollution problems from indoor microorganisms result from growth of the organism on some water reservoir or moist surface within the residence. Thus, any area where flooding has occurred or where moisture condenses may host a colony of microorganisms. When the host site is attached or adjacent to a residential central air-handling system, the microorganisms have a potential path for distribution beyond their immediate growth area. Because outdoor air flows into a residence through the building's envelope (ceiling, floor, and exterior walls), microorganisms around the foundation of a residence and in the intrawall space can also be sources of indoor pollution.

There are many sources of moisture in residential structures. These include respiration and perspiration from humans and pets; occupant activities including laundry (washing and mechanical drying), cooking, cleaning, showering, bathing, indoor hot tubs and saunas; water vapor transported into the home in moisture-laden air from the outside air and diffusing from the soil through cracks in the flooring and foundation; use of humidifiers; plants; construction materials; and use of unvented gas appliances.

A typical family of 4 will generate from 13-44 lb (6-20 liters) per day of moisture indoors depending upon its activity levels and ventilation (air exchange rate) of the residence (Kadulski 1988; National Research Council of Canada 1984). The ultimate indoor humidity (moisture) level of a residence is a function of the number of sources of moisture and their source strength, the rate of fresh air ventilation of the home, and the ventilation effectiveness.

The recent advances in tightly-built residences with low air exchange rates and the increasing interest in the quality of the indoor environment have heightened the awareness of the effects of too much or too little moisture in the home. With the availability of controlled ventilation systems in many tightly constructed homes, moisture levels (indoor relative humidity) can be controlled along with the other indoor air contaminants.

In general, the health effects of indoor moisture have been neglected and are difficult to quantify. Moisture by itself is not a contaminant: it is the biological agents that thrive in moist conditions and the chemicals released through hydrolysis that create moisture-related health problems.

A recent study investigated the effects of indoor moisture on the accumulation of chemical and biological air contaminants (Sterling et al. 1985). The study concluded that high relative humidity promotes the growth of biological organisms such as bacteria, viruses, fungi (mold and mildew), spores, and mites. This phenomenon is particularly acute at indoor relative humidity levels above 60%. The classic example of health effects associated with bacteria and viruses associated with moisture in the indoor environment is the outbreak of Legionella pneumonia at a Philadelphia convention in 1976 (ASHRAE 1981).

Sterling et al. 1985 showed that levels of humidity that are either too low or too high will affect human comfort and health. High (>60%) as well as low (<40%) relative humidity levels tended to aggravate allergies in hypersensitive people. Occupants in residences with low relative humidities (<40%) tended to have fewer respiratory infections. However, low relative humidity (<50%) enhances the formation of ozone indoors. Ozone has an irritating effect on the nose, eyes, and throat. The study concluded that the optimum relative humidity indoors should be between 40% and 60% to maintain comfort and reduce these health effects.

Table 3.5 shows the range of air exchange rates required to maintain 40% to 60% relative humidity at an indoor temperature of 70°F in the three prototype structures with occupants that produce 30 lb a day of water vapor. The calculation assumes that the outdoor air is at 32°F and 50% relative humidity. An air exchange rate greater or smaller than the range shown will result in either a higher or lower relative humidity respectively. Also, outside air

TABLE 3.5. Air Exchange Rate Required to Maintain 40% to 60% Relative Humidity Indoors at 70°F

Structure Type	Area, ft^2	Volume, ft^3	Air Exchange Rate (ACH)
single family	1,540	12,320	0.12-0.26
multi-family unit	600	4,800	0.32-0.66
manufactured home	902	7,216	0.21-0.44

that is colder or warmer than 32°F will require a greater or smaller air exchange rate, respectively, to maintain the range of 40 to 60% relative humidity.

In addition to potential health effects described above, excessive moisture indoors (high relative humidity) will cause water vapor to condense on cold surfaces in the winter. This water can cause considerable damage to construction material by accumulating within walls. Severe damage results when the wall surface is penetrated, destroying the studs and reducing the effectiveness of the wall or ceiling insulation.

3.3.4 Other Health and Safety Concerns

All design modifications to buildings must conform to building safety codes. Similarly, heating and cooling equipment and cooking appliances must meet national safety standards. These codes reflect the informed judgment of trained, experienced professionals and are specifically designed to protect public health and safety. Laboratory testing is usually the basis for information on the expected frequency of adverse impacts for particular energy conservation measures. However, the probability that hazards manifested in the laboratory will actually occur in most buildings is uncertain because combinations of factors not accounted for in the laboratory tests may be involved. In such cases, a conservative approach is usually adopted by the organizations responsible for these codes. That is, the level of requirements generally adopted eliminates or reduces to an acceptable degree all of the likeliest hazards or suspected hazards.

3.4 OUTDOOR ENVIRONMENTAL IMPACTS

Building new energy-efficient housing to the proposed voluntary standard would affect the outdoor environment in two ways. The first would be a reduction in the emission of pollutants into the atmosphere from the burning of fossil fuel, either directly by residences with gas, oil or propane heating systems, or by a reduction in the amount of electricity for new houses with electrical heating/cooling systems generated by fossil-fueled power plants. If it is assumed that the proposed voluntary standard reaches full penetration in five years, roughly estimated total annual savings for each of the four fuel types would be 4.7, 27.7, 1.9,and 4.0 million Btus for gas, propane, electricity and oil, respectively.

The second effect would result from changes in the amount of insulation materials used in the manufacturing of the houses built to the proposed voluntary standard and resultant changes in manufacturing-related emission of outdoor pollutants, primarily suspended particulates. The levels of insulation in houses increased as a result of the VOLRES standard in some case studies (e.g., electrically-heated, single-family residence in Atlanta) and decreased in others (e.g., gas-heated, multi-family residences in Minneapolis). Due to the uncertainty of how states with more (or less) stringent current codes will respond to the proposed voluntary standard, no attempt was made to quantify this impact. However, it is estimated that the net effects resulting from changes to insulation production would be very small.

3.5 ECONOMIC IMPACTS

A detailed economic analysis of the potential impacts of the proposed voluntary standard was conducted, and the results of that analysis are contained in a companion report to this environmental assessment (Marsh et al. 1988). The conclusions of this report concerning estimated direct and indirect economic impacts are summarized below.

3.5.1 Direct Economic Impacts of the Proposed Standard

The economic analysis of the proposed voluntary standard for new residential buildings concludes that there are no significant adverse effects of adopting the VOLRES standard. The proposed voluntary standard would result in a positive net flow of benefits from energy savings that more than offset higher capital construction and other costs, when compared to current practice. This conclusion was reached by comparing the life-cycle cost of case study prototypes constructed to currently required/used levels, and the costs of residences that meet the proposed standard. The incremental costs and benefits of compliance with the voluntary standard were aggregated to reflect total societal costs and benefits. Incremental costs and benefits to individual homeowners were addressed in the sensitivity analysis only. Different time horizons, discount rates, and tax effects were used to account for the economic perspective of the homeowner as opposed to that of society as a whole. Aggregated effects were determined for two penetration rate scenarios (i.e., assumptions about the adoption of the VOLRES standard as a mandatory code by the states). Impacts were estimated on the basis of these scenarios for housing starts projected to the year 2005. The major conclusions of the analysis (expressed in constant 1986 dollars) can be summarized as follows. The national net (societal) effect of the voluntary standard, assuming its immediate and full penetration, ranges from nearly $930 million in net benefit for 1988 construction to $1,035 million for 1992 construction. This effect is based on the net present value of energy savings and capital costs using a time frame of 15 years. For construction in 1992, the year with the largest net effect, the capital costs of compliance to the standard are $1.2 billion. The net present value of energy savings accrued over the 15-year time frame are nearly $2.2 billion. The difference represents a net benefit of $1.0 billion for construction in 1992 alone.

Because the standard is voluntary, the net benefits were also calculated assuming penetration of the proposed standard was staged over a five-year period (1988-1992). Full penetration of the voluntary standard does not occur until 1992 in this scenario. The national net effect of the voluntary standard ranges from nearly $186 million in net benefit for construction in 1988 to $1,035 million for construction in 1995.

The voluntary standard also creates a net benefit for all regions individually. Assuming full penetration of the voluntary standard, the Northeast receives the greatest annual benefit until 1993, when the net benefits in the South overtake those of the Northeast. The net benefit to the Northeast increases from $336 million for 1988 construction to $384 billion in 1992, after which the net benefit drops steadily until the 2001-2005 construction period when it reaches $220 million. The West region's net benefit is the smallest of all regional benefits over the study period. Changes in the relative share of net costs and benefits are attributable to forecasted trends in the regional distribution of new housing.

3.5.2 Total Economic Impacts of the Proposed Voluntary Standard

Total impacts (indirect plus direct) were estimated using the 1977 U.S. input-output (I/O) structure of the economy. The difference between capital costs that would be incurred in the construction of the ARES-configured building and those of the buildings constructed according to current practice are introduced as changes in final demands. These changes are then inserted in the I/O Table to simulate the effect of the direct costs of the voluntary standard on the U.S. economy. The changes in energy expenditures, allocated to the different fuels, are likewise introduced as changes in final demand and used to simulate the changes that result from the proposed standard. These changes in industry output, in turn, are multiplied by labor-intensity for each industry to yield the change in employment that would result from the voluntary standard.

The total impacts of the proposed voluntary standard are assessed in terms of the additional output and employment that would result from the increase in capital costs and the loss of output and employment that would occur due to lower energy expenditures. The total changes resulting from the voluntary standard represent only a very small fraction of the U.S. economy's total output and employment. For purposes of illustration, the effects of the energy savings have been assumed to occur in the year of construction, when in reality the energy savings occur over the fifteen-year time horizon. In 1992, the year with the greatest total impacts, the combined effect of output changes results in a net loss of approximately $2.4 billion in output due to the effect of the standard. This net decrease in output results from a $2.3 billion increase in output resulting from increased capital expenditures for construction and the $4.7 billion decrease in output resulting from lower energy expenditures. The greatest total effect on employment results from 1991 construction and shows a loss of 10,800 jobs. This is composed of an increase of 31,800 jobs due to increased capital costs and a loss of 42,600 jobs from decreased energy expenditures.

Even when the combined effects on output resulting from decreased energy expenditures over the fifteen-year period are assumed to occur in the initial year, the output change represents only 0.05 percent of the U.S. Gross National

Product. If, in fact, the effects on output due to energy savings were distributed over the fifteen-year period, the loss of output would be greatly minimized. Concommitantly, the near-term effects (production and employment associated with housing construction) would be increased.

An extensive analysis of the sensitivity of ARES and the resulting life-cycle cost to fuel prices was performed. Fuel prices were increased and decreased by 50 percent in the ARES runs, and the new life-cycle cost was calculated for the ARES-configured housing using the increased and decreased fuel prices. As would be anticipated, ARES is sensitive to these major changes in fuel prices. When fuel prices are increased by 50 percent, the net benefit of the proposed voluntary standard increases substantially. The national net benefit reaches its highest level for construction in 1992 with a net benefit of $2.2 billion. On the other hand, when fuel prices are decreased by 50 percent, the proposed voluntary standard results in less energy-efficient construction than is currently required by many state codes.

The effect of modifying the time horizon used in the ARES program was also tested. The calculation of the net benefit of the proposed voluntary standard with a seven-year time horizon, the proposed voluntary standard would result in a net cost to society in all construction years. Extending the time horizon to 30 years results in a national net benefit that is substantially higher than the net benefit produced by the 15-year time horizon.

The homeowner's perspective was also assessed as part of the sensitivity analysis. For all years of construction, the proposed voluntary standard would generate a net benefit for homeowners (assuming typical 1986 fuel prices).

3.6 INSTITUTIONAL IMPACTS

The proposed voluntary standard is intended to be a voluntary guideline for the private sector construction of residential buildings. Because it is not a binding code, there are no institutional impacts that directly result from its issuance by DOE. However, adoption of the proposed voluntary standard as a mandatory code by states and local code entities could have several significant institutional effects, discussed below. This discussion is conjectural, since the ultimate use of the VOLRES standard by code jurisdictions and other entities cannot be predicted.

Because of the widespread existence of mandatory energy codes that stipulate minimum ECM levels for new residences, adoption of VOLRES (to update existing codes) is unlikely to adversely impact state and local institutions. This does not imply, however, that adoption would be straightforward or politically uncontroversial. On the contrary, adoption of and changes to state energy codes have often been accompanied by intensive lobbying by the building trades, utilities, homeowner groups, code official organizations and others. Adoption of the VOLRES standard is likely to generate at least as much political controversy as was the case with present state codes. While the large number of user-modifiable parameters in the proposed voluntary standard make it very flexible, this feature also increases the likelihood that when the standard is adopted as a code, it will contain a number of politically-negotiated values for parameters.

In a majority of states with mandatory codes, building energy performance requirements are based on average state-wide values for heating and cooling degree days. However, other states attempt to account for climate diversity by designating requirements by climate zone. The most prominent example of the latter is California, where code variations were developed for fourteen zones. The climate zone approach is typically used to strike a balance between two principal (but somewhat contradictory) needs of energy codes--climate sensitivity and simplicity of compliance and enforcement. While the use of zone variations give an energy code more climate sensitivity than a single code, zones also serve to limit the potential geographic variability of requirements that could accompany unrestricted HDD-based performance codes (important to the building trades). The latter need increases the possibility that states will modify the high climate-related flexibility of the proposed voluntary standard if they choose to adopt it to update current codes.

Adoption of a fuel-specific code such as the VOLRES standard may also cause some political and institutional impacts in states where energy codes are presently fuel-blind. Most mandatory energy codes do not differentiate between energy sources (NCSBCS 1985), although this is becoming an increasingly common approach as states update their codes. Selection of appropriate fuel prices to use in ARES may also prove to be controversial, particularly if VOLRES is adopted on the basis of zones or regions within a state. One final fuel-related effect may occur. Application of ARES creates separate component packages for different fuels in a given locale (to avoid giving preferential treatment to any fuel). The resulting voluntary standards usually have different ECM requirements and associated life-cycle and construction costs. The cost differences may cause some change in the local market share held by a given fuel. This so-called "fuel switching" is actually the change in existing patterns of heating fuel choices for new homes by consumers.

Enforcement of the voluntary standard as part of local building codes could require different procedures than those typically used in most states for current energy codes (visual inspection and/or measurement). Compliance with the proposed voluntary standard is most easily verified by those methods if the ECM package generated by ARES is used as the code. If other compliance paths (energy budget or point system) are used, code enforcement officials may also need additional training and/or equipment (computers) to determine compliance. However, the nature and extent of enforcement-related impacts would depend on the features of the proposed voluntary standard as adopted by state or local governments and the compliance paths that are permitted.

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APPENDIX A

DESCRIPTION OF CASE-STUDY RESIDENCES UNDER THE PROPOSED STANDARD

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A.1 SELECTION OF THE CASE STUDY RESIDENCES

Over seventy case study homes were created for this analysis using the Automated Residential Energy Standard (ARES) software to determine ECM levels that would meet the proposed voluntary standard. These case study homes cover three types of residential housing, up to five fuel/heating appliance specifications and ten locations. In addition, each case study for site built homes included insulation requirements for four alternative foundations. Considerations used to select the residences to be studied included the following:

Building Prototypes. The ARES software produces voluntary standards for three types of residential structures: single family and multi-family site-built homes and single-wide manufactured (mobile) homes. Each type is represented as a generic, relatively simple prototype, with set dimensions and features. Each site-built prototype also comes with several foundation options, while the manufactured home is modeled only on the crawl space foundations. Packages of energy conservation measures (ECMs) generated by the voluntary standard show required insulation levels for each foundation type selected for consideration by the user. Tables A.1 and A.2 list the building types, their dimensions, and the foundation options that were studied in this analysis. Voluntary standards were created for all four foundation variations for the site-built prototypes, and indoor air quality effects were estimated for each of those variations. Although the economic analysis was based on those same prototypes, a somewhat different approach to determine impacts. In that study, aggregate impacts were determined by deriving regional allocations of each foundation type (U.S. Department of Commerce 1986) for single and multi-family residences. Regional costs and benefits and the national total were determined on the basis of those distributions.

TABLE A.1. Prototype Residential Units

House Type	Foundation Type
1) single-family residence	crawl space
2) single-family residence	unconditioned basement
3) single-family residence	conditioned basement
4) single-family residence	slab
5) multi-family residence	crawl space
6) multi-family residence	unconditioned basement
7) multi-family residence	conditioned basement
8) multi-family residence	slab
9) manufactured home	crawl space

TABLE A.2. Residential Housing - Selected Unit Dependent Characteristics

Component	Single Family	Multi-Family	Manu. Home
ceiling square feet	1540	600	902
wall square feet	1328	640	1162
floor square feet	1540	600	902
slab perimeter linear feet	166	40	NA
basement wall perimeter linear feet	166	40	NA

Case Study Locations. Ten cities distributed across the continental United States were selected as locations where VOLRES would be compared to existing energy efficiency-related building practices and requirements. These locations represent a range of heating and cooling degree day values that span the predominant climatic conditions in the United States. Regions where new residential construction has been and is expected to be particularly heavy were slightly emphasized in the selection of the locations. Table A.3 shows the cities that were selected for this analysis.

TABLE A.3. Locations and Fuels Examined in the Assessment

Location	Single and Multi-Family Gas	Single and Multi-Family Elect.	Single and Multi-Family HP	Single and Multi-Family Oil	Manufactured Homes Gas	Manufactured Homes Elect.	Manufactured Homes LPG	Manufactured Homes Oil
Atlanta	x	x	x		x	x	x	
Denver	x	x	x		x	x	x	
Fort Worth	x	x	x		x	x	x	
Minneapolis	x	x	x		x	x	x	
Pasadena	x	x	x		x	x	x	
Phoenix	x	x	x		x	x	x	
Seattle	x	x	x		x	x	x	
Tampa	x	x	x		x	x	x	
Albany	x	x	x	x	x	x	x	x
Providence	x	x	x	x	x	x	x	x

Fuels. The voluntary standards generated for VOLRES by the ARES software are specific to the fuel/heating appliance combinations selected by the user from among the five choices provided in the ARES program. In order to somewhat limit the number of voluntary standards at each location, it was decided to develop VOLRES standards for only the two predominant heating fuels in each city. (When electricity was one of those fuels, however, there actually were three variations of the voluntary standard created, since ARES creates separate requirements for electric forced-air and electric heat-pump appliances.) Baseline residences were also modeled using only the two predominant heating fuels, except as noted below. The two primary heating fuels were selected using data from recent Bureau of Census New Housing Construction reports that showed the distribution by heating fuels of recently constructed new homes. In two locations (Albany and Providence), a third fuel (electricity) was also considered because of its widespread use as a heating source for multi-family housing. Table A.3 shows the fuels selected for each location.

A.2 GENERATION OF ECM LEVELS FOR THE CASE-STUDY RESIDENCES

Generation of the ECM package with the ARES software requires the user to make a number of choices that tailor the voluntary standard to local conditions, prices, and construction trends. The choices that were used to develop the proposed voluntary standard case study homes are listed below.

Fuel Prices. Prices used for selected fuels were current (1986) location-specific prices obtained from published sources. The primary source of natural gas and fuel oil prices for each study location was the Annual Househeating Survey published by the American Gas Association (AGA 1986). Electricity prices were obtained from The Electrical World Directory of Electric Utilities, 1985-1986 94th Edition, (McGraw-Hill 1987). Fuel oil and LPG prices were obtained from the State Energy Price and Expenditure Report, 1985, published by the Energy Information Administration (1987). Sensitivity of ARES output to variations in fuel price were studied extensively in the economic analysis. Results of the fuel price sensitivity analysis are included in Section 3.5.

Construction Costs. The ARES program contains resident data bases with average ECM construction costs (1986 dollars) for eleven regions covering the continental United States. These costs are default values that can be modified by individual users of the software. For the purpose of this study, no changes were made to the default values, which were set by the ASHRAE Technical Evaluation Committee of Special Project 53.

ECM and Heating Appliance Efficiencies. The life-cycle minimization process assesses a variety of envelope ECMs, HVAC systems and their associated energy efficiency and costs. For example, the ARES program can examine the relative cost-effectiveness of six levels of ceiling insulation thicknesses (with efficiencies ranging from R-11 to R-60). Appliance efficiency values in ARES are not allowed to drop below the minimum efficiencies mandated in the National Appliance Energy Conservation Act (NAECA) of 1987 (42 USC 6201). However, the software can select higher efficiencies, if the life cycle cost of the home can be lowered by doing so. Minimum efficiencies allowable under NAECA become mandatory between 1990 and 1992 (the date varies by type of appliance) for new space conditioning equipment. The NAECA minimum values were used to develop the comparative life-cycle costs and energy use of the baseline (current code) prototypes.

Windows. Users of the ARES program can set the amount (window-to-floor-area ratio) and percent of south-facing fenestration (except in manufactured housing) in the prototypes. Users can also limit the types of glazing that are to be considered in creating the voluntary standard. Modifying any of these parameters often produces adjustments in the required efficiency of other ECMs. The proposed voluntary standard and baseline case study residences were created by using the following parameters: 1) window area was set at 12 percent of floor area; 2) one-fourth of the window area was placed on the south-facing wall; and 3) ARES was not allowed to consider single pane/thermal break, triple pane/no thermal break, and reflective low emissivity (low E-sun) glazing options for the windows. While those types of glazing are commercially available, they are not yet widely marketed for residential construction and are seldom used by builders (although low E-reflective glazing is becoming more popular in sunbelt states).[a]

Economic Parameters. ARES contains a file listing the economic parameters that guide its life-cycle cost calculations. In conjunction with other files and programming, the software generates the package of ECM components that represents minimized building life-cycle cost in any location. The user can edit the initial (default) values assigned to these economic parameters. A slightly different voluntary standard often results from such changes. For the purposes of this assessment, the default values for the economic parameters (shown in Table A.4) were used. The economic parameters used for the analysis of manufactured housing were changed in some cases to more accurately reflect manufactured home buyers' environment. Extensive sensitivity testing of important variables (e.g., the discount rate) was conducted as part of the economic analysis.

(a) Telephone conversation between Todd Taylor, Pacific Northwest Laboratory, and Steve Selkowitz, Lawrence Berkeley Laboratory, March 15, 1988.

TABLE A.4. Economic Parameters Used to Create Case Study Residences

	Single- and Multi-Housing	Manufactured Housing
Inflation Rate	4% annually	4% annually
Mortgage Interest Rate	9% annually	12% annually
Points	1.50	0.0
Alternative Investment Rate	5.5% annually	5.5% annually
Income Tax Rate	21%	19%
Property Tax Rate	1%	1%
Down Payment Percentage	10%	10%
Loan Fee Percentage	3.3%	0%
Term of Mortgage	30%	15 years
Time Horizon	7 years	7 years

These settings were used to guide creation of the package of ECMs that would allow each prototype variant in each location to meet the proposed standard. The results are displayed as Tables A.5 through A.7.

TABLE A.5 Description of Prototype ECM's for the Single Family Residence

		Base Line Tampa	Ares Tampa	Change In Insulation (inches) FG Sheath	Base Line Phoenix	Ares Phoenix	Change In Insulation (inches) FG Sheath	Base Line Atlanta	Ares Atlanta	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-19	R-19	0.0	R-30	R-19	-6.5	R-19	R-30	6.5
	wall insulation	R-11	R-11	0.0	R-19	R-13	-2.0	R-11	R-23	2.5 1.0
	crawlspace insulation	R-8	R-0	0.0	R-11	R-13	0.5	R-11	R-19	2.5
	base. floor insulation	R-0	R-0	0.0	R-0	R-0	0.0	R-11	R-11	0.0
	base. wall insulation	R-0	R-0	0.0	R-0	R-5_4 ft	1.0	R-0	R-0	0.0
	slab insulation	R-0	R-0	0.0	R-0	R-0	0.0	R-5_2 ft	R-0	-1.0
	glazing type	s w/o tb	Dbl w/o tb		s_w/o tb	Dbl w/o tb		s w/o tb	Dbl w/o tb	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 78%	AFUE 90%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	ceiling insulation	R-30	R-19	-6.5	R-30	R-38	3.5	R-19	R-49	14.5
	wall insulation	R-11	R-19	2.5	R-19	R-23	0.0 1.0	R-11	R-26	2.5 2.0
	crawlspace insulation	R-0	R-11	3.5	R-11	R-30	5.5	R-11	R-30	5.5
	base. floor insulation	R-0	R-0	0.0	R-0	R-19	6.0	R-11	R-30	5.5
	base. wall insulation	R-0	R-0	0.0	R-0	R-10_4 ft	2.0	R-0	R-10_4 ft	2.0
	slab insulation	R-0	R-0	0.0	R-0	R-5_2 ft	1.0	R-5_2 ft	R-5_4 ft	0.0
	glazing type	s w/o tb	Dbl w/o tb		s_w/o tb	Dbl_low-e		s w/o tb	Dbl_low-e	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficency	-	-		-	-		-	-	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	ceiling insulation	R-30	R-19	-6.5	R-30	R-30	0.0	R-19	R-30	6.5
	wall insulation	R-11	R-1	0.0	R-19	R-13	-2.0	R-11	R-23	2.5 1.0
	crawlspace insulation	R-0	R-0	0.0	R-11	R-30	5.5	R-11	R-30	5.5
	base. floor insulation	R-0	R-0	0.0	R-0	R-0	0.0	R-11	R-11	0.0
	base. wall insulation	R-0	R-0	0.0	R-0	R-5_4 ft	1.0	R-0	R-10_4 ft	2.0
	slab insulation	R-0	R-0	0.0	R-0	R-0	0.0	R-5_2 ft	R-5_2 ft	0.0
	glazing type	s w/o tb	Dbl w/o tb		s_w/o tb	Dbl_low-e		s w/o tb	Dbl w/o tb	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	house type	NA	NA		NA	NA		NA	NA	
	heat eq. type									
	ceiling insulation									
	wall insulation									
	crawlspace insulation									
	base. floor insulation									
	base. wall insulation									
	slab insulation									
	glazing type									
	infiltration									
	heating efficiency									
	cooling efficiency									

TABLE A.5 (Cont.)

		Base Line Seattle	Ares Seattle	Change In Insulation (inches) FG Sheath	Base Line Denver	Ares Denver	Change In Insulation (inches) FG Sheath	Base Line Minneapol	Ares Minneapol	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-30	R-30	0.0	R-30	R-30	0.0	R-38	R-30	-3.5
	wall insulation	R-11	R-23	2.5 1.0	R-13	R-23	2.0 1.0	R-19	R-23	0.0 1.0
	crawlspace insulation	R-19	R-30	3.0	R-13	R-13	0.0	R-19	R-30	3.0
	base. floor insulation	R-19	R-19	0.0	R-13	R-11	-0.5	R-19	R-13	-2.0
	base. wall insulation	R-5_2 ft	R-0	-1.0	R-5_2 ft	R-10_4 ft	1.0	R-5_2 ft	R-10_4 ft	1.0
	slab insulation	R-5_2 ft	R-5_2 ft	0.0	R-5_2 ft	R-5_2 ft	0.0	R-5_2 ft	R-5_2 ft	0.0
	glazing type	Dbl w/o tb	Dbl w/o tb		Dbl w/o-tb	Dbl w/o tb		Dbl_tb	Dbl_low-e	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	AFUE-85%	AFUE 85%		AFUE-80%	AFUE 80%		AFUE 78%	AFUE 90%	
	cooling efficiency	SEER-10	SEER 10		SEER-10	SEER 10		SEER-10	SEER 10	
Electric Forced Air	ceiling insulation	R-38	R-30	-3.5	R-30	R-30	0.0	R-38	R-30	-3.5
	wall insulation	R-19	R-26	0.0 2.0	R-13	R-23	2.0 1.0	R-19	R-26	0.0 2.0
	crawlspace insulation	R-19	R-30	3.0	R-13	R-30	5.0	R-19	R-30	3.0
	base. floor insulation	R-19	R-30	3.0	R-13	R-30	5.0	R-19	R-30	3.0
	base. wall insulation	R-5_2 ft	R-10_4 ft	1.0	R-5_2 ft	R-10_4ft	1.0	R-5_2 ft	R-10_4ft	1.0
	slab insulation	R-5_2 ft	R-5_4 ft	0.0	R-5_2 ft	R-5_4 ft	0.0	R-5_2 ft	R-5_4 ft	0.0
	glazing type	Dbl_tb	Dbl_low-e		Dbl w/o-tb	Dbl_low-e		Dbl_tb	Dbl_low-e	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	-	-		-	-		-	-	
	cooling efficiency	SEER 10	SEER 10		SEER-10	SEER-10		SEER-10	SEER 10	
Electric Heat Pump	ceiling insulation	R-30	R-30	0.0	R-30	R-30	0.0	R-38	R-30	-3.5
	wall insulation	R-13	R-23	2.0 1.0	R-13	R-23	2.0 1.0	R-19	R-23	0.0 1.0
	crawlspace insulation	R-19	R-30	3.0	R-13	R-30	5.0	R-19	R-30	3.0
	base. floor insulation	R-19	R-11	-2.5	R-13	R-30	5.0	R-19	R-30	3.0
	base. wall insulation	R-5_2 ft	R-0	1.0	R-5_2 ft	R-10_4 ft	1.0	R-5_2 ft	R-10_4 ft	1.0
	slab insulation	R-5_2 ft	R-5_2 ft	0.0	R-5_2 ft	R-10_2 ft	1.0	R-5_2 ft	R-5_4 ft	0.0
	glazing type	Dbl w/o tb	Dbl w/o tb		Dbl w/o-tb	Dbl_low-e		Dbl_tb	Dbl_low-e	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 9.8	
	cooling efficiency	SEER 10.0	SEER 10.0		SEER 10.0	SEER 10.0		SEER 10.0	SEER 12.0	
Oil	ceiling insulation	NA	NA		NA	NA		NA	NA	
	wall insulation									
	crawlspace insulation									
	base. floor insulation									
	base. wall insulation									
	slab insulation									
	glazing type									
	infiltration									
	heating efficiency									
	cooling efficiency									

TABLE A.5 (Cont.)

		Base Line Ft Worth	Ares Ft Worth	Change In Insulation (inches) FG Sheath	Base Line Albany	Ares Albany	Change In Insulation (inches) FG Sheath	Base Line Providence	Ares Providence(a)	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-19	R-30	6.5	R-30	R-30	0.0	R-19	R-30	6.5
	wall insulation	R-13	R-19	2.0	R-23	R-23	0.0	R-11	R-23	2.5 1.0
	crawlspace insulation	R-13	R-13	4.0	R-19	R-30	3.0	R-11	R-30	5.5
	base. floor insulation	R-0	R-0	0.0	R-19	R-30	3.0	R-11	R-30	5.5
	base. wall insulation	R-0	R-0	0.0	R-10_2 ft	R-10_4 ft	0.0	R-5_4 ft	R-10_4 ft	1.0
	slab insulation	R-0	R-0	0.0	R-10_8 ft	R-5_2 ft	-1.0	R-0	R-5_2 ft	1.0
	glazing type	Dbl_tb	Dbl w/o tb		Dbl-ht_abs	Dbl_Low-E		Dbl_tb	Dbl_Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 85%		AFUE 78%	AFUE 95%	
	cooling efficiency	SEER-10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	ceiling insulation	R-19	R-30	6.5	R-38			R-19		
	wall insulation	R-13	R-23	2.0 1.0	R-26			R-11		
	crawlspace insulation	R-13	R-30	8.0	R-19			R-11		
	base. floor insulation	R-0	R-30	8.0	R-19			R-11		
	base. wall insulation	R-0	R-10_4ft	1.0	R-10_8 ft			R-5_4 ft		
	slab insulation	R-0	R-10_2 ft	1.0	R-10_2 ft			R-0		
	glazing type	Dbl_tb	Dbl_Low-E		Tri_h_abs			Dbl_tb		
	infiltration	normal	normal		normal			normal		
	heating efficiency	-	-		-			-		
	cooling efficiency	SEER-10	SEER 10		SEER 10	SEER-10				
Electric Heat Pump	ceiling insulation	R-19	R-30	6.5	R-30			R-19		
	wall insulation	R-13	R-11	-0.5	R-23			R-11		
	crawlspace insulation	R-13	R-19	6.0	R-19			R-11		
	base. floor insulation	R-0	R-13	4.0	R-19			R-11		
	base. wall insulation	R-0	R-10_4 ft	2.0	R-10_2 ft			R-5_4 ft		
	slab insulation	R-0	R-5_2 ft	1.0	R-10_8 ft			R-0		
	glazing type	Dbl_tb	Dbl_Low-E		Dbl-ht_abs			Dbl_tb		
	infiltration	normal	normal		normal			normal		
	heating efficiency	HSPF 7.3	HSPF 7.3		HSPF 7.3			HSPF 7.3		
	Cooling efficiency	SEER 10.0	SEER 10		SEER 10.0			SEER 10		
Oil	ceiling insulation				R-30	R-30	0.0	R-19	R-30	6.5
	wall insulation				R-23	R-23	0.0	R-11	R-23	2.5 1.0
	crawlspace insulation				R-19	R-30	3.0	R-11	R-30	5.5
	base. floor insulation				R-19	R-30	3.0	R-11	R-13	0.5
	base. wall insulation				R-10_2 ft	R-10_4 ft	0.0	R-5_4 ft	R-10_4 ft	1.0
	slab insulation				R-10_8 ft	R-5_2 ft	-1.0	R-0	R-5_2 ft	1.0
	glazing type				Dbl-ht_abs	Dbl_Low-E		Dbl_tb	Dbl_Low-E	
	infiltration				normal	normal		normal	normal	
	heating efficiency				AFUE 78%	AFUE 95%		AFUE 78%	AFUE 95%	
	cooling efficiency				SEER 10	SEER 10		SEER 10	SEER 10	

(a) Rhode Island has adopted a new, fuel-specific energy code that went into effect on October 1, 1988. Baseline codes included in this study, however, reflect the code in place in March 1988, which was not fuel specific.

TABLE A.5 (Cont.)

		Base Line Pasadena	Ares Pasadena	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-19	R-30	6.5
	wall insulation	R-11	R-19	2.5
	crawlspace insulation	R-19	R-11	-2.5
	base. floor insulation	R-19	R-0	-6.0
	base. wall insulation	R-0	R-0	0.0
	slab insulation	R-0	R-0	0.0
	glazing type	s-w/o-tb	dbl_w/o tb	
	infiltration	normal	normal	
	heating efficiency	AFUE-78%	AFUE 78%	
	cooling efficiency	SEER-10	SEER 10	
Electric Forced Air	ceiling insulation	R-19	R-30	6.5
	wall insulation	R-11	R-23	2.5 1.0
	crawlspace insulation	R-19	R-13	-2.0
	base. floor insulation	R-19	R-11	-2.5
	base. wall insulation	R-0	R-5_4 ft	1.0
	slab insulation	R-0	R-5_2 ft	1.0
	glazing type	S-w/o-tb	Dbl_w/o tb	
	infiltration	normal	normal	
	heating efficiency	-	-	
	cooling efficiency	SEER-10	SEER 10	
Electric Heat Pump	ceiling insulation	R-19	R-30	6.5
	wall insulation	R-11	R-19	2.5
	crawlspace insulation	R-19	R-13	-2.0
	base. floor insulation	R-19	R-0	-6.0
	base. wall insulation	R-0	R-0	0.0
	slab insulation	R-0	R-0	0.0
	glazing type	S-w/o-tb	Dbl w/o tb	
	infiltration	normal	normal	
	heating efficiency	HSPF-7.3	HSPF 7.3	
	cooling efficiency	SEER 10.0	SEER 10	
oil	ceiling insulation	NA	NA	NA
	wall insulation			
	crawlspace insulation			
	base. floor insulation			
	base. wall insulation			
	slab insulation			
	glazing type			
	infiltration			
	heating efficiency			
	cooling efficiency			

TABLE A.6 Description of Prototype ECM's for the Multi-Family Residence

		Base Line Tampa	Ares Tampa	Change In Insulation (inches) FG Sheath	Base Line Phoenix	Ares Phoenix	Change In Insulation (inches) FG Sheath	Base Line Atlanta	Ares Atlanta	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-19	R-19	0.0	R-30	R-19	-6.5	R-30	R-30	0.0
	wall insulation	R-19	R-11	-2.5	R-13	R-23	2.0 1.0	R-13	R-13	0.0
	crawlspace insulation	R-0	R-0	0.0	R-0	R-13	4.0	R-11	R-11	0.0
	base. floor insulation	R-0	R-0	0.0	R-0	R-0	0.0	R-0	R-0	-3.5
	base. wall insulation	R-0	R-0	0.0	R-0	R-5_4 ft	1.0	R-11	R-5_4 ft	1.0
	slab insulation	R-10_2 ft	R-0	-2.0	R-0	R-0	0.0	R-0	R-0	0.0
	glazing type	S_w/o TB	S_H_Abs		S_w/o TB	Dbl_Low-E		Dbl TB	Dbl w/o TB	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 95%	AFUE 80%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	ceiling insulation	R-19	R-19	0.0	R-30	R-30	0.0	R-30	R-30	0.0
	wall insulation	R-19	R-11	-2.5	R-13	R-23	2.0 1.0	R-13	R-23	2.0 1.0
	crawlspace insulation	R-0	R-11	3.5	R-0	R-30	9.0	R-11	R-30	5.5
	base. floor insulation	R-0	R-0	0.0	R-0	R-11	3.5	R-0	R-11	0.0
	base. wall insulation	R-0	R-0	0.0	R-0	R-10_4 ft	2.0	R-11	R-10_4 ft	2.0
	slab insulation	R-10_2 ft	R-0	-2.0	R-0	R-0	0.0	R-0	R-5_2 ft	1.0
	glazing type	S_w/o TB	Dbl w/o TB		S_w/o TB	Dbl_TB		Dbl TB	Dbl w/o TB	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	-	-		-	-		-	-	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	ceiling insulation	R-19	R-30	6.5	R-30	R-30	0.0	R-30	R-30	0.
	wall insulation	R-19	R-11	-2.5	R-13	R-19	2.0	R-13	R-13	0.0
	crawlspace insulation	R-0	R-0	0.0	R-0	R-11	3.5	R-11	R-11	0.0
	base. floor insulation	R-0	R-0	0.0	R-0	R-0	0.0	R-0	R-0	-3.5
	base. wall insulation	R-0	R-0	0.0	R-0	R-5_4 FT	1.0	R-11	R-5_4 FT	1.0
	slab insulation	R-10_2 FT	R-0	-2.0	R-0	R-0	0.0	R-0	R-0	0.0
	glazing type	S w/o TB	Dbl w/o TB		S_w/o TB	Dbl_Low-E		Dbl TB	Dbl w/o TB	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	house type	NA	NA		NA	NA		NA	NA	
	heat eq. type									
	ceiling insulation									
	wall insulation									
	crawlspace insulation									
	base. floor insulation									
	base. wall insulation									
	slab insulation									
	glazing type									
	infiltration									
	heating efficiency									
	cooling efficiency									

TABLE A.6 (Cont.)

		Base Line Seattle	Ares Seattle	Change In Insulation (inches) FG Sheath	Base Line Denver	Ares Denver	Change In Insulation (inches) FG Sheath	Base Line Minneapol	Ares Minneapol	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-38	R-30	-3.5	R-30	R-30	0.0	R-38	R-30	-3.5
	wall insulation	R-19	R-23	0.0 1.0	R-13	R-23	2.0 1.0	R-19	R-23	0.0 1.0
	crawlspace insulation	R-19	R-30	3.0	R-13	R-13	0.0	R-19	R-30	3.0
	base. floor insulation	R-19	R-11	-2.5	R-0	R-11	3.5	R-19	R-11	-2.5
	base. wall insulatoin	R-5_4 ft	R-5_4 ft	0.0	R-0	R-5_4 ft	1.0	R-10_4 ft	R-5_4 ft	-1.0
	slab insulation	R-5_2 ft	R-5_2 ft	0.0	R-0	R-5_2 ft	1.0	R-5_4 ft	R-5_2 ft	0.0
	glazing type	Dbl_Low-E	Dbl w/o TB		Dbl TB	Dbl w/o TB		Dbl TB	Dbl_Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 80%	AFUE 78%		AFUE 78%	AFUE 78%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	ceiling insulation	R-38	R-30	-3.5	R-30	R-30	0.0	R-38	R-30	-3.5
	wall insulation	R-19	R-23	0.0 1.0	R-13	R-23	2.0 1.0	R-19	R-26	0.0 2.0
	crawlspace insulation	R-19	R-30	3.0	R-13	R-30	5.0	R-19	R-30	3.0
	base. floor insulation	R-19	R-30	3.0	R-0	R-30	9.0	R-19	R-11	-2.5
	base. wall insulation	R-5_4 ft	R-10_4 ft	1.0	R-0	R-10_4 ft	2.0	R-10_4 ft	R-10_8 ft	0.0
	slab insulation	R-5_2 ft	R-10_2 ft	1.0	R-0	R-10_2 ft	2.0	R-5_4 ft	R-10_4 ft	1.0
	glazing type	Dbl_Low-E	Dbl_TB		Dbl TB	Dbl_TB		Dbl TB	Dbl_Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiencies	-	-		-	-		-	-	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	ceiling insulation	R-38	R-30	-3.5	R-30	R-30	0.0	R-38	R-30	-3.5
	wall insulation	R-19	R-23	0.0 1.0	R-13	R-23	2.0 1.0	R-19	R-26	0.0 2.0
	crawlspace insulation	R-19	R-11	-2.5	R-13	R-30	5.0	R-19	R-30	3.0
	base. floor insulation	R-19	R-11	-2.5	R-0	R-11	3.5	R-19	R-11	-2.5
	base. wall insulation	R-5_4 ft	R-5_4 ft	0.0	R-0	R-5_4 ft	1.0	R-10_4 ft	R-10_4 ft	0.0
	slab insulation	R-5_2 ft	R-5_2 ft	0.0	R-0	R-5_2 ft	1.0	R-5_4 ft	R-10_2 ft	1.0
	glazing type	Dbl_Low-E	Dbl w/o TB		Dbl TB	Dbl w/o TB		Dbl TB	Dbl_Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	ceiling insulation	NA	NA		NA	NA		NA	NA	
	wall insulation									
	crawlspace insulation									
	base. floor insulation									
	base. wall insulation									
	slab insulation									
	glazing type									
	infiltration									
	heating efficiency									
	cooling efficiency									

TABLE A.6 (Cont.)

		Base Line Ft Worth	Ares Ft Worth	Change In Insulation (inches) FG Sheath	Base Line Albany	Ares Albany	Change In Insulation (inches) FG Sheath	Base Line Providence	Ares Providence[(a)]	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-19	R-30	6.5	R-38	R-30	-3.5	R-19	R-30	6.5
	wall insulation	R-13	R-19	2.0	R-26	R-23	0.0-1.0	R-11	R-23	2.5 1.0
	crawlspace insulation	R-0	R-13	4.0	R-19	R-30	3.0	R-11	R-30	5.5
	base. floor insulation	R-0	R-0	0.0	R-19	R-13	-2.0	R-11	R-13	0.5
	base. wall insulation	R-0	R-5_4 ft	1.0	R-10_4 ft	R-5_4 ft	-1.0	R-0	R-5_4 ft	1.0
	slab insulation	R-0	R-0	0.0	R-10_2 ft	R-5_2 ft	-1.0	R-0	R-5_2 ft	1.0
	glazing type	Dbl TB	Dbl w/o TB		Tri_TB	Dbl w/o TB		Dbl TB	Dbl_Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced air	ceiling insulation	R-19	R-30	6.5	R-38	R-49		R-19	R-60	
	wall insulation	R-13	R-23	2.0 1.0	R-26	R-26		R-11	R-26	
	crawlspace insulation	R-0	R-30	9.0	R-19	R-30		R-11	R-30	
	base. floor insulation	R-0	R-13	4.0	R-19	R-30		R-11	R-30	
	base. wall insulation	R-0	R-10_4 ft	2.0	R-10_4 ft	R-10_4 ft		R-0	R-10_8 ft	
	slab insulation	R-0	R-5_2 ft	1.0	R-10_2 ft	R-10_4 ft		R-0	R-10_4 ft	
	glazing type	Dbl TB	Dbl w/o TB		Tri_TB	Dbl_Low E		Dbl TB	Dbl_Low E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	-	-		-	-		-	-	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	ceiling insulation	R-19	R-30	6.5	R-38	R-30		R-19	R-38	
	wall insulation	R-13	R-13	0.0	R-26	R-23		R-11	R-23	
	crawlspace insulation	R-0	R-13	4.0	R-19	R-30		R-11	R-30	
	base. floor insulation	R-0	R-0	0.0	R-19	R-30		R-11	R-30	
	base. wall insulation	R-0	R-5_4 ft	1.0	R-10_4 ft	R-10_4 ft		R-0	R-10_4 ft	
	slab insulation	R-0	R-0	0.0	R-10_2 ft	R-10_2 ft		R-0	R-10_2 ft	
	glazing type	Dbl TB	Dbl_Low-E		Tri_TB	Dbl_Low-E		Dbl TB	Dbl_Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	heating efficiency	HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3		HSPF 7.3	HSPF 7.3	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	ceiling insulation	NA	NA		R-38	R-30	-3.5	R-19	R-30	6.5
	wall insulation				R-26	R-23	0.0 -1.0	R-11	R-23	2.5 1.0
	crawlspace insulation				R-19	R-30	3.0	R-11	R-30	5.5
	base. floor insulation				R-19	R-30	3.0	R-11	R-13	0.5
	base. wall insulation				R-10_4 ft	R-10_4 ft	0.0	R-0	R-10_4 ft	2.0
	slab insulation				R-10_2 ft	R-10_2 ft	0.0	R-0	R-10_2 ft	2.0
	glazing type				Tri_TB	Dbl_Low-E		Dbl TB	Dbl_Low-E	
	infiltration				normal	normal		normal	normal	
	heating efficiency				AFUE 78%	AFUE 80%		AFUE 78%	AFUE 78%	
	cooling efficiency				SEER 10	SEER 10		SEER 10	SEER 10	

(a) Rhode Island has adopted a new, fuel-specific energy code that went into effect on October 1, 1988. Baseline codes included in this study, however, reflect the code in place in March 1988, which was not fuel specific.

TABLE A.6 (Cont.)

		Base Line Pasadena	Ares Pasadena	Change In Insulation (inches) FG Sheath
Gas	ceiling insulation	R-30	R-30	0.0
	wall insulation	R-11	R-13	0.5
	crawlspace insulation	R-19	R-11	-2.5
	base. floor insulation	R-19	R-0	-6.0
	base. wall insulation	R-0	R-0	0.0
	slab insulation	R-0	R-0	0.0
	glazing type	S w/o TB	Sgl w/o TB	
	infiltration	normal	normal	
	heating efficiency	AFUE-78%	AFUE 78%	
	cooling efficiency	SEER-10	SEER 10	
Electric Forced Air	ceiling insulation	R-30	R-30	0.0
	wall insulation	R-11	R-19	2.5
	crawlspace insulation	R-19	R-13	-2.0
	base. floor insulation	R-19	R-0	-6.0
	base. wall insulation	R-0	R-5_4 ft	1.0
	slab insulation	R-0	R-0	0.0
	glazing type	S w/o TB	Dbl w/o TB	
	infiltration	normal	normal	
	heating efficiency	-	-	
	cooling efficiency	SEER-10	SEER 10	
Electric Heat Pump	glazing type	S w/o TB	Dbl w/o TB	
	infiltration	normal	normal	
	ceiling insulation	R-30	R-30	0.0
	wall insulation	R-11	R-13	0.5
	crawlspace insulation	R-19	R-11	-2.5
	slab insulation	R-0	R-0	0.0
	base. wall insulation	R-0	R-0	0.0
	base. floor insulation	R-19	R-0	-6.0
	heating efficiency	HSPF-7.3	HSPF 7.3	
	cooling efficiency	SEER 10.0	SEER 10	
oil	ceiling insulation	NA	NA	
	wall insulation			
	crawlspace insulation			
	base. floor insulation			
	base. wall insulation			
	slab insulation			
	glazing type			
	infiltration			
	heating efficiency			
	cooling efficiency			

TABLE A.7 Description of Prototype ECM's for the Manufactured Homes

		Base Line Tampa	ARES Tampa	Change in Insulation (inches) FG Sheath	Base Line Phoenix	ARES Phoenix	Change in Insulation (inches) FG Sheath	Base Line Atlanta	ARES Atlanta	Change in Insulation (inches) FG Sheath
Gas	glazing type	S_w/o TB	S_w/o TB		S_w/o TB	Dbl_w/o TB		Single TB	Dbl_w/o TB	
	infiltration	normal	normal		normal	normal		tight	normal	
	ceiling insulation	R-19	R-11	-3.2	R-30	R-19	-4.4	R-14	R-11	-1.2
	wall insulation	R-11	R-7	-1.4	R-11	R-11	0.0	R-7	R-11	1.4
	crawlspace insulation	R-11	R-7	-1.4	R-11	R-19	2.5	R-4	R-14	3.0
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	glazing type	S_w/o TB	S_w/o TB		S_w/o TB	Dbl_w/o TB		Single TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		tight	normal	
	ceiling insulation	R-19	R-19	0.0	R-30	R-30	0.0	R-14	R-19	2.0
	wall insulation	R-11	R-11	0.0	R-11	R-19	2.5	R-7	R-19	3.9
	crawlspace insulation	R-11	R-11	0.0	R-11	R-19	2.5	R-4	R-19	4.8
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	--	--		--	--		--	--	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	glazing type	S_w/o TB	S_w/o TB		S_w/o TB	Dbl_w/o TB		Single TB	Dbl_w/o TB	
	infiltration	normal	normal		normal	normal		tight	normal	
	ceiling insulation	R-19	R-11	-3.2	R-30	R-19	-4.4	R-14	R-19	2.0
	wall insulation	R-11	R-11	0.0	R-11	R-13	0.5	R-7	R-11	1.4
	crawlspace insulation	R-11	R-11	0.0	R-11	R-19	2.5	R-4	R-19	4.8
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	glazing type	NA	NA		NA	NA		NA	NA	
	infiltration									
	ceiling insulation									
	wall insulation									
	crawlspace insulation									
	slab insulation									
	base. wall insulation									
	base. floor insulation									
	heating efficiency									
	cooling efficiency									

TABLE A.7 (contd)

		Base Line Seattle	ARES Seattle	Change in Insulation (inches) FG Sheath	Base Line Denver	ARES Denver	Change in Insulation (inches) FG Sheath	Base Line Minneapolis	ARES Atlanta	Change in Insulation (inches) FG Sheath
Gas	glazing type	Dbl_w/o TB	Dbl_w/o TB		S_w/o TB	Dbl_w/o TB		Dbl TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	ceiling insulation	R-19	R-19	0.0	R-19	R-19	0.0	R-30	R-19	-4.4
	wall insulation	R-11	R-11	0.0	R-19	R-11	-2.5	R-19	R-11	-2.5
	crawlspace insulation	R-11	R-19	2.5	R-11	R-19	2.5	R-11	R-19	2.5
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	glazing type	Dbl_w/o TB	Dbl Low-E		S_w/o TB	Dbl Low-E		Dbl TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	ceiling insulation	R-19	R-19	0.0	R-19	R-33	5.6	R-30	R-33	1.2
	wall insulation	R-11	R-19	2.5	R-19	R-19	0.0	R-19	R-19	0.0
	crawlspace insulation	R-11	R-19	2.5	R-11	R-28	5.0	R-11	R-28	5.0
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	--	--		--	--		--	--	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	glazing type	Dbl_w/o TB	Dbl_w/o TB		S_w/o TB	Dbl_w/o TB		Dbl TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	ceiling insulation	R-19	R-19	0.0	R-19	R-19	0.0	R-30	R-30	0.0
	wall insulation	R-11	R-13	0.5	R-19	R-11	-2.5	R-19	R-19	0.0
	crawlspace insulation	R-11	R-19	2.5	R-11	R-19	2.5	R-11	R-28	5.0
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%		AFUE 78%	AFUE 78%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	glazing type	NA	NA		NA	NA		NA	NA	
	infiltration									
	ceiling insulation									
	wall insulation									
	crawlspace insulation									
	slab insulation									
	base. wall insulation									
	base. floor insulation									
	heating efficiency									
	cooling efficiency									

TABLE A.7 (contd)

		Base Line Ft Worth	ARES Ft Worth	Change In Insulation (inches) FG Sheath	Base Line Albany	ARES Albany	Change In Insulation (inches) FG Sheath	Base Line Providence	Ares Providence[(a)]	Change In Insulation (inches) FG Sheath
Gas	glazing type	S w/o TB	Dbl w/o TB		DDbl TB	Dbl w/o TB		Dbl w/o TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	ceiling insulation	R-19	R-11	-3.2	R-19	R-19	0.0	R-14	R-19	2.0
	wall insulation	R-11	R-11	0.0	R-11	R-13	0.5	R-11	R-13	0.5
	crawlspace insulation	R-11	R-14	0.7	R-11	R-19	2.5	R-7	R-19	3.9
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 85%		AFUE 78%	AFUE 85%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Forced Air	glazing type	S w/o TB	Dbl Low-E		Dbl TB	Dbl Low-E		Dbl w/o TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	ceiling insulation	R-19	R-19	0.0	R-19	R-33	5.6	R-14	R-38	9.9
	wall insulation	R-11	R-19	2.5	R-11	R-19	2.5	R-11	R-24	2.5
	crawlspace insulation	R-11	R-19	2.5	R-11	R-28	5.0	R-7	R-28	6.4
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	-	-		-	-		-	-	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Electric Heat Pump	glazing type	S w/o TB	Dbl w/o TB		Dbl TB	Dbl Low-E		Dbl w/o TB	Dbl Low-E	
	infiltration	normal	normal		normal	normal		normal	normal	
	ceiling insulation	R-19	R-19	0.0	R-19	R-19	0.0	R-14	R-19	2.0
	wall insulation	R-11	R-11	0.0	R-11	R-19	2.5	R-11	R-19	2.5
	crawlspace insulation	R-11	R-19	2.5	R-11	R-22	3.2	R-7	R-19	3.9
	slab insulation	R-0	R-0		R-0	R-0		R-0	R-0	
	base. wall insulation	NA	NA		NA	NA		NA	NA	
	base. floor insulation	NA	NA		NA	NA		NA	NA	
	heating efficiency	AFUE 78%	AFUE 78%		AFUE 78%	AFUE 90%		AFUE 78%	AFUE 90%	
	cooling efficiency	SEER 10	SEER 10		SEER 10	SEER 10		SEER 10	SEER 10	
Oil	glazing type	NA	NA		Dbl TB	Dbl Low-E		Dbl w/o TB	Dbl Low-E	
	infiltration				normal	normal		normal	normal	
	ceiling insulation				R-19	R-30	4.4	R-14	R-19	2.0
	wall insulation				R-11	R-19	2.5	R-11	R-11	0.0
	crawlspace insulation				R-11	R-28	5.0	R-7	R-19	3.9
	slab insulation				R-0	R-0		R-0	R-0	
	base. wall insulation				NA	NA		NA	NA	
	base. floor insulation				NA	NA		NA	NA	
	heating efficiency				AFUE 78%	AFUE 78%		AFUE 78%	AFUE 90%	
	cooling efficiency				SEER 10	SEER 10		SEER 10	SEER 10	

(a) Rhode Island has adopted a new, fuel-specific energy code that went into effect on October 1, 1988. Baseline codes included in this study, however, reflect the code in place in March 1988, which was not fuel specific.

TABLE A.7 (Cont.)

		Base Line Pasadena	Ares Pasadena	Change In Insulation (inches) FG Sheath
Gas	glazing type	S w/o TB	S w/o TB	
	infiltration	normal	normal	
	ceiling insulation	R-19	R-11	-3.2
	wall insulation	R-7	R-11	1.4
	crawlspace insulation	R-7	R-11	1.4
	slab insulation	R-0	R-0	
	base. wall insulation	NA	NA	
	base. floor insulation	NA	NA	
	heating efficiency	AFUE-78%	AFUE 78%	
	cooling efficiency	SEER-10	SEER 10	
Electric Forced Air	glazing type	S w/o TB	S w/o TB	
	infiltration	normal	normal	
	ceiling insulation	R-19	R-19	-0.0
	wall insulation	R-7	R-19	3.9
	crawlspace insulation	R-7	R-11	3.9
	slab insulation	R-0	R-0	
	base. wall insulation	NA	NA	
	base. floor insulation	NA	NA	
	heating efficiency			
	cooling efficiency	SEER-10	SEER 10	
Electric Heat Pump	glazing type	S w/o TB	Dbl w/o TB	
	infiltration	normal	normal	
	ceiling insulation	R-19	R-19	-0.0
	wall insulation	R-7	R-11	1.4
	crawlspace insulation	R-7	R-19	3.9
	slab insulation	R-0	R-0	
	base. wall insulation	NA	NA	
	base. floor insulation	NA	NA	
	heating efficiency	AFUE-78%	AFUE 78%	
	cooling efficiency	SEER-10	SEER 10	
Oil	glazing type	NA	NA	
	infiltration			
	ceiling insulation			
	wall insulation			
	crawlspace insulation			
	slab insulation			
	base. wall insulation			
	base. floor insulation			
	heating efficiency			
	cooling efficiency			

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APPENDIX B

DEVELOPMENT OF THE BASELINE CASE STUDY RESIDENCES

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DEVELOPMENT OF THE BASELINE CASE STUDY RESIDENCES

Levels of energy conservation measures (ECMs) in new homes vary widely across the United States, as a result of local codes, climate, building practices, energy prices, and the extent of consumer awareness. Because of this variation, it was inappropriate to select a single baseline level of efficiency to develop estimates of environmental and economic impacts that could result from adoption and enforcement of the proposed voluntary standard.

Accordingly, a number of baseline ECM packages (at least one for each basic prototype in each study location) were developed. These packages reflect levels of ECMs that represent typical current building practices in each location. Eight of the ten study locations are in states that have mandatory state-wide energy codes. The two remaining locations are in states with model standards or guidelines that provide recommended energy efficiency levels for residences. In these states (Arizona and Texas), recommended ECM levels are mandatory only if adopted by local governments. In neither study location (Phoenix and Fort Worth) was this the case.

B.1 CURRENT ECM LEVELS IN SITE-BUILT HOMES

Factors that influence the level of ECMs currently used in new site-built housing are discussed in the following sections.

B.1.1 State Energy Codes for Site-Built Homes

By 1987, thirty-three states had adopted a mandatory energy efficiency code for residential buildings. Most other states adopted model energy codes that are enforced at the discretion of local governments. Most energy codes are based on several prominent model standards that were developed in the late 1970's and early 1980's by such organizations as The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and the Council of American Building Officials (CABO), and Building Officials and Code Administrators International, Inc. (BOCA). These parent standards tend to be technically similar to one another and to some extent are variations and updates of the original standard, ASHRAE 90-75. Energy efficiencies in these standards are usually expressed as maximum allowable overall thermal transmittance values (U_0) for major envelope components and minimum allowable thermal resistance values (R) for perimeter insulation of slabs-on-grade (NCSBCS 1985). Criteria are expressed as, or drawn from graphs based on, annual heating degree days.

Most states with mandatory codes have made some modifications to the parent standards in their adoption process. One common approach taken by states is to establish set ECM performance requirements for the entire state, using a representative value of heating degree days. In other states, several levels of performance are adopted, based on a limited number of geographic (climate) zones. These approaches are taken to avoid the problems of enforcing a code that could fluctuate substantially due to the presence of numerous micro climates. Other modifications may also be adopted, such as prescribing envelope efficiency performance on the basis of the heating fuel and appliances (and their efficiencies) selected for a new home. State energy codes are reviewed and updated from time to time. Most states have updated the code at least once since initial adoption (NCSBCS 1985).

Several states (including California, Florida, Hawaii, Louisiana, Nevada, North Carolina, Washington, Oregon and Alaska) have developed their own codes rather than adopting modified versions of the parent standards (although there frequently is a perceptible relationship to the latter). Some of these codes have sophisticated compliance mechanisms using computer software (e.g., the CALPAS program used as one compliance path in California). Almost all these codes permit compliance via a variety of paths so as not to limit design of and construction techniques for homes.

Most state and local energy codes exist in the form of performance requirements for individual components or combinations of components, with a variety of ways to demonstrate compliance. As performance codes, trade-offs among components (e.g., installing more insulation or a heat pump in order to use a higher window-to-floor area ratio) are commonly allowed and used, especially for custom homes. However, many builders prefer to use a somewhat more prescriptive approach to ECMs (i.e., set levels for each component, that, in combination, allow the home to meet code) in order to comply with energy codes. Therefore, states usually develop illustrative prescriptive compliance paths in addition to performance requirement levels as a simpler alternative means of compliance.

B.1.2 Other Factors that Influence ECM Levels in Site-Built Homes

ECM levels in new homes are also influenced by factors other than model or mandatory energy codes. Consumer awareness of the value of ECMs for reducing home energy costs has been steadily increasing since the energy crisis of the 1970's (see, for example, Hendrickson 1984; Kaiser et al. 1982 and Vines et al. 1987). This awareness has created a demand that gradually has influenced builders to construct new homes that are more energy-efficient. Consumer surveys by such organizations as the NAHB have consistently shown that energy efficiency is a factor of considerable importance among buyers' home selection criteria (Hendrickson 1984).

In some areas, building practices have also been influenced by utility demand management efforts. Programs to encourage energy efficiency in newly-constructed homes can often be justified by cost-effectiveness comparisons with traditional generation and other supply resources. In order to qualify for these programs, new homes often must use ECM levels that exceed the applicable state energy codes. These programs are generically referred to as home energy rating systems (HERS). Utilities typically support HERS programs through marketing efforts, consumer awareness campaigns and by providing advertising assistance to participating builders. Many programs now in operation also offer builders or homebuyers cash or energy credits as incentives to build homes to specific performance levels. Utilities also frequently use appliance rebates to encourage builders (and home buyers) to select high-efficiency furnaces, heat pumps, water heaters or solar systems. In a number of areas, utilities claim to have achieved high levels of penetration (40 to 60 percent) of both the single- and multi-family housing markets with their programs. (For further information on these programs see Vines et al. 1987, Callaway 1986 or Hendrickson 1986.)

The cross-influence of consumer demand, utility programs and other factors frequently lead to typical levels of efficiency in new site-built construction that exceed present state codes. This is particularly likely in states where the codes are based on the earliest model energy standards and have not been recently updated.

B.2 CURRENT ECM LEVELS IN MANUFACTURED HOMES

Energy efficiency in manufactured homes is also influenced by both mandatory requirements and consumer demand. The energy efficiency of manufactured homes (so-called mobile homes or HUD-code homes)[a] is established in a preemptive national standard promulgated by HUD. There are three levels of this standard, corresponding to three climate zones covering the United States, including Alaska. In general, these codes specify ECM performance that is considered to fall below cost-effective levels (Congressional Record H9727, November 6, 1987). HUD was directed by recent legislation to develop new, cost-effective energy standards for manufactured housing by 1989.

Consumer demand for energy-efficient housing frequently prompts manufacturers of HUD-code housing to offer many models with enhanced energy efficiency features. A recent analysis (Nesse et al. 1987) indicated that ECM levels currently used in the most popular home models exceed the existing HUD standard in many parts of the country.

B.3 DEVELOPMENT OF BASELINE CODES AND BUILDING PRACTICES

The variability introduced by existing code requirements and other factors influencing ECM levels required the use of a common approach to guide the baseline development. The approach that was selected was to identify the prevalent ECM efficiency levels in each location. These levels may be those typically used for compliance with the relevant state code or the predominant building practices used by local builders (primarily nonmandatory-code states). The information was obtained from a telephone survey of code enforcement officials

(a) Constructed in accordance with guidelines established by the U.S. Department of Housing and Urban Development (HUD).

at the state and local level, builders, architects and utility staff in each study location. This quasi-delphi approach provided estimates for ceiling, foundation and wall insulation; window area; and glazing in new homes.

In mandatory code states, the baseline ECM packages usually represent the state's prescriptive version of the its code. In three locations (Atlanta, Fort Worth and Phoenix), estimated current ECM levels also reflect utility HERS requirements, since those programs have achieved fairly high penetration levels there.

Current practice in manufactured housing for the states containing study locations was estimated from a survey conducted in the 1987 (Nesse et al. 1987). Over 80 manufacturers in 40 states were surveyed by Pacific Northwest Laboratory to identify typical levels of ECMs in their most popular single- and double-wide units. In states where there were several respondents, current practice was set at levels representing a simple average for each component.

Baseline prototype homes were modeled by using the estimates of ECM levels drawn from these sources. The results appear in Tables A.5 through A.7 in Appendix A. Estimates of the cost and energy use of these homes included an assumption (as does the proposed standard) that space conditioning appliances and hot water heaters in baseline homes would meet the mandatory national minimum requirements set by the National Appliance Efficiency Conservation Act of 1987 (NAECA).

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APPENDIX C

INDOOR AIR QUALITY ANALYSIS

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INDOOR AIR QUALITY ANALYSIS

This appendix describes the methods used to compute pollutant levels for six primary pollutants and presents information on the source and character of a number of pollutants that cannot be quantified. For these primary pollutants, information is available to allow computation of the incremental effects that design changes may have on the annual average concentrations in indoor air in residences.

C.1 APPROACH

Indoor air pollutants can be transported to or released directly into the indoor environment from outside sources, building materials, or from occupants or their activities. Considerable information is available about sources and emission rates of such pollutants as particulates, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), radon, and formaldehyde. For these six pollutants, quantitative evaluations were made using a computer model to estimate steady-state concentrations of pollutants. For many other pollutants, quantitative information is not as complete, so the estimated incremental change in pollution concentration levels attributable to building design changes were not computed. Qualitative information is provided as a guide in determining if design changes could influence the level of these pollutants.

C.1.1 Computed Pollutant Levels

Long-term average concentrations of indoor pollutants were modeled for each of the prototype residences for the baseline and for the proposed standard. Both residence ventilation rates and indoor pollutant source terms are required as inputs to the model. Three release rates for each pollutant in each case-study residence were studied: low, medium, and high. The estimates produced by the model bracket the expected range of incremental pollutant concentrations, based on available information and methodologies.

C.1.2 Nonquantified Pollutants

Hundreds of pollutants have been identified in residential indoor air. The literature was reviewed for information on these pollutants. Of particular interest is the range of chemical compound pollutants found in residential air and the sources for these pollutants, since building materials can be one of those sources. However, except for formaldehyde, little quantitative information is available on these chemicals. Even less empirical information is available about the presence and concentration of microorganisms in residences. Accordingly, no attempt was made to estimate the effect of the proposed standard on the levels of these pollutants in the home. The latter part of this appendix focuses on factors that influence the presence of chemicals and the growth of microorganisms in the residential environment.

C.2 COMPUTATION METHODOLOGY

Methods for computing indoor pollutant concentrations that provide reasonable and comparable estimates of indoor air quality across different building types and styles were screened. Those that provided the most reliable estimates without introducing unnecessary complicating factors were selected. The methods are relatively simple and are based primarily on the use of empirical emission factors that were derived from measurements of indoor air quality obtained from recent literature. The use of these factors, combined with the use of consistent ventilation rates for the case study residence's provide a suitable method for assessing incremental indoor air quality differences.

Although the computational methods selected are adequate for indoor air quality comparisons in this assessment, these methods are not necessarily sufficient for evaluating special air quality problems requiring highly sophisticated models. In general, those more detailed methods require more information on building characteristics, air-handling equipment, emissions, and ambient outdoor concentrations than were available for this study. Examples of such models can be found in documents by the U.S. Environmental Protection Agency (EPA) (1978) and the Electric Power Research Institute (1981, 1985).

C.2.1 Method Used to Evaluate Continuous Sources

Continuous sources of contaminants were computed using a simple steady-state approach. Emanation rates from soils and building materials for contaminants such as radon and formaldehyde were obtained from the literature; these rates are shown in Table C.1. Continuous rates are usually given as mass emission per time per unit of either a surface area or a mass of material.

Equations for computing pollutant concentrations at steady state are based on a completely mixed single-zone model and take the following general form (typical units are shown below in parentheses):

$$\text{Indoor Pollutant Concentration From Each Source} = \text{Average Annual Outdoor Concentration} + \left[\text{Pollutant Emanation Rate} \times \text{Mass of Emanating Material} \div \text{Fresh Air Exchange Rate} \div \text{Building Volume}\right]$$

$$(g/m^3) = (g/m^3) + [(g/kg\text{-}h) \times (kg) \div (1/h) \div (m^3)] \qquad (C.1)$$

When literature surveys indicated a range of values for emanation rates, maximum values are used to determine "worst-case" situations.

The relationship for computing concentration from a number of indoor sources for one pollutant is:

$$C = C_o + \sum_{i = 1,S} \frac{(E_i \times M_i)}{V \times I} \qquad (C.2)$$

where C = long-term average pollutant concentration (g/m^3),

C_o = average annual pollutant concentration in outdoor air (g/m^3),

i = pollutant source material

E_i = emanation rate for pollutant source material (i g/kg-h),

TABLE C.1. Pollutant Source Terms for Indoor Air Concentration Computations

Pollutant	Source	Emanation Rate or Concentration	Comments	References
Respirable Particulate Matter	Tobacco smoking	10.8 mg/cigarette	Average sidestream	NRC 1981a
	Gas stove	0.01 to 0.03 g/hr	Per burner	Girman 1981
Carbon Monoxide (CO)	Tobacco smoking	105 mg/cigarette	Average sidestream plus mainstream	NRC 1981a
	Gas stove	1.3 to 3 g/hr	Oven	Girman 1981
		0.2 to 1.8 g/hr	Per burner	Cole et al. 1983
	Respiration	8.9 mg/sec	Per person	
Carbon Dioxide (CO_2)	Tobacco smoking	143 mg/cigarette	Average sidestream plus mainstream	NRC 1981a
	Gas stove	383 to 400 g/hr	Oven	Girman 1981
		483 to 550 g/hr	Per burner	Girman 1981
Nitric Oxide (NO)	Gas stove	0.03 to 0.09 g/hr	Oven	Girman 1981
		0.13 to 0.21 g/hr	Per burner	Cole et al. 1983
	Outdoor	274 $\mu g/m^3$	1-hr maximum	
		48 $\mu g/m^3$	Annual arithmetic mean	
Nitrogen Dioxide (NO_2)	Gas stove	0.08 to 0.13 g/hr	Oven	Girman 1981
		0.07 to 0.12 g/hr	Per burner	Cole et al. 1983
Nitrogen Oxides (as NO_2)	Gas stove	0.13 to 0.27 g/hr	Oven - calculated from NO and NO_2 data	
		0.25 to 0.14 g/hr	Per burner - calculated from NO and NO_2 data	
	Tobacco smoking	0.065 mg/cigarette	Mainstream and sidestream average	NRC 1981a
Radon (^{222}RN)	Soil	0.1 to 1 pCi/m^2-sec	Nonmineralized region	Bruno 1981
	Soil	1 to 10 pCi/m^2-sec	Mineralized locality	Bruno 1981
	Soil (under concrete slab)	0.01 to 0.1 pCi/m^2-sec	Nonmineralized region	Bruno 1981
	Soil (under concrete slab)	0.1 to 1 pCi/m^2-sec	Mineralized locality	Bruno 1981
	Concrete	0.4 to 1.2 pCi/kg-hr	All areas of country	Hollowell 1981
	Brick	0.10 to 0.35 pCi/kg-hr	Includes red and adobe	Hollowell 1981
	Wood	0.02 pCi/kg-hr	Mean--western wood	Hollowell 1981
	Well water	10,000 pCi/ℓ	Average nationwide concentration	U.S. EPA 1979
	Surface water	0 to 14 pCi/ℓ	Columbia River and tributaries	Soldat 1961
Organics	Carpet	1.0 mg/h-ft^2		Miksch 1982
	New building materials	10 g/h	Nominal emission rate	Miksch 1982
Formaldehyde (HCHO)	Particle board	0.4-8.1 μg/g-day		Gupta 1982
	Plywood	0.03-9.2 μg/g-day		Gupta 1982
	Paneling	0.84-2.1 μg/g-day		Gupta 1982
	Fiberglass insulations	0.3-2.3 μg/g-day		Gupta 1982
	Clothing	0.2-4.9 μg/g-day		Gupta 1982
	Drapery	ND[a] -3.0 μg/g-day		Gupta 1982
	Paper products	0.03-0.36 μg/g-day		Gupta 1982
	Carpet	ND[a] -0.06 μg/g-day		Gupta 1982
	Tobacco smoking	1 mg/cigarette	Average	NRC 1981a
	Gas stove	25 mg/hr	Average-oven	NRC 1981a
		15 mg/hr	Average per burner	NRC 1981a NRC 1981b
Benzo-[a]-pyrene	Tobacco smoking	0.17 μg/cig.	Average respirable particulates	NRC 1981a
	Outdoor	0.1 ng/m^3	Average, rural areas - no coking areas	Moschandreas 1981

(a) ND = not detectable.

M_i = mass of emanating material for pollutant i (kg),

S = number of sources of the pollutant in the building

V = volume of building, m^3

I = the fresh air exchange rate, 1/h.

C_o is the average annual outdoor concentration, reduced by any air cleaning equipment on the intake air. The fresh air exchange rate is computed for each pollutant using

$$I = \left(\frac{T + (R \times f)}{V}\right) \quad (C.3)$$

where T = the volume of outdoor air supplied per unit time within the building, m^3/h

R = recirculation flow, m^3/h

f = average removal efficiency for filtration on recirculating air, percent (%)

V = volume of building, m^3.

Using the expressions given above, pollutant concentrations were computed for both the baseline and proposed standard cases. The increment of change in pollutant concentrations between these two cases represents the estimated effect resulting from the use of the proposed standard.

C.2.2 Method Used to Compute Particulate Matter, Carbon Dioxide, Carbon Monoxide, and Nitrogen Dioxide Concentrations

To estimate contributions of the particulate matter, CO_2, CO and NO_2 from combustion sources, the following equation is used:

$$C = C_o + \frac{(E \times t_1)}{24 \text{ h} \times I \times V} \quad (C.4)$$

where C = average daily concentration, mg/m^3

E = the constant source term emission rate, mg/h

t = the duration of that source term, h

I = the fresh air exchange rate, 1/h

V = the building volume, m^3

C_0 = average annual pollutant concentration in outdoor air, mg/m^3.

The ambient (background) concentration of these pollutants introduced into the residence may vary from location to location.

C.2.3 Method Used to Compute Radon Concentrations

Indoor radon concentrations are computed using

$$C = \frac{S + B + W}{V \times I} + C_0 \tag{C.5}$$

where C = radon concentration, pCi/ℓ

S = soil emission rate, pCi/h

B = building materials emission rate, pCi/h

W = water emission rate, pCi/h

V = building volume, ℓ

I = fresh air exchange rate, 1/h

C_0 = average annual ambient outdoor radon concentration, pCi/ℓ.

Radon emission rates in Table C.1 are used as typical values. To compute concentration levels, building characteristics, water use, and soil emission rates must be considered. The radon's emission rate from soil into a building depends primarily on the characteristics of the foundation. Table C.1 shows an order-of-magnitude drop in the soil emanation rate into the building when the soil is covered by concrete. Depressurizing the soil under the residence and venting radon directly to the outdoor environment will also reduce the amount of radon entering the residence. The general formula for computing soil emission rates into a residence is:

$$S = F \times R \times G \times 3600 \tag{C.6}$$

where S = radon emission rate, pCi/h

F = fraction of radon emanating from the soil that enters a structure[a]

R = rate of radon emanation from the source, pCi/m^2-s (see Table C.1)

G = residence base area, m^2.

Building material emission rates were computed based on flux-per-unit mass of material in the walls, floors, and ceiling. The general formula is:

$$B = p_f a_f t_f e_f + p_w a_w t_w e_w + p_c a_c t_c e_c \quad \text{(C.7)}$$

where f = floor area, m^2

w = wall area, m^2

c = ceiling area, m^2

p = densities of building material, kg/m^3

a = emission surface area, m^2

t = effective thickness of building material (1/2 actual value for exterior walls), m

e = emanation rate, pCi/kg-h.

Well water is the source of almost all of the water-derived radon. Radon levels are very low in surface water, and the radon that is released from this source is usually small compared with that from soil. The formula used for steady-state radon emission rate is: An empirically-derived constant of 0.6 is assumed for the fraction of radon in the water that is released to the indoor environment.

$$W = 0.6 \times U \times E \quad \text{(C.8)}$$

(a) F is unity (one) for residences built slab-on-grade and with unvented crawl spaces (all radon emanating from the soil is assumed to enter the indoor environment). For residences with basement or vented crawl spaces, F is less than 1 (a fraction of the radon emanating from the soil is assumed to enter the indoor environment; the remaining radon is dispersed to the atmosphere).

where W = water emission rate, pCi/h

U = the average water use per hour in the building, ℓ/h

E = radon content of water, pCi/ℓ (Table C.1).

Emanation values given in Table C.1 are only guides for computing relative changes in indoor concentration levels. In actual measurements, the radon content of well water, for example, may range over many orders of magnitude. Thus, the release rates of radon from well water must be measured at the site to provide reasonably accurate estimates. Table C.2 contains typical water-use values for certain activities for each member of a family. The use values may then be combined with the occupancy to obtain estimates of usage. For specific buildings, the usage per fixture may be used as an alternative computation approach.

Building volume is computed using the physical dimensions of the building's usable area. To estimate indoor radon concentrations, the concentrations resulting from each source alone are computed and added together and to an assumed background value.

TABLE C.2. Water-Use Fixture Rates in Residences (Golden et al. 1980)

Water-Use Activity	Fixture Rate
Water-Use Per Fixture	
Fill lavatory	2 gal/use
Fill bathtub	30 gal/use
Shower/bath	30-60 gal/use
Flush toilet	6 gal/use
Dishwasher	3 gal/load
Automatic Laundry Machine	30-50 gal/load
Average Personal Use per Family Member (includes kitchen, laundry and bath)	40 gal/day

C.2.4 Method Used to Compute Indoor Formaldehyde Concentrations

Continuous sources of formaldehyde were treated with a simple steady-state approach. Using the emanation rates presented in Table C.1, indoor formaldehyde concentrations may be estimated for the various sources with the equation:

$$C = C_o + \sum_{i=1,n} \frac{F_i \times M_i}{V \times I} + \frac{W}{V \times I} + \frac{E}{I} \qquad (C.9)$$

where C = indoor formaldehyde concentration, $\mu g/m^3$

F_i = emission factors for n groups of building and furnishings, $\mu g/kg\text{-}h$

M_i = mass of building material for ith source, kg

W = wall and ceiling insulation emission rate, $\mu g/h$

E = the sum of formaldehyde emanation rate from smoking and gas stoves, $\mu g/m^3\text{-}h$

V = the volume of the residence, m^3

I = fresh air exchange rate, 1/h

C_o = average annual outdoor formaldehyde concentration, $\mu g/m^3$.

The amount of formaldehyde released from insulation is highly variable. Although urea formaldehyde foam insulation (UFFI) is generally not used in new residential buildings, formaldehyde and organic emissions from other types of insulation and building materials that are currently used have been documented (Gupta, Ulsamer and Preuss 1982, Molhave 1982). The total organics emission rates from new building materials decrease as the materials age (Miksch, Hollowell and Schmidt 1982).

The following relationship provides a typical emission rate from insulation:

$$W = (S_w \times A_w) + (S_c + A_c) \qquad (C.10)$$

where W = typical emission rate of wall and ceiling insulation, μg/h

S_w = the formaldehyde emission rate from wall insulation, μg/m^2-h

A_w = the total insulated wall area computed from the dimensions of the buildings, m^2

S_c = the formaldehyde emission rate from ceiling insulation, μg/m^2-h

A_c = the total insulated ceiling area, m^2.

Unlike the first two categories above (building materials and UFFI) combustion sources of formaldehyde are intermittent in nature. Therefore, the approach and computational methods are also different. Indoor concentrations of formaldehyde from combustion (C in Equation C.11 below) are determined along with a corresponding average air exchange rate (I). From these values, the following relationship is derived:

$$E_i = (C_s \times I) + (C_g \times I) \qquad \text{(C.11)}$$

where E_i = derived steady-state emanation of formaldehyde, μg/m^3-h

C_s = the measured air concentrations from smoking at a known air exchange rate (I), μg/m^3

C_g = the measured concentrations from an unvented gas stove for a known air exchange rate (I), μg/m^3

I = the measured average air exchange rate, 1/h.

Table C.3 summarizes the pollutant emission values that were used to bracket possible 1AQ situations in homes (low, medium and high pollutant emission rates).

TABLE C.3. Summary of Pollutant Emission Values Used in Computing Indoor Air Quality

Pollutant	Source	Low	Medium	High	Units
Radon	Concrete	0.4	0.7	1.2	pCi/kg-h
Radon	Red brick	0.1	0.1	0.1	pCi/kg-h
Radon	Adobe brick	0.35	0.35	0.35	pCi/kg-h
Radon	Drinking water	10	100	1,000	pCi/ℓ
Radon	Wood	0.02	0.02	0.02	pCi/kg-h
Radon	Mix soil	0.1	0.32	1	pCi/m^2-s
Particulate	Tobacco sm	10.8	10.8	10.8	mg/cigarette
Particulate	Gas stove	10	17	30	mg/burner-h
Formaldehyde	Tobacco sm	1	1	1	mgcigarette
Formaldehyde	Gas oven	25	25	25	mg/oven-h
Formaldehyde	Gas stove	15	15	15	mg/burner-h
Formaldehyde	Plywood	0.03	0.5	9.2	μg/g-day
Formaldehyde	Particle board	0.4	1.8	8.1	μg/g-day
Formaldehyde	Fiberglass	0.3	0.8	2.3	μg/g-day
Formaldehyde	Carpet	0	0	0.06	μg/g-day
CO	Tobacco sm	86	86	86	mg/cigarette
CO	Gas oven	1,300	2,000	3,000	mg/oven-h
CO	Gas stove	200	1,000	1,800	mg/burner-h
CO_2	Tobacco sm	80	80	80	mg/cigarette
CO_2	Gas oven	383,000	391,000	400,000	mg/oven-h
CO_2	Gas stove	483,000	515,000	550,000	mg/burner-h
CO_2	Respiration	8.91	8.91	8.91	mg/person-s
NO_2	Gas oven	80	105	130	mg/oven-h
NO_2	Gas stove	70	95	120	mg/burner-h
NO_2	Tobacco sm	0.065	0.065	0.065	mg/cigarette

C.2.5 Fresh Air Ventilation

The exchange of outside air and indoor air is measured in air changes per hour (ACH). The measure of the air exchange rate of a structure is based on the infiltration of fresh outdoor air expressed in units of volume of air/time. Therefore:

$$ACH = \frac{\text{Infiltration Rate, m}^3\text{/hr}}{\text{Building Volume, m}^3} \qquad (C.12)$$

The principal means of exchanging indoor and outdoor air is through air entering and leaving the envelope of the residence through the naturally occurring cracks and openings. The principal determinants of a building's natural infiltration rate (or air exchange rate) are the amount of cracks and other openings in a building's envelope combined with the temperature differential between indoor and outdoor air, and wind speed that cause the outside air to be exchanged with the inside air.

Other factors influence the air exchange rate including opening windows and doors, use of bath and kitchen ventilation fans, use of a clothes dryer and wood burning. Under special conditions of very low naturally-occurring infiltration rates, mechanical ventilation systems can be incorporated into the design of residential structures to increase the air exchange rate. These include air-to-air heat exchangers and whole-house exhaust-only systems.

C.2.5.1 Air Exchange Rates

The correlation of residential air exchange rate with construction practices and weather and climate parameters is not well understood. Proposed models of air infiltration recognize three independent mechanisms driving air infiltration: 1) the temperature difference between indoors and outdoors causes a pressure differential in the building because of the buoyancy effects (as air is heated it rises and exits pulling cold air into the building from the lower levels); 2) wind incident upon a building also creates a pressure differential across the building envelope; and 3) occupant behavior such as opening of doors and windows also contributes to infiltration. The two driving forces related to induced-pressure differential should, in theory, result in infiltration rates that are proportional to the leakage area in the building envelope. Leakage areas are difficult to measure directly and are typically inferred from pressurization tests.

A study by Grimsrud, Sherman and Sondregger (1982) summarized annual infiltration rates for over 300 houses with published data in the literature. This sample is biased towards recently constructed, energy-efficient homes. A mean infiltration rate of 0.63 ACH and a median rate of 0.50 ACH were found for the sample.

A study by W. S. Fleming and Associates (Nitschke 1985) of the infiltration rate in 60 houses in New York showed a mean of 0.26 ACH for tracer measurements covering an entire year in the sample. The sample was biased toward homes less than 5 years old.

Measurements in over 200 homes in the Pacific Northwest region built since 1984 show a mean air exchange rate of 0.45 ACH for single family housing (BPA 1988), 0.30 for multifamily housing and 0.41 for manufactured housing.

The average infiltration rates for the surveyed homes in various locations do not exhibit any logical relation to the climatic driving forces. In many cases the average rates in milder, less windy climates are higher than those in colder, windier climates. This would suggest that construction practices, rather than climate, are a major determinant of the air exchange rate of new homes. It may be that construction is tighter, on average, in colder climates. Occupancy also affects the air exchange rate in a home. ASHRAE (1985) suggests that occupancy contributes approximately 0.10 to 0.15 ACH to the total measured air exchange rate.

C.2.5.2 Air Exchange Rates Used to Analyze the Proposed Voluntary Standard

The proposed voluntary standard provides two alternative air change rates (these actually are specifications of the tightness of the construction). The "normal" package specifies a rate of 0.42 ACH excluding occupant effects. This package conforms to all requirements described in the standard development document (ASHRAE 1987). The normal air change rate is similar to the rates measured in newer homes by BPA (1988). A lower air change rate of 0.27 ACH is achieved by selecting the "tight" package in the ARES program. An additional 0.1 ACH for occupant contributions is assumed for both the normal and tight packages, bringing the ACH totals to 0.52 and 0.37 ACH, respectively. The construction requirements for the tight package are also given in the ASHRAE development document (ASHRAE 1987).

C.3 PRESENCE OF NONQUANTIFIED POLLUTANTS

Residential air contains many pollutants other than the six for which concentrations changes have been estimated. The following sections provide overview information on chemical compounds and microorganisms found in residential indoor air. The techniques and equipment for conducting research on these pollutants are still in an early stage of evolution. Therefore, for chemical or microorganism sources and emanation rates, there is not a large literature data base that can be used to accurately predict the extent to which these pollutants may exist in any one residence.

C.3.1 Chemical Compounds

Over 300 chemical compounds have been identified in residential air. Several studies have addressed the problem of quantifying the concentrations of chemical compounds in residential air, especially compounds having indoor air concentrations greater than outdoor levels. Compounds identified in five studies of residential air are shown in Table C.4. This table identifies chemical compounds found in residential indoor air, the ratio of the mean indoor concentration to the outdoor concentration, the mean and maximum indoor concentration measured during the sampling period, the location of the residences, and the number of residences evaluated. The residence number in parentheses is the total number of residences tested for that pollutant. For some residences, the pollutant concentrations were below measurable levels.

The presence of chemical compounds in residential air results from one or more of the following sources:

- infiltration of outdoor chemicals
- episodic events (i.e., cooking, cleaning)
- natural consequences of indoor living (respiration, perspiration)
- outgassing from household appliances and building materials.

TABLE C.4. Chemical Compounds Found in Residential Indoor Air[a]

Selected Chemical Compound	Indoor-to-Outdoor Ratio	Pollutant Concentration Level: Mean ($\mu g/m^3$)	Pollutant Concentration Level: Maximum ($\mu g/m^3$)	Location of Evaluated Residence	Number of Residences[b]
Acetaldehyde	4.9	16	48	Northern Italy	15
Butanol	2.3	15	34	Northern Italy	3(15)
Hexanol	5	12	20	Northern Italy	3(15)
Nonanol	5	11	17	Northern Italy	3(15)
Acetone	4	40	157	Northern Italy	15
Butanone-2	2.7	17	38	Northern Italy	9(15)
Trichlorofluoromethane	10	45	230	Northern Italy	9
Bromodichloromethane	1.1	0.55	9	Greensboro, NC	20
Dichloromethane	58	1290	5000	Northern Italy	7(8)
Dichloroethylene	1.5	0.015	0.062	Baton Rouge, LA	27
	1.00	0.025	0.025	Greensboro, NC	20
1,2-Dichloroethane	1.64	3.6	69	Baton Rouge, LA	27
	1.00	0.025	15	Greensboro, NC	20
	0.89	0.04	4.74	Houston, TX	11
1,2-Dichloropropane	2.00	0.01	2.1	Baton Rouge, LA	27
	1.00	0.025	45	Greensboro, NC	20
Chloroform	28.2	3.67	26	Greensboro, NC	20
	4.1	2.9	215	New Jersey	355
	2.17	7.6	47	Houston, TX	11
	2	8.5	15	Northern Italy	5(14)
	1.6	0.008	6.4	Baton Rouge, LA	27
1,1,1 Trichloroethane	7.84	20	31	Northern Italy	11
	3.7	15.6	880	New Jersey	355
	3.5	6.22	155	Greensboro, NC	20
	3.3	22	60	Baton Rouge, LA	15
	2.48	1.5	243	Houston, TX	27
Carbon Tetrachloride	7.0	1.4	14	New Jersey	355
	4.14	0.17	13	Greensboro, NC	20
	1.3	6.9	12	Northern Italy	15
	0.70	1.30	3.75	Houston, TX	11
	0.5	0.75	17	Baton Rouge, LA	27
Trichloroethylene	5	0.075	6.35	Baton Rouge, LA	27
	3.84	0.096	2	Greensboro, NC	20
	2.6	19	86	Northern Italy	15
	1.5	2.0	47	New Jersey	355
	1.5	0.86	1.30	Houston, TX	11
Tetrachloroethylene	26.7	0.40	69	Baton Rouge, LA	27
	2.2	5.6	250	New Jersey	355
	2.01	1.62	28	Greensboro, NC	20
	1.8	17	47	Northern Italy	15
	1.75	2.45	34	Houston, TX	11
	1.2	4.1	205	Holland	62(134)
1,4-Dichlorobenzene	35.3	2.12	120	Baton Rouge, LA	27
	22	62	230	Northern Italy	9(15)
	12	7.2	140	Holland	45
	9.82	5.52	20.6	Houston, TX	11
	3.5	2.8	915	New Jersey	355
	1.02	0.09	60	Greensboro, NC	20

TABLE C.4. (contd)

Selected Chemical Compound	Indoor-to-Outdoor Ratio	Pollutant Concentration Level: Mean ($\mu g/m^3$)	Pollutant Concentration Level: Maximum ($\mu g/m^3$)	Location of Evaluated Residence	Number of Residences[b]
n-Hexane	21.9	7.3	107	Holland	134
	10	81	590	Northern Italy	13
n-Heptane	2.8	5.3	68	Holland	134
	2.1	19	76	Northern Italy	13
n-Octane	6.5	5.2	60	Holland	134
	4.3	21	65	Northern Italy	12(13)
n-Nonane	16	18	270	Dutch	133(134)
	9.2	30	165	Northern Italy	10(13)
n-Decane	19	31	430	Holland	133(134)
	5	25	1100	Northern Italy	13
n-Undecane	16	13	190	Holland	129(134)
	7.5	93	950	Northern Italy	10 (13)
n-Dodecane	15	4.5	120	Holland	129(134)
	3	11	220	Northern Italy	10
Benzene	3.9	52	204	Northern Italy	15
	1.9	13	120	New Jersey	355
	1.5	9.9	150	Holland	134
Toluene	6.2	127	378	Northern Italy	15
	3.4	55	700	Holland	134
Ethylbenzene	8.2	40	109	Northern Italy	9
	1.9	6.1	320	New Jersey	355
	1.7	5.0	45	Holland	133(134)
1,3-Xylene & 1,4-Xylene	7.9	92	390	Northern Italy	13
	2.1	21	180	Holland	134
	1.6	15.5	120	New Jersey	355
1,2-Xylene	3.0	33	132	Northern Italy	14
	1.7	5	4.6	New Jersey	355
1,2,3-Trimethylbenzene	4.6	2.3	40	Holland	129(134)
1,3,5-Trimethylbenzene	4.5	3.6	99	Holland	
	2.6	19	59	Northern Italy	9
1,2,4-Trimethylbenzene	23	14	280	Holland	133(134)
	10	46	150	Northern Italy	9
a-Pinene	21	122	605	Northern Italy	10
Limonene	54	38	216	Holland	129(134)
	40	126	480	Northern Italy	13
Napthalene	4	15	70	Northern Italy	3(9)
	3	1.0	14	Holland	56(134)
Styrene	2.6	1.8	54	New Jersey	355
Vinylidene Chloride	0.08	0.015	12	Baton Rouge, LA	27
n-Propylbenzene	3.6	1.8	27	Holland	115(134)
i-Propylbenzene	2	0.7	11	Holland	68(134)
o-Methylethylbenzene	4.9	4.4	72	Holland	129(134)
m-Methylethylbenzene	3.9	8.1	165	Holland	133(134)
p-Methylethylbenzene	4.4	4	78	Holland	125(134)
Methylcyclohexane	2.9	2.9	50	Holland	134

TABLE C.4. (contd)

Selected Chemical Compound	Indoor-to-Outdoor Ratio	Pollutant Concentration Level Mean ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	Location of Evaluated Residence	Number of Residences[b]
Dimethylcyclopentane	2.0	1.0	7.8	Holland	117(134)
3-Methylpentane	2.0	4.9	1.0	Holland	134
2-Methylpentane	2.0	4.3	54	Holland	134
3-Methylhexane	1.9	3.4	44	Holland	134
Cyclohexane	4.0	2.0	22	Holland	130(134)
n-butylbenzene	8	2.3	40	Holland	96(134)
p-Methyl-i-propylbenzene	5	1.6	32	Holland	110(134)
n-Tridecane	6	1.9	19	Holland	122(134)
n-Tetradecane	7	2.1	8	Holland	133(134)
n-Pentadecane	5	1.5	3.6	Holland	127(134)

(a) Lebret et al. 1984; Wallace et al. 1984; Hartwell et al. 1984; DeBortoli et al. 1984; Gammage et al. 1984.
(b) Numbers in parentheses are the total numbers of residences tested for that pollution; for some residences, the pollutant concentration was below measurable levels.

The following sections provide some information about each of these sources.

C.3.1.1 Infiltration

Chemical compounds can enter into the residential environment through infiltration of air coming from outside the living space. For example, ambient automobile fumes or vapors of chemicals stored in an attached garage for a long period of time can be important sources of indoor chemical pollutants. Chemical concentrations in soil can be another source; unwanted chemicals disposed of improperly in the soil can be slowly released into the indoor environment through cracks in the foundation.

C.3.1.2 Episodic Events and Household Activities

Episodic events are a major indoor source of chemical pollutants. These are events that are short-lived and involve direct injection of chemicals into the air (i.e. spraying, painting, opening containers). Chemicals can also be generated as a result of normal household activities (i.e. cooking, operating self-cleaning oven). The effect of these events on indoor air quality depends on whether the activity is normally done in a well-ventilated area. In almost all cases, adequate ventilation can be provided by operating kitchen or bathroom fans or by opening windows.

Although adequate ventilation can decrease the effects of chemicals generated from indoor episodic events, the chemicals are of concern for three reasons. First, users might not operate the ventilation devices consistently. Secondly, even trace amounts of organics that escape the ventilation system can be noxious. Finally, harmless organics can react in the indoor environment to produce irritating or harmful substances. For example, commonly used household hydrocarbons can be induced by sunlight to photochemically form aldehydes, ketones, organic acids and free radical intermediates, which cause respiratory discomfort (Meyer 1983).

Three common types of episodic events--consumer products, cooking and cigarette smoking--are discussed in more detail below.

Consumer Products. Common chemical compounds directly injected into household air include petroleum distillates, chlorinated hydrocarbons, ammonium compounds, and many others (see Table C.5). Typical sources include aerosol sprays such as deodorants, insecticides, varnishes, window cleaners, metal cleaners, wall cleaners, and pesticides. The highest exposure to chemical compounds occurs just after the initial application. Unless proper ventilation is available and used, the chemicals remain in indoor air for long periods of time, although at diluted concentrations. Many compounds applied in liquid or solid form can outgas for days because of the low vapor pressure of the chemical ingredients.

Cooking. Carcinogenic organic substances are potentially formed during the cooking of proteins, and the quantity of mutagens appears to be greatest in the smoke. Benzo(a)pyrene is a well-publicized carcinogen formed at high temperatures, but many others are formed at temperatures as low as 140°C. For example, several mutagens have been identified in beef cooked at 140°C to 190°C. As much as 99% of the mutagenic compounds were found in the vapors as opposed to the surface of the meat. The mutagens formed during the cooking of proteins are all of the same structural type (i.e., 3-ring cyclic molecules with an attached amino group on a carbon adjacent to a ring nitrogen). The

TABLE C.5. Classification of Organics Found in Homes from Consumer Products (Gosselin et al. 1984)

Compound	Source
Acetates	Adhesives
Acetone	Adhesives
Acrolein	Overheating Cooking Oils and Fats
Aniline	Paints/Varnishes
Ammonia	Household Cleaners/Disinfectants Window Sprays Plant Fertilizers
Benzene	Metal Cleaners Floor/Wall Cleaners Paint Brush Cleaners Paints/Varnishes Insecticides Adhesives Solvents
Butanol	Paint Thinners
Butyl Acetate	Paint Thinners
Camphor	Adhesives
Ethyl Acetate	Paint Thinners
Ethylene Glycol	Cosmetics
Chlorobromomethane	Fire Extinguishers
Chlorophenols	Disinfectants Toilet Bowl Cleaners Chlorine Bleaches
Dichloroethane	Dyes
Dichloroethylene	Saran Wrap Painting Inks Degreasers Adhesives
Diethylenetriamine	Adhesives
Diisocyanates	Foam Paddings
Dinitrobenzene	Polishes
Dioxane	Adhesives

TABLE C.5. (contd)

Compound	Source
Ethanol	Dyes Rubbing Alcohol Paints/Varnishes Air Freshener Hair Spray
Ethylene Glycol	Window Cleaners
Formaldehyde	Deodorizers
Gasoline	Paints/Varnishes Adhesives
Hexane	Adhesives
Isopropanol	Disinfectants Stain Removers Deodorizers
Isoamy/Acetates	Stain Removers
Kerosine	Metal Cleaners Floor/Wall Cleaners
Methanol	Stain Removers Paints/Varnishes Paint Strippers
Methylene Chloride	Aerosol Propellant Degreaser Paint/Varnish Stripper Miticides Adhesives
Mineral Spirits	Dyes Paints/Varnishes Polishes
Naptha	Floor/Wall Cleaners Cigarette Lighters
Napthalene	Deodorizers
Nitrobenzene	Dyes
Paradichlorobenzee	Deodorizers Cat Spray Dog Repellant
Pentachlorophenol	Wood Preservatives
Perchloroethylene	Spot Remover Prewash Spray

TABLE C.5. (contd)

Compound	Source
Pine Oil	Disinfectants Floor/Wall Cleaners
Polyurethane	Protective Coatings
o-Phenylphenol	Lysol
1,1,1-Trichloroethane	Polishes Drain Cleaners
Turpentine	Paints/Varnishes Polishes
Vinyl Acetate Copolymers	Hair Spray
Xylenes	Paint Removers Degreasers Lacquers Glues Cements Solvents Insecticides
Toluene	Metal Cleaners Floor/Wall Cleaners Adhesives Paint Thinners Solvents Insecticides
Trichloroethane	Cleaning Fluids Decaffeinated Coffee Metal Cleaners Dyes Lubricants Polishes
Trichloroethylene	Metal Cleaners

health effects of these compounds are mostly unknown, but exposure is easily minimized by using the kitchen ventilation system during cooking (Wishnok 1984).

Cigarette Smoking. Cigarette smoke contains many organic compounds (see Table C.6), including methane (5 mg/cig), C2-C6 hydrocarbons (2.5 mg/cig), and carbonyls (1.9 mg/cig). Suspected carcinogens include not only benzo(a)pyrene, but also dibenzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene,

TABLE C.6. Composition of Organics in Mainstream and Sidestream Smoke (National Research Council 1981b)

Characteristic or Compound	Concentration (mg/cigarette)[a] Mainstream Smoke (1)	Sidestream Smoke (2)	Concentration Ratio[b]
General Characteristics:			
Duration of smoke production, s	20	550	27.5
Tobacco burned	347	411	1.2
Particles, no. per cigarette	1.05×10^{12}	3.5×10^{12}	3.3
Particles:			
Tar (chloroform extract)	20.8	44.1	2.1
	1.2[c]	34.5[c]	3.4
Nicotie	0.92	1.69	1.8
	0.46[c]	1.27[c]	2.8
Benzo[a]pyrene	3.5×10^{-5}	1.35×10^{-4}	3.9
	4.4×10^{-5}	1.99×10^{-4}	4.5
Pyrene	1.3×10^{-4}	3.9×10^{-4}	3.0
	2.70×10^{-4}	1.011×10^{-3}	3.7
Fluoranthene	2.72×10^{-4}	1.255×10^{-3}	4.6
Benzo[a]fluorene	1.84×10^{-4}	7.51×10^{-4}	4.1
Benzo[b/c]fluorene	6.9×10^{-5}	2.51×10^{-4}	3.6
Chrysene, benz[a]anthracene	1.91×10^{-4}	1.224×10^{-3}	6.4
Benzo[b/k/j]fluoranthrene	4.9×10^{-5}	2.60×10^{-4}	5.3
Benzo[e]pyrene	2.5×10^{-5}	1.35×10^{-4}	5.4
Perylene	9.0×10^{-6}	3.9×10^{-5}	4.3
Dibenz[a,j]anthracene	1.1×10^{-5}	4.1×10^{-5}	3.7
Dibenz[a,h]anthracene, ideno-[2,3-ed]pyrene	3.1×10^{-5}	1.04×10^{-4}	3.4
Benzo[ghi]perylene	3.9×10^{-5}	9.8×10^{-5}	2.5
Anthanthrene	$2.2. \times 10^{-5}$	3.9×10^{-5}	1.8
Phenols (total)	0.228	0.603	2.6
Cadmium	1.25×10^{-4}	4.5×10^{-4}	3.6

TABLE C.6. (contd)

Characteristic or Compound	Concentration (mg/cigarette)[a] Mainstream Smoke (1)	Sidestream Smoke (2)	Concentration Ratio[b]
Gases and Vapors			
Water	7.5[d]	298[e]	39.7
Carbon monoxide	18.3	86.3	4.7
	--	72.6	--
Ammonia	0.16	7.4	46.3
Carbon dioxide	63.5	79.5	1.3
NO_x	0.014	0.051	3.6
Hydrogen cyanide	0.24	0.16	0.67
Acrolein	0.084	--	--
	--	0.825	--
Formaldehyde	--	1.44	--
Toluene	0.108	0.60	5.6
Acetone	0.578	1.45	2.5
Polonium 210, pCi	0.04-0.10	0.10-0.16	1-4

(a) Unless otherwise noted.
(b) Sidestream smoke concentration ÷ mainstream smoke concentration.
(c) Filtered cigarettes.
(d) 3.5 mg in particulate phase, rest in vapor phase.
(e) 5.5 mg in particulate phase, rest in vapor phase.

benzo(j)fluoranthene, and indeno(1,2,3-cd)pyrene. The smoker inhales the largest concentration of these contaminants; however, sidestream cigarette smoke is a major contributor to indoor pollution (Meyer 1983). Because smoking is a voluntary activity, the best mitigation strategy is to smoke in well-ventilated areas.

C.3.1.3 Natural Consequences of Indoor Living

Many chemical contaminants are associated with normal human biological processes (see Table C.7), but they also contribute to indoor air pollution. These compounds generally are eliminated by natural air exchange. Some scientists argue that chemicals emitted from the human body can be tolerated at relatively high exposures, but many scientists do not believe that external exposures can be generalized from the amount of chemicals the body generates. Since DNA repair enzymes are limited in our bodies, even our own naturally occurring organic metabolites can possibly cause cancer in much the same way that naturally occurring radiation in the body causes cancer (Environmental Science and Technology 1984).

C.3.1.4 Outgassing of Building Materials and Household Furnishings

Long-term emission of chemical contaminants from building materials and household furnishings can occur by two mechanisms. Residual solvents and agents such as catalysts, surfactants, or plastic monomers can be released slowly over time or produced slowly as a result of degradation by air oxidation, photoinitiation, or retropolymerization reactions. Contamination from these mechanisms will be greatest in homes with reduced air exchange rates.

A recent study by Molhave (1982) concluded that building materials may be the main source of many organic compounds in the indoor home environment. In

TABLE C.7. Emission Rates of Organic Bioeffluents (National Research Council 1981b)

Effluent	Emission Rate (mg/person-day)
Acetone	50.7 ± 27.3
Acetaldehyde	6.2 ± 4.5
Acetic Acid	3.6 ± 3.6
Allyl Alcohol	19.9 ± 2.3
Amyl Alcohol	21.9 ± 20.8
Butyric Acid	44.6 ± 21.5
Diethyl Ketone	20.8 ± 11.4
Ethyl Acetate	25.4 ± 4.8
Ethyl Alcohol	44.7 ± 21.5
Methyl Alcohol	74.4 ± 5.0
Phenol	9.5 ± 1.5
Toluene	7.4 ± 4.9

this study, the main sources of organic gases and vapors from building materials were products related to flooring (filler, glue, carpet). Painting and sealing agents were of minor importance.

The Molhave (1982) study measured emissions of organics from 42 commonly used building materials (see Table C.8). Over 52 different compounds were identified (see Table C.9). About 68% of the compounds were aliphatic or aromatic hydrocarbons, and the remainder were ketones, alcohols, esters, aldehydes, and halogenatedalcanes.

Table C.10 summarizes the measurement results for each type of building material. The emission rates in Columns 3 and 4 represent the sum for all individual contaminants detected or identified; specific concentration and emission rates were not determined for each contaminant. The average concentration for organic gases was 3.2 mg/m^3, and the average emission rate was 0.25 mg/m^2-hr. The table also categorizes the potential health effects of the compounds in the study. About 82% of the compounds were suspected irritants, 25% were suspected carcinogens, and 30% had odor thresholds below study concentrations.

The ten most commonly occurring compounds are listed in Table C.11. Also shown are the compounds found to have the highest average air concentration. Toluene, 2-xylene, and 3-xylene are found in both categories.

A recent study by Lawrence Berkeley Laboratories (LBL) (Hodgson et al. 1983) supports the conclusions of the Molhave study (1982). The LBL study also identified the contaminants from several building construction and interior-finish materials (Table C.12). These included a variety of floor, wall, and ceiling treatments, structural or insulating construction materials, and adhesives (used for bonding carpets, vinyl floors, subfloor assemblies, and other miscellaneous applications). Sixty-eight major compounds were identified in these materials, as shown in Table C.12. The most frequently occurring compounds are footnoted. Compounds emitted by individual building construction and interior finish materials are listed by component in Table C.13, while compounds emitted by adhesives are listed in Table C.14. Many minor compounds

TABLE C.8. The 42 Materials Studied and the Classification of Their Normal Use (Molhave 1982)

No.	Type of Material	Description	Type of Material[(a)]
1	Particle board	Urea-formaldehyde glued	3
2	Particle board	Urea-formaldehyde glued	3
3	Plaster board	12 mm, paper-coated	3
4	Calcium silicate board	22.8-mm board	3
5	Sealing agent	Plastic, compound	5
6	Sealing agent	Plastic, silicone compound	5
7	Sealing agent	Putty, strips 5 x 7 mm^2	5
8	Insulation batch	Mineral wool	3
9	Particle board	Urea-formaldehyde glued	3
10	Plywood lining	Teak	3
11	Woodfiber board	12-mm board	3
12	Tightening fillet	Neoprene/polyethylene	5
13	Tightening fillet	Plasticized PVC/polyethene	5
14	Felt carpet	Synthetic fibers/plastic backing	1
15	Felt carpet	Synthetic fibers	1
16	Wallpaper	Vinyl and paper	3
17	Wallpaper	Vinyl and glass fibers	3
18	Wallpaper	Printed paper	3
19	Floor covering	Linoleum	1
20	Wall and floor glue	Water-based PVA (poly vinyl acetate)	3
21	Texture glue	Water-based PVA	1
22	Filler	PVA glue/cement	3
23	Filler	Sand, cement, water-based hardener	3
24	Wall covering	Hessian	3
25	Floor covering	Synthetic fibers/PVC (poly vinyl chloride)	1
26	Floor covering	Rubber	1
27	Wallpaper	PVC foam	3
28	Tightening fillet	Heat expanding neoprene	5
29	Fiber board	Glass fiber reinforced polyester	4
30	Paint	Acryllatex	3
31	Floor varnish	Epoxy, clear	1
32	Floor varnish	2-component, isocyanate	1
33	Floor varnish	Acid hardener	1
34	Wall covering	PVC	3
35	Laminated board	Plastic	4
36	Floor covering	Soft plastic	1
37	Insulation foam	Polystyren	3
38	Insulation foam	Polyurethane	3
39	Floor covering	Homogeneous PVC	1
40	Floor and wall covering	Textile	3
41	Floor and wall covering	Textile	3
42	Cement flag	Concrete	3

(a) 1 - floor only, 2 - floor and ceiling, 3 - walls, 4 - casing, frames, sills, 5 - sealings, putty, etc.

TABLE C.9. The 52 Compounds Identified in the Air Around 42 Common Building Materials (Molhave 1982)

Compound	Compound
Alkanes	Aromatic compounds (contd)
n-Hexane	n-Propylbenzene
n-Heptane	iso-Propylbenzene
n-Octane	1,2,3,4-Tetramethylbenzene
iso-Octane	1,3-Diethylbenzene
n-Nonane	n-Pentylbenzene
n-Decane	Benzaldehyde
n-Undecane	Styrene
n-Dodecane	Methyl styrene
3-Methylheptane	Ketones
Alkenes	2-Propanone
1-Heptene	2-Butanone
1-Octene	3 Methyl 2 buthanone
1-Nonene	4 Methyl 2 pentanone
1-Decene	2 Pentanone
Terpenes	Alcohols
α-Pinene	Ethanol
Δ-3 Carene	n-Propanol
Limonene	n-Butanol
Cyclohexanes	n-Pentanol
Ethyl methyl cyclohexane	n-Hexanol
Aromatic compounds	Esters
Toluene	Ethylacetate
2-Xylene	n-Butylacetate
3-Xylene	tert.Butylacetate
4-Xylene	tert.Butylformiate
ethylbenzene	Ethoxyethylacetate
1,2,4-Trimethylbenzene	Aldehydes
1,3,5-Trimethylbenzene	n-Pentanal
1,2-Ethylmethylbenzene	n-Hexanol
1,3-Ethylmethylbenzene	Halogenated Alkanes
1,4-Ethylmethylbenzene	1.2 Dichloroethylene

were also identified but they were not listed by Hodgson et al. (1983) because they were assumed to be of lesser importance. Emission rates have not yet been determined by LBL for the individual components because of the complexity of such a study.

The number of volatile compounds varied greatly among the building materials, but the most frequently occurring was dibutyl phthalate and 2,2,4-trimetyl-1,3-pentanedial di-i-butyrate. Toluene, styrene, and a variety of normal and cyclic alkanes were identified in the adhesives. Emission rates for

TABLE C.10. Analysis of the Air Around 42 Building Materials[(a)] (Molhave 1982)

No.	Type[(a)]	Organic Gases: Concentration (mg/m^3)	Organic Gases: Emission Rate (mg/m^2-hr)	No. of Contaminants: Detected	No. of Contaminants: Identified	Suspected Carcinogens	Airway Irritants	Odorous Compounds
1	C	1.56	0.12	29	10	5	7	2
2	C	1.73	0.13	28	11	6	7	3
3	S	0.66	0.026	17	3	3	3	1
4	S	1.69	0.064	20	5	4	3	3
5	P	169	72	35	19	3	7	4
6	P	77.9	26	23	4	1	1	2
7	P	1.38	0.34	20	0	0	0	0
8	C	0.38	0.012	13	1	1	1	1
9	C	3.56	0.14	24	7	5	6	4
10	S	1.07	0.044	16	0	0	0	0
11	S	2.96	0.12	23	7	4	5	3
12	P	0.81	0.16	19	9	4	4	3
13	P	1.05	0.056	18	0	0	0	0
14	S	3.15	0.11	24	11	3	5	1
15	S	1.95	0.080	28	8	3	5	1
16	S	0.95	0.040	21	5	2	3	2
17	S	7.18	0.30	32	12	3	7	3
18	S	0.74	0.031	12	2	1	1	0
19	S	5.19	0.22	21	6	1	3	2
20	P	1410.0	271.0	34	11	3	2	3
21	P	9.81	2.1	29	18	4	10	3
22	P	57.8	10.2	9	2	1	1	0
23	P	3.95	0.73	31	15	5	9	4
24	S	0.09	0.0054	7	1	1	0	0
25	S	1.62	0.12	12	6	3	2	2
26	S	28.4	1.4	30	7	2	3	0
27	S	5.50	0.23	25	12	1	6	1
28	P	0.35	0.016	12	2	1	1	0
29	C	0.40	0.017	6	3	2	3	0
30	S	2.00	0.43	23	5	2	3	2
31	S	5.45	1.3	42	10	3	8	2
32	S	28.9	4.7	10	8	2	4	3
33	S	3.50	0.83	10	3	0	3	0
34	S	2.43	0.10	19	5	2	4	1
35	C	<0.01	<0.0004	0	0	0	0	0
36	S	3.84	0.59	5	1	1	0	0
37	C	40.5	1.4	15	5	2	4	2
38	C	3.59	0.12	5	2	1	1	0
39	S	54.8	2.3	62	27	5	15	6
40	S	39.6	1.6	61	23	5	17	7
41	S	1.98	0.083	28	15	4	9	3
42	C	1.45	0.073	12	9	4	7	3

(a) Type of material: C = used inside the construction; S = used on surface; P = putty or sealing compound.

TABLE C.11. Ten Most Commonly Occurring Compounds and Compounds with Highest Average Air Concentration in the 42 Materials (Molhave 1982)

Compound	Average Concentration ($\mu g/m^3$)	Frequency
Most Common		
Toluene	39.7	22
n-Decane	1.49	20
1,2,4-Trimethyl benzene	0.56	18
n-Undecane	1.00	17
3-Xylene	23.0	16
2-Xylene	3.81	14
n-Propyl benzene	0.20	13
Ethyl benzene	1.79	12
n-Nonane	1.05	11
1,3,5-Trimethyl benzene	0.36	11
Highest Air Concentration		
Toluene	39.7	22
3-Xylene	23.0	16
$C_{10}H_{16}$ (Terpene)	20.8	6
n-Butylacetate	15.2	1
n-Butanol	9.4	5
n-Hexane	8.8	5
4-Xylene	7.3	8
Ethoxyethylacetate	5.9	1
n-Heptane	5.0	2
2-Xylene	3.8	14

total alkanes and toluene were determined for various adhesives and ranged from 0.6 to 60 μg/g-hr for solvent-based products and 600 to 800 μg/g-hr for water-based products.

TABLE C.12. Major Compounds Emitted by Building Construction and Interior Finish Materials (Hodgson et al. 1983)

No.	Molecular Weight	Chemical Identification
1	94	Phenol
2	104	Styrene
3[a]	106	Ethyl benzene
4[a]	106	o-Xylene
5[a]	106	m-Xylene
6	128	Naphthalene
7	134	Benzene, 1-methyl-4-(1-methylethyl)-
8[a]	136	-Pinene
9	136	Camphene
10[a]	136	Limonene
11	140	2-Nonenal
12	142	Nonanal
13	142	Napththalene, 1-methyl
14[a]	144	Butyl butyrate
15	146	2-Ethyl hexanol
16[a]	150	Thymol
17	150	Phenol, 4-(1,1-dimethylethyl)-
18	152	2-Cyclohexen-1-one, 6-methyl-3-(1-methylethyl)-
19[a]	154	-Terpineol
20	154	7-Oxabicyclo[2.2.1]heptane, 1-methyl-4-(1-methylethyl)-
21	156	Naphthalene, 1,4-dimethyl-
22	158	Benzene, 3-cyclohexen-1-yl-
23	164	Benzoic acid, 4-(1-methylethyl)-
24	170	2-Hydroxy biphenyl
25[a]	178	Benzene propanoic acid, B,B-dimethyl-
26[a]	180	Phenol, (1,1-dimethylethyl)-4-methoxy-
27[a]	182	Benzophenone
28[a]	186	1-Dodecanol
29	190	2-Phenyl octane
30[a]	192	Butanoic acid, 4-(2,5-xylyl)-
31[a]	194	Dimethyl phthalate
32	194	Benzene, 1,4-dimethoxy-2,3,5,6-tetramethyl-
33	196	1,4-Benzoquinone, 2,6-bis (1,1-dimethylethyl)-
34	196	Octyl cyclohexane
35	196	Benzene, 1,2-dimethyl, 4-benzyl-
36	198	Phenyl benzoic acid
37[a]	198	n-Tetradecane
38	210	Nonyl cyclohexane
39	210	Pentadecene
40[a]	212	n-Pentadecane
41	218	5-Phenyl decane
42[a]	222	Diethyl phthalate
43	224	Decyl cyclohexane
44	226	4-Ethyl tetradecane

TABLE C.12. (contd)

No.	Molecular Weight	Chemical Identification
45	226	2-Methyl pentadecane
46[a]	226	n-Hexadecane
47	232	5-Phenyl undecane
48	234	Phenol, 2,6-bis (1,1-dimethylethyl)-4-ethyl-
49	236	Indane, 1,1,3-trimethyl-3-phenyl-
50	238	Undecyl cyclohexane
51[a]	238	Heptadecene
52	240	2-Methyl hexadecane
53[a]	240	n-Heptadecane
54	246	Decyl xylene
55	252	Octadecene
56[a]	254	n-Octadecane
57[a]	268	Pristane
58[a]	268	n-Nonadecane
59	272	Thunbergene ($C_{20}H_{32}$ branched cycloalkene)
60[a]	278	Dibutyl phthalate
61[a]	278	Di-i-butyl phthalate
62	282	Phytane
63	282	n-Eicosane
64[a]	286	Di-i-butyrate, 2,2,4-trimethyl-1,3-pentanediol
65[a]	290	Manoyl oxide
66[a]	322	2-Butoxyethyl butyl phthalate
67	444	Cyclohexasiloxane, dodecamethyl-
68[a]	458	Hexasiloxane, tetradecamethyl-

(a) Most abundant compounds.

Because building materials and household goods are a necessary consequence of twentieth century living, the only alternative is source control to mitigate excessive emissions. Studies have shown that emissions from building materials decrease greatly as the building ages (Miksh, Hollowell and Schmidt 1982; Berglund, Johansson and Lindvall 1982). An important option to mitigating excessive emissions is allowing new buildings to "dry out" until emission rates decline to acceptable levels. Other measures include 1) testing and labeling products, 2) selecting the least emissive or harmful materials in building design, and 3) isolating unavoidable harmful products from occupants. Unfortunately, implementing some of these measures still requires considerable R&D and the combined efforts of building designers and contractors, manufacturers, and government agencies (Hodgson et al. 1983).

TABLE C.13. Compounds Emitted by Individual Building Construction and Interior Finish Material (Hodgson et al. 1983)

Sample ID	Material	Identified Compounds(a,b)
CS-1	Particle board	19, 25*, 30, 42, 53, 56, 58*, 59, 60*, 62?, 63, 65?*, [+ 11 unident.]
CS-2	Plywood	7, 8*, 9, 10*, 19*, 30*, 60, [+ 5 unident.]
CS-3	Cedar	7, 16*, 18, 20, 23, 26* (2 isomers), 32, 42-I, [+ 2 unident.]
CI-1	Fiberglass insulation	None detected
CI-2	Polyurethane foam	3*, 4*, 5*, 57*, 60*, 67, [+ 13 unident.]
IF-1A	Carpet padding	64
IF-1B	Carpet padding	27, 28?*, 37*, 40*, 43?, 53*, 56, 57, 60, 62, 64*, [+ 10 unident.]
IF-2	Carpet	11, 29, 31*, 37*, 40*, 41, 47,64*, [+ 10 unident.]
IF-3	Vinyl floor covering	15, 27*, 36, 40*, 51, 56, 64*, [+ 7 unident.]
IW-1	Vinyl floor covering	1, 27, 31*, 40, 42, 53*, 56, 57, 60*, 61*, 62, 64*, [+ 17 unident.]
IW-2a	Soft wall covering	6, 12, 13, 14*, 21?, 22, 24, 28?, 31, 34, 35, 37*, 38?, 40*, 42, 43, 44, 45?, 46, 50, 52, 53, 54, 55?, 56*, 57?, 58, 60, 64, [+ 31 unident.]
IW-2B	Soft wall covering	1, 28, 31*, 35, 37, 40, 42*, 49, 53*, 56*, 57*, 58, 60, 63, 64, [+ 13 unident.]
IW-3	Wall panel	2, 17, 31*, 33, 42, 48, 53*, 57, 60*, 64*, 66*, 68*, [+ 9 unident.]
IC-1A	Ceiling panel	40*, 46*, 57, 60, 64*, [+ 3 unident.]
IC-1B	Ceiling panel	38, 51*, 53*, 56, 60, [+ 8 unident.]

(a) Numbers correspond to the compounds listed in Table C.16.
(b) * - Most abundant compounds.
? - Identification uncertain.
I - Impurity.

TABLE C.14. Compounds Emitted by Adhesives (Hodgson et al. 1983)

Adhesive	Chemical Identifications
S-1	Toluene; styrene
S-2	Low-molecular-weight alcohols; toluene
S-3	Toluene
S-6	n-Decane; n-undecane; C_{10}-C_{11} branched alkanes (9+ compounds); C_{10} cyclohexanes (4 compounds)
S-7	Methyl cyclopentane; cyclohexane; toluene
W-1	n-Octane; n-nonane; C_8-C_9 branched alkanes (7+ compounds); methyl cyclohexane; C_8-C_9 cyclohexanes (10+ compounds)
W-2	Same compounds as W-1
W-3	Toluene; n-nonane; n-decane; n-undecane; C_{10}-C_{11} branched alkanes (9+ compounds); C_{10} cyclohexane

C.3.2 MICROORGANISMS

As far back as 1546, it was speculated that infection and contagion might be caused by invisible organisms. Louis Pasteur, a French chemist, and Robert Koch, a German physician, established the relationship between microorganisms and disease by the late nineteenth century, and in 1910, C. V. Chapin wrote a chapter entitled "Infection by Air" in his book Sources and Modes of Infections (Chapin 1910).

C.3.2.1 Airborne Microorganisms in Indoor Environments

Hundreds of articles on microorganisms as airborne pollutants have appeared in the professional journals throughout the twentieth century. The National Research Council (1981b) has a reference list of 94 journal articles for indoor air contagion and 168 references to lung diseases and allergens dating back to one in 1916, "Human Sensitisation" appearing in the Journal of Immunology (Cooke and VanderVeer 1916).

Dr. F. Marc LaForce (1984), in a presentation at the 3rd International Conference on Indoor Air Quality and Climate, August 1984, summarized the historical advance of opinions and concepts. Generally accepted concepts have been arrived at largely from landmark incidents or outbreaks. He cites, for example, an article written for the Journal of Hygiene (1959) concerning a contagion incident in a tuberculosis ward in the 1950s. Another incident noted by Dr. LaForce (1984) was the "Byrd outbreak," an unusual epidemic of tuberculosis aboard the submarine USS Richard S. Byrd in 1965-66. The outbreak was also included in the "History and Epidemiology" segment of the Airborne Contagion Conference, December 1980, chaired by Ruth B. Kundsin and published in Annals of New York Academy of Sciences (Kundsin 1980).

The Epidemic Intelligence Service at the Communicable Disease Centers--now the Centers for Disease Control (CDC)--in Atlanta, Georgia, investigated such diseases as histoplasmosis, brucellosis and inhalation anthrax in the 1950s and 1960s. The CDC's investigative study of the "Byrd outbreak" by their Environmental Health Services Division provided more information than had previously been available on the epidemiology of tuberculosis. The study also tested a generally held theory about one mode of transmission of tuberculosis--that infection was acquired from inhaling the tubercle bacillus in a droplet-nucleus which had been emitted into the atmosphere.

The significance of the "Byrd outbreak" comes from tracing the paths of infection and the role that a closed environment has on the spread of infection. The conclusion was that droplet nuclei from 2 to 10 microns were capable of being rapidly and evenly dispersed throughout a closed environment by the recirculation ventilation system. Therefore, droplet nuclei may infect others who have little or no contact with an infected individual.

There is a possibility that anyone having the tubercle bacillus organisms in their pulmonary secretions, whether that person is actively infected or is a "carrier" showing a positive tuberculin skin test with a normal chest x-ray, may transmit the infection to susceptible individuals. It is also possible that disease outbreaks or contamination can occur in resuspended particles which are deposited on surfaces such as telephones and headsets, and later are disturbed or dislodged and become airborne. The pathogens once again are introduced into the indoor air and recirculated.

Airborne pathogens present in a ventilation system can be circulated and introduced to the indoor air and subsequently become a problem as an indoor air pollutant. The ventilation process can amplify transmission of the microorganism and consequently the contamination of air. Another specific example in more recent years was the outbreak of an unknown disease at the American Legion Convention in 1976. The ventilation system in the convention hotel in Philadelphia was implicated in the transmission and contamination the disease. The Centers of Disease Control in Atlanta carried out a massive epidemiologic investigation of the mysterious respiratory illness, which in some cases was fatal and in others produced an influenza-like illness. The organism causing the illness, Legionella pneumophila, was first identified in 1977. Several Legionella epidemics since have implicated ventilation systems as sources for or modes of transmitting the pollutant.

Airborne microorganisms have thus been recognized as a factor in indoor air quality. A broad collection of algae, bacteria, fungi, protozoa, mites (arachnids), and viruses presents a complex and varied set of pollutants. They are capable of provoking toxicity, infection, and allergenic responses, dermal conditions, and membraneous irritations which defy an automatic chemical assay or neutralization.

C.3.2.2 Types of Microorganisms

The types of pollutants identified and characterized below are relevant to residential indoor environments. These microorganisms are potential air pollutants that can affect human health under selected conditions.

- Algae
  - simple plants that range in size from microscopic cells to the macroscopic seaweed that people recognize
  - species grown in presence of fresh water, salt water, soil, sand, hot water and even near-freezing habitats
  - species primarily found in the resident environment proliferate on surfaces that are wet and often dark, such as on the wall of a toilet flush tank or in an air conditioning or humidity control system

- Bacteria
  - probably the most familiar type of microorganism known to the public for causing disease and illness, such as epidemics from salmonella, and streptococcal or staphylococcal infections
  - innumerable species.
- Fungi
  - plants devoid of chlorophyll, thus unable to synthesize their own food (not all are microorganisms)
  - includes yeast and molds
  - body parts and spores of these organisms can become airborne and invade the respiratory system of occupant(s), causing illness or a dermatitis condition may result from a fungal growth on the body, i.e., on hands, in ears
  - allergenic reactions have also been identified
- Mites
  - minute four-legged insects of the arachnid class that inhabit the indoor environment, either in dust or on the dander flakes of pets and humans
  - either source can become airborne and thus be a pollutant as a respiratory agent, or as a dermal or mucus membrane irritant
- Protozoa
  - one-celled animals
  - the most familiar is the Amoeba, which is best known as a causative agent in an enteric illness known as "amoebic dysentery"
  - some inhabit fresh water, some can be parasitic, and some live in mutualistic relationships

- Viruses
  - submicroscopic, intracellular entities growing in living cells of plants or animals
  - generally require an electron microscope to be observed
  - causative agent for diseases such as measles and influenza.

C.3.2.3 Human Response to Microorganisms

Some bacterial flora is normal in and on our bodies, as well as in the atmosphere, and does not cause illness (is nonpathogenic) when in the "right place." This assemblage of microorganisms is seldom the same from one time to another, but it consists mostly of nonpathogenic organisms together with some potential pathogens (organisms capable of causing disease). This "normal flora" performs a valuable function for the body by keeping the numbers of potential pathogens at a low level by competing successfully with them for available nutrients. However, if unusual circumstances develop within the body, the flora is disturbed so that the pathogen concentration increases to a level that initiates a clinical condition; that is, the pathogenic organisms produce disease symptoms in the host. Key contributors in a microorganism becoming an indoor air pollutant are the spatial and temporal conditions combined with receptance characteristics of occupants (immunity).

Two factors are important in the incidence of a microorganism becoming a pollutant in the indoor air environment. First, some organisms are more virulent than others; that is, they "more readily enter a host and produce a diseased condition." Second, "immunity," or the state of protection that includes all the mechanisms that provide resistance to some specific disease, varies with individuals. There are two primary types of immunity: natural, or inborn, and acquired. Microorganisms become viable causative agents and thus airborne pollutants if a) circumstances develop where one or more microorganisms invade the body of a resident who is susceptible, or b) if immunity is reduced--or not even present--in an occupant who is exposed to a microorganism or simultaneously exposed to two or more of them. Allergenic responses, toxic reactions, infections, and dermal or mucous membrane irritations all are characterized by the individual response to exposure, or susceptibility, as well as the level of concentration of a pollutant. The time lapse and accumulated time of exposure, plus the location or space which harbors the pollutant, are the basic additional contributing factors.

Difficulties in sampling and getting definable, or even qualitative positive results have deterred progress in studying and analyzing pollutants. While indoor chemical pollution, along with ambient air quality, has received a great deal of public interest, efforts to fully understand, quantify and qualify the potential, indoor biological pollution have only recently been of broad interest. Harriet A. Burge, University of Michigan Medical School, states "The airborne bioflora is inherently complex and variable to a point that defies quantification" (Gammage and Kaye 1985). She observes that as many as four sampling modalities, for instance, would be necessary to accurately assess the measurable particles from a single room in a "clean" house because it may contain hundreds of different kinds of biological particles and technology does not exist to quantify all of them.

Eighty percent (80%) of the average person's time is spent indoors but because people move from one place to another, not all of that time is necessarily spent in the same indoor environment. Because of this mobility pattern, people are not only exposed to both active and potential pollutants--chemical, respirable suspended particulates (RSP), and biological (microorganisms) pollutants--but often are exposed simultaneously to more than one. The effects of simultaneous exposures are yet not really known.

C.3.2.4 Host Areas for Microorganisms

Some epidemics of illness have no secondary spread of (infection) illness from one person to another. An example of this is a building outbreak of hypersensitivity pneumonitis (humidifier fever), where the source of the etiology was a bacillus species from the humidifier. Of the 26 occupants, 7 (27%) developed the pulmonary illness (Kreiss and Hodgson 1984). The indoor residential atmosphere has the same potential for harboring or hosting pollutants that cause both the building outbreak type of illness and the secondary spread of illness from person to person.

Most severe indoor biological or microorganism pollution problems result from the growth of the offending organism on some surface within the structure. Therefore, these structures' designs should be examined for places where potential growth could be supported. The usual substrate or materials required for growth are water and a carbon source. A primary need is often a consistent source of moisture, and in some cases even a high relative humidity is sufficient. Air circulating, heating and cooling systems are prime candidates for habitats where microorganisms may proliferate. Some sources for microorganism growth are listed in Table C.15. As shown in Table C.15, some systems or places in buildings that have been known to harbor or transmit pollutants are humidifiers, water in ventilation ducts, air filters, tap water, furnace humidifiers, heating and air conditioning systems, and conversely, dust sources, where humidity would not seem to be sufficient.

C.3.2.5 Design Considerations

Parts of the air system may contribute to the spread of airborne microorganisms, some of which may be pathogenic. Particularly critical to stopping the spread of airborne pathogen by a ventilation system are keeping the filters, ducts, and on-line or free-standing humidifiers or de-humidifiers clean and functioning efficiently. Any high-humidity site, such as the reservoir in an air-to-air heat exchanger or a furnace humidity pan, is a high-potential growth area for microorganisms. If microorganisms are introduced to indoor air in any manner and find compatible conditions for growth, they can proliferate and their concentration level will increase.

Humidity control is the single most contributing component in an indoor environment to discourage, remove or lessen the basic requirement for growth of most microorganisms (Buffaloe and Ferguson 1976; Pelczar and Reid 1972). Moisture is generated in residences by people, plants, and cooking. A family of 4 can generate as much as 5 gallons of moisture in a day (The Energy Business Association of Washington 1984). The new housing designs often do not specifically address humidity control.

TABLE C.15. Building-Related Microorganism Outbreaks (Walsh, Dudney and Copenhaver 1984)

Source	Etiology	Remedial Measures and Comments	Author
Ceiling dust	Amoebae, other organisms	Modified humidifier; water run to waste; replaced ceiling; discarded carpet; moved office workers to new building; no recurrence in 24 months	Edwards 1980; Edwards, Griffiths and Mullins 1976
Water in ventilation ductwork	Thermophilic actinomyces	Cleaned ductwork	Hales and Rubin 1979
Contaminated air filters	Amoebae	Closed school and dispersed staff to other schools; in 1 mo. 1/3 were well, 2/3 improved	Baxter 1982
Tap water	Undetermined	Removed humidifier	Miller et al. 1976
Furnace humidifier	Micropolyspora faeni	Removed furnace and humidifier	Fink et al. 1971[a]
Furnace humidifier	Thermophilic actinomyces	Removed humidifier	Sweet et al. 1971[a]
Heating or air conditioning systems	Thermophilic actinomyces	Moved from contaminated environment or removed contaminated appliance	Fink et al. 1976[a]
Humidifier, air conditioner, or tap water source	Cephalosporium in 1 case; undocumented in 5 cases	Removed humidifier or air conditioner	Patterson et al. 1978[a]

(a) Although these are documented from nonresidential buildings, they are systems common to the newly designed housing.

Other areas of a building are also important considerations for controlling microorganisms in residential indoor air. For example, microorganisms around the foundation of a house and in the intrawall space can be sources of indoor pollution. Concrete slab-type foundations are well suited to control the transfer of molds into the living area (Pfeiffer 1980).

Each house has a breathing process--movement of air into a house, out of the house, and through the house walls--that occurs by means other than the usual heating and air-conditioning systems and window and door systems. The intrawalls can harbor dust that is allergenic, and a mold that is unseen can grow and disseminate spores into the living area via the passing air currents within the walls and vents, electrical outlets, etc. These may become a health hazard or an irritant to the hypersensitive resident.

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APPENDIX D

HEALTH IMPACTS OF SELECTED AIR POLLUTANTS

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In this appendix the health impacts of the six residential indoor air pollutants that have been the most thoroughly studied for their impacts on human health are discussed: particulate matter, carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde, and radon.

D.1. PARTICULATE MATTER

This section discusses the population groups sensitive to particulate matter, the short-term and long-term effects of the pollutant, and the recommended outdoor standard for particulate matter.

D.1.1 Sensitive Population Groups

One of the major considerations for setting air quality standards is the protection of sensitive population groups, who are most likely to be affected by indoor air pollutants. Table D.1 summarizes various sensitive population subgroups, and also provides the rationale and supporting evidence on health effects of particulate matter. Studies based on lower levels of community exposures and other sources suggest that some segments of the population may be at higher-than-average risk. These include children, asthmatics, smokers, obligatory mouth breathers and persons with pneumoconiosis or influenza. Because much individual variation exists among subgroups, at any given level of particulate matter, children may note only symptomatic irritation, while members of other subgroups or others in the subgroup may suffer deterioration of respiratory function.

Results from the U.S. National Health Interview Survey for 1970 indicate that chronic respiratory disease comprises 10% of all conditions causing disability of one week or more [U.S. Department of Health, Education and Welfare (DHEW) 1973]. In 1970, there were about 6.5 million chronic bronchitics, 6.0 million asthmatics, 1.3 million individuals with emphysema and about

TABLE D.1. Sensitive Population Subgroups to Particulates (EPA 1982)

Subgroup	Population Estimates	Rationale (or Criteria)	Observational/Associations Supporting Increased Sensitivity
Individuals with chronic obstructive pulmonary diseases . Bronchitis . Bronchiectasis . Emphysema	7,800,000 (DHEW, 1973)	-Mucus hypersecretion and blocked airways may predispose individuals to bronchospasm -Enlarged airspaces increase blood flow resistance through the pulmonary capillary network, increasing cardiac stress	Many of the deaths and illnesses during and after air pollution episodes were among people with pre-existing obstructive diseases (Ministry of Health, 1954; Martin, 1964; Lawther et al., 1970; Martin and Bradley, 1960)
Individuals with cardiovascular disease	16,100,000 (DOC, 1980)	-Enhanced sensitivity to difficulties in breathing	Many deaths and hospitalizations during pollution episodes among cardiovascular patients (Ministry of Health, U.K., 1954; Martin, 1964)
Individuals with influenza	Unknown	-Increased sensitivity of respiratory epithelium (Utell et al., 1980)	Influenza patients were more sensitive to $NaNO_3$ during their period of sickness (Utell et al., 1980). Highest mortality during influenza epidemic on days with highest PM. (Martin and Bradley, 1960).
Asthmatics	6,000,000 (DHEW, 1973)	-Hyperreactive airways (Boushey et al., 1980)	Sulfuric acid enhanced response to bronchoconstrictive agent in asthmatics, not in normals (Utell et al., 1981)
Elderly	24,658,000 >65 years old (DOC, 1980)	-Reduced lung elasticity (Cotes, 1979) -Immunologically deficient	-Many of the deaths and illnesses during air pollution episodes were among elderly (Ministry of Health, 1954; Martin and Bradley, 1960; Greenburg et al., 1962).
Children	46,300,00 >14 years old (DOC, 1980)	-Immunological immaturity implies diminished protection (Eisen, 1976) -Childhood respiratory infection might prevent the lungs from reaching their full size at maturity (Bouhuys, 1977; Speizer et al., 1980) -Children likely to spend a greater amount of time outdoors and to be more active. Probably higher ventilation rates and thus, increased inhalation of pollutants.	-Increased acute respiratory disease with high particles, SO_x (Lebowitz et al. , 1972; Douglas and Waller, 1966) -Effects of acute respiratory disease acquired during childhood persisted until adolescence or young adulthood (Colley et al. , 1973; Kiernan et al. , 1976).
Smokers	50,000,000 (DHEW, 1977)	-Urban lung cancer in smokers greater (Doll, 1978) -Combinations of PM and carcinogens may enhance response -Increased tracheobronchial deposition (Albert et al. , 1973)	-Frequency of respiratory symptoms and diseases greater in smokers exposed to same occupational or community pollution as non-smokers (Lambert and Reid, 1970; NIOSH, 1976).
Mouth or oronasal breathers	15% of population (Niinimaa et al. , 1981; Saibene et al. , 1978)	-Increased particle penetration (CD, p. 11-20)	

10 million adults with heart disease severe enough to limit activity (DHEW 1973). These are rough estimates since some surveys have reported higher figures depending on age, sex, and the definition of disease that is used. Limited physiological studies suggest that about 15% of the population are habitual mouth or oronasal breathers (Saibene et al. 1978; Niinimaa et al. 1981). (Anyone may temporarily switch to mouth breathing during exercise, illness, or conversation.)

Although there are about 50 million smokers, the number of people at a higher-than-expected risk because of smoking may also include children living with smokers, and ex-smokers (DHEW 1977). In addition, some workers who are occupationally exposed to dusts might become more susceptible to residential particulate pollution, even if they are not classified as having respiratory disease. The more sensitive individuals, however, often do not remain in such environments (Morgan 1978).

D.1.2 Short-Term Impacts

Based on evaluation of epidemiological studies on particulate matter, the Environmental Protection Agency (EPA) (1982) presented its assessment of concentration levels at which short-term health effects might be expected (Table D.2). The lowest pollutant levels of interest in the short-term studies

TABLE D.2. Staff Assessment of Short-Term Epidemiological Studies (EPA 1982)

	Measured British Smoke Levels ($\mu g/m^3$)			Equivalent TP[a] Levels ($\mu g/m^3$)
Effects/ Study	Daily Mortality in London[b]	Aggravation of Bronchitis[c]	Combined Range	Combined Range[d]
Effects Likely	500-1000	250*-500*	250-500	360-600
Effects Possible	150*-500	<250*	150-250	150-350

* Indicates levels used for upper or lower bound of range.
(a) TP: thoracic particles less than a nominal 10 μm.
(b) Martin and Bradley 1960; Ware et al. 1981; Mazumdar, Schimmel and Higgins 1981.
(c) Lawther, Waller and Henderson 1970.
(d) Boundary assumptions for estimating TP levels from British smoke readings detailed in EPA (1982).

were 150 to 500 $\mu g/m^3$ (British smoke) and 150 to 500 $\mu g/m^3$ (SO_2) (based on mortality studies), and 250 $\mu g/m^3$ (British smoke) and 500 $\mu g/m^3$ SO_2 (based on the bronchitic studies). On particles EPA staff made the conservative assumption that similar responses might have occurred without substantial amounts of SO_2 present (EPA 1982).

D.1.3 Long-Term Impacts

Table D.3 is an EPA staff assessment of the levels of interest derived from the most useful long-term epidemiological studies (EPA 1982). Based on their assessment, levels of interest for effects measured in these studies are as follows: 1) decreased lung function and increased acute respiratory disease in children may occur at levels below 230 $\mu g/m^3$ British smoke (Lunn, Knowelden and Handyside 1967); 2) decreased lung function in adults may occur at TSP levels as low as 140 to 180 $\mu g/m^3$ (Bouhuys, Beck and Schoenberg 1978); and 3) some risk of increased respiratory disease and/or symptoms in adults may exist at levels of 110 to 180 $\mu g/m^3$ TSP (Bouhuys, Beck and Schoenberg 1978; Ferris et al. 1973).

D.1.4 Recommended Outdoor Standard for Particulate Matter

Selecting a level with an adequate margin of safety for a standard for particulate matter will involve several uncertainties in addition to those involved in making judgments on health risks associated with other pollutants such as CO and SO_2. Epidemiological studies are generally subject to several inherent difficulties involving confounding variables and somewhat limited sensitivity. Most studies have used British smoke [a pseudo mass indicator related to small particle (<4.5 μm darkness)] or total suspended particulates (TSP) (<25-45 μm) as particle indicators.

The current U.S. standard has been based on TSP levels measured by high-volume sampler. However, this TSP standard might have directed control efforts towards particles of lower risk to health because it included larger particles which can dominate the measured mass concentration and which are deposited only in the extrathoracic region. Thus, the EPA staff has recommended a new particle indicator representing particles capable of penetrating the thoracic regions, defined as the particle size less than a nominal <u>10 μm</u> (EPA 1982).

TABLE D.3. Staff Assessment of Long-Term Epidemiological Studies (EPA 1982)

	Measured BS Levels (as $\mu g/m^3$)	Measured TSP Levels			Equivalent TP Levels ($\mu g/m^3$)
Study/Effect	Increased Respiratory Disease, Reduced Lung Function in Children[1]	Increased Respiratory Disease Symptoms, Small Reduction in Lung Function in Adults[2]	Increased Respiratory Symptoms in Adults[3]	Combined Range	Combined Range[4]
Effects Likely	230-300 BS	180*	--	$\geq$ 180	90-110
Effects Possible	< 230 BS	130-180*	60-150 (110*)	110-180	55-110
No Significant Effects Noted	--	80*-130	--	80-110	40-55

*Indicates levels used for upper or lower bound of range.

[1]Study conducted in Sheffield, England (Lunn et al., 1967).

[2]Studies conducted in Berlin, NH (Ferris et al., 1973, 1976).

[3]Study conducted in Ansonia, CT (Bouhuys et al., 1978)

[4]Conversion assumes range of TP/TSP of 0.5 to 0.6.

As a result of the EPA staff risk assessment (EPA 1982) of epidemiological studies, the following ambient air quality standards for thoracic particles (TP) have been recommended:

24-hour standard	150-350 $\mu g/m^3$
annual standard	55-110 $\mu g/m^3$

The upper end of the above range may contain no identifiable margin of safety; however, neither the studies summarized in Tables D.1 and D.2 nor the effects in controlled human studies provide scientific support for health risks of consequences below the lower end of the above range.

D.2 CARBON MONOXIDE

On April 30, 1971, the Environmental Protection Agency promulgated national ambient air quality standards (NAAQS) for CO at levels of 9 parts per million (ppm), 8-hour average, and 35 ppm, 1-hour average, neither to be exceeded more than once per year. In July 1984, an EPA staff paper was published describing their evaluation of the key studies and scientific information on CO and their recommendation on the possible revision of the current primary and secondary NAAQS for CO. This section summarizes that EPA Staff paper (EPA 1984).

D.2.1 Sensitive Population Groups

Table D.4 briefly summarizes the rationale for the judgments that these groups are more likely to be affected by low-level CO exposures and presents population estimates for each group. For most of the groups listed in Table D.4, there is little specific experimental evidence to clearly demonstrate that they are at increased risk for CO-induced health effects. However, individuals with pre-existing illnesses or physiological conditions which limit oxygen absorption into blood or its transport to body tissues would be expected to be more susceptible to the hypoxic (i.e., oxygen starvation) effects of CO.

In the EPA staff's judgment, the available health effects' evidence still suggests that persons with angina, peripheral vascular disease, and other types

TABLE D.4. Summary of Potentially Sensitive Population Groups[a] (EPA 1984)

Group	Rationale	Population Estimates	Percent of Population	Reference
Coronary Heart Disease	Anderson et al. (1973 suggests reduced time until onset of exercise-induced angina in 2.9 - 4.5% COHb range	7.9 million (in 1979)	5.0 (of the adult population)	DHEW, 1975
. Angina Pectoris		6.3 million (in 1979)	4.0 (of the adult population)	
Chronic Obstructive Pulmonary Diseases	Reduced reserve capacities for dealing with cardiovascular stresses and already reduced oxygen supply in blood likely to hasten onset of health effects associated with CO-induced hypoxia.			DHEW, 1973
. Bronchitis		6.5 million (1970)	3.3	
. Emphysema		1.5 million (1970)	0.7	
. Asthma		6.0 million (1970)	3.0	
Fetuses and Young Infants	Several animal studies (Longo, 1977) report deleterious effects in offspring (e.g., reduced birth weight, increased newborn mortality, and lower behavioral activity levels).	3.1 million live births/year (1975)		DHEW, 1978
Pernicious and Deficiency Anemias	Oxygen-carrying capacity due deformed red blood cells is already reduced increasing likelihood of CO-induced hypoxia effects at lower CO exposure levels than for non-anemic individuals.	.15 million (1973)	0.07	
Peripheral Vascular Disease	Aronow et al. (1974) suggests reduced time until onset of exercise-induced leg pain after exposure to CO.	0.75 million (in 1979)	0.3	DHEW, 1974
Elderly	CO exposures may increase susceptibility of elderly individuals to other cardiovascular stresses due to already reduced reserve capacities to maintain adequate oxygen supply to body tissues.	24.7 million 65 years old		DOC, 1980

[a] All subgroups listed are not necessarily sensitive to CO exposure at low levels.

of cardiovascular disease are the group at greatest risk from low-level, ambient exposures to CO. This judgment is based principally on the Anderson et al. (1973) study, which indicates that individuals with angina may be affected at carboxyhemoglobin (COHb) levels ranging from 2.9% to 4.5%. In addition, while there is less confidence in the results reported in Aronow et al. (1974), that study still suggests that individuals with peripheral vascular disease may be at risk from ambient exposures to CO.

D.2.2 Reported Effects, Levels of Effects and Severity of Effects

Table D.5 summarizes key clinical studies reporting human health effects associated with low-level exposures to CO. This table is based on evidence discussed in the 1979 Criteria Document (EPA 1979) and in the Draft Addendum[a] but excludes a series of studies by Dr. Aronow (1974) because of problems that substantially limit the validity and usefulness of the Aronow studies (Horvath et al. 1983).

The lowest observed CO exposure levels that produce human health effects have been reported in studies involving individuals suffering from chronic angina pectoris. Angina pectoris, commonly referred to as angina, is a symptom of cardiovascular stress in which mild exercise or excitement can produce pressure or pain in the chest because of insufficient oxygenation of heart muscle.

D.2.3 Relationship Between CO Exposure and COHb Levels

The health effect studies discussed above report the effects observed at varying COHb levels. To set ambient CO standards based on these studies, the ambient concentrations of CO that are likely to result in COHb levels at or near those observed in the studies must be estimated. A model known as the Coburn equation (Coburn, Forster and Kane 1965) has been developed to estimate COHb levels resulting from CO concentrations as a function of time and various physiological factors (e.g., blood volume, endogenous CO production rate).

(a) EPA. 1983 (draft). "Revised Evaluation of Health Effects Associated with Carbon Monoxide Exposure: An Addendum to the 1979 EPA Air Quality Criteria Document for Carbon Monoxide." Research Triangle Park, North Carolina.

TABLE D.5. Lowest Observed Effect Levels for Human Health Effects Associated with Low-Level Carbon Monoxide Exposure (EPA 1984)

Effects	COHb concentration (Percent)	References
Statistically significant decreased (~3 - 7Δ) work time to exhaustion in exercising young healthy men	2.3 - 4.3	Horvath et al., 1975 Drinkwater et al., 1974 Raven et al., 1974
Statistically significant decreased exercise capacity (i.e., shortened duration of exercise before onset of pain) in patients with angina pectoris and increased duration of angina attacks	2.9 - 4.5	Anderson et al., 1973
Statistically significant decreased maximal oxygen consumption and exercise time during strenuous exercise in young healthy men	5 - 5.5	Klein et al., 1980 Stewart et al., 1978 Weiser et al., 1980
No statistically significant vigilance decrements after exposure to CO	Below 5	Haider et al., 1976 Winneke, 1973 Christensen et al., 1977 Benignus et al., 1977 Putz et al., 1976
Statistically significant impairment of vigilance tasks in healthy experimental subjects	5 - 7.6	Horvath et al., 1971 Groll-Knapp et al., 1972 Fodor and Winneke, 1972 Putz et al., 1976
Statistically significant diminution of visual perception, manual dexterity, ability to learn, or performance in complex sensorimotor tasks (such as driving)	5 - 17	Bender, et al., 1971 Schulte, 1973 O'Donnell et al., 1971 McFarland et al., 1944 McFarland, 1973 Putz et al., 1976 Salvatore, 1974 Wright et al., 1973 Rockwell and Weir, 1975 Rummo and Sarlanis, 1974 Putz et al., 1979 Putz, 1979
Statistically significant decreased maximal oxygen consumption during strenuous exercise in young healthy men	7 20	Ekblom and Huot, 1972 Pirnay et al., 1971 Vogel and Gleser, 1972

[a]The physiologic norm (i.e., COHb levels resulting from the normal catabolism of hemoglobin and other heme-containing materials) has been estimated to be in the range of 0.3 to 0.7 percent (Coburn et al., 1963).

Table D.6 presents baseline estimates (a typical set of physiological parameters was used) of COHb levels expected to be reached by nonsmokers exposed to various constant concentrations of CO for either 1 or 8 hours, based on the Coburn model. The estimates are based on variations in physiological parameters upon exposure to different patterns of CO levels which just meet a given CO standard. The estimates given in Table D.7 and others contained in a sensitivity analysis report of the Coburn Model (Biller and Richmond 1982) are based on the assumption that the entire adult population is exposed to CO levels just meeting a given standard.

The impact of fluctuating air quality levels on COHb uptake can be roughly estimated by comparing the result of a constant 9 ppm exposure for 8 hours (1.4% COHb from Table D.6) with a "typical" (50th percentile) adult exposed to several different air quality patterns that result in the same maximum 8-hour dose (i.e., 9 ppm, 8-hour average). The various patterns examined in the Sensitivity Analysis indicate that COHb levels ranging from 1.4% to 1.9% (from Table D.7) can be reached for the "typical" adult exposed to air quality reaching a 9 ppm, 8-hour average (Biller and Richmond 1982). A similar comparison of the results for air quality with a 12 ppm, 8-hour average peak exposure indicates that the impact of fluctuating CO levels can increase the peak COHb value by up to 0.5% to 0.6% COHb.

The Sensitivity Analysis results in Table D.7 also illustrate the effect of using distributions for each physiological parameter rather than just a representative set of physiological parameters in applying the Coburn model. For any given air quality pattern, the effect of the distribution of physiological parameters is to generate a distribution that is fairly tight around the 50th percentile individual. For example, 95% of the population is estimated to be within ± 0.3% COHb of the median adult value after exposure to the mid-range pattern with a peak 9 ppm, 8-hour average (Biller and Richmond 1982).

D.2.4 Recommended Outdoor Standard for Carbon Monoxide

Because of the lack of negative controlled human exposure evidence concerning the impact of COHb levels below 3.0% on individuals with cardiovascular

TABLE D.6. Predicted COHb Response to Exposure to Constant CO Concentrations (EPA 1984)

Percent COHb Based on Coburn Equation[a]
Exposure Time

	1 hour exposure		8 hours exposure	
CO (ppm)	Intermittent Rest/Light Activity	Moderate Activity	Intermittent Rest/Light Activity	Moderate Activity
7.0	0.7	0.7	1.1	1.1
9.0	0.7	0.8	1.4	1.4
12.0	0.8	0.9	1.7	1.8
15.0	0.9	1.1	2.1	2.2
20.0	1.1	1.3	2.7	2.9
25.0	1.2	1.5	3.4	3.6
35.0	1.5	2.0	4.6	4.9
50.0	2.0	2.7	6.4	6.9

[a]Assumed parameters: alveolar ventilation rates = 10 liters/min (intermittent rest/light activity) and 20 liters/min (moderate activity); hemoglobin = 15 g/100 ml (normal male); altitude = sea level; initial COHb level = 0.5 percent; endogenous CO production rate = 0.007 ml/min; blood volume = 5500 ml, Haldane constant (measure of affinity of hemoglobin for CO) = 218; lung diffusivity for CO = 30 ml/min/torr.

TABLE D.7. Relationship Between Human Carboxyhemogloben and Carbon Monoxide Concentrations (EPA 1984)

Peak COHb %	9 ppm, 8-hr 1 Expected Exceedance			12 ppm, 8-hr 1 Expected Exceedance		
	Low Pattern	Midrange Pattern	High Pattern	Low Pattern	Midrange Pattern	High Pattern
3.7						0.01
3.5						0.01
3.3						0.1
3.1					0.01	0.6
2.9			0.01		0.01	2
2.7			0.02	0.01	0.2	9
2.5		0.01	0.2	0.01	2	36
2.3		0.02	2.	0.2	12	84
2.1	0.01	0.4	10	4	49	100
1.9	0.05	5	53	36	88	100
1.7	3	35	98	91	99	100
1.5	39	88	100	100	100	100
1.3	97	100	100	100	100	100
1.1	100	100	100	100	100	100

[a]COHb responses to fluctuating CO concentrations were dynamically evaluated using the Coburn model prediction of the COHb level resulting from one hour's exposure as the initial COHb level for the next hour. The series of 1-hour CO concentrations used were from 20 sets of actual air quality data. Each pattern was proportionally rolled back or up so that its peak 8-hour CO concentration equalled the level of the 8-hour standard. Of the 20 selected patterns, results from 3 patters are presented here. The low pattern tends to give the lowest peak COHb levels, the midrange pattern tends to give a midrange value, and the high pattern tends to give the highest value.

[b]Haldane constant = 218. Alveolar ventilation rate = 10 liters/min. Altitude = 0.0 ft.

[c]The estimation of distributions for each of the physiological parameters used in the Coburn model and the Monte Carlo procedure used to generate these estimates are discussed in the Sensitivity Analysis (Biller & Richmond, 1982).

disease, the margin of safety considerations and the precautionary nature of the Clean Air Act, the EPA staff (EPA 1984) is concerned that 8-hour standards at the upper end of the range 9 to 15 ppm (10 to 17 mg/m^3) would provide little or no margin of safety. Accordingly, the EPA staff (EPA 1984) recommends the following CO standards:

8-hour average: 9 to 12 ppm (10 to 14 mg/m^3)
1-hour average: 25 to 35 ppm (29 to 40 mg/m^3).

D.3 NITROGEN DIOXIDE

The national ambient air quality standard for nitrogen dioxide (NO_2) has been 100 $\mu g/m^3$ or 0.05 ppm of average concentrations since 1970. Recently, EPA's Office of Air Quality Planning and Standards has completed its scientific review of NO_2 studies and has recommended a new NO_2 standard (EPA 1982). This section summarizes their health risk assessment and recommendations.

D.3.1 Sensitive Population Groups

On the basis of the available health data, the EPA staff is focusing on children and persons with asthma, chronic bronchitis, and emphysema as the most sensitive population groups (see Table D.8). Other persons, such as those with hay fever or liver, hematological or hormonal disorders, also may be affected at low levels of NO_2. Because human experimental data are lacking for these latter groups, however, EPA staff (EPA 1982) intends to recommend to its Administrator that the potential effects on such persons should be considered only in determining the margin of safety for primary NO_2 standard(s).

D.3.2 Controlled Human Exposure Studies (NO_2 with Other Pollutants)

Controlled human exposure studies, summarized in Table D.9, provide little support for additive or greater-than-additive effects being associated with exposure to ambient concentrations of NO_2 in the presence of other pollutants such as O_3, CO, or SO_2. The principal exception is the increase in sensitivity to a bronchoconstrictor (acetylcholine) after exposure to a mixture containing NO_2, O_3, and SO_2, reported by Von Nieding et al. (1977). The EPA staff explains that Von Nieding's findings are difficult to interpret because of

TABLE D.8. Sensitive Population Groups to Nitrogen Dioxide (EPA 1982)

Sensitive Group	Supporting Evidence	References for Supporting Evidence	Population Estimates
Children	Children under age 2 exhibit increased prevalence of respiratory infection when living in homes with gas stoves. Children up to age 11 exhibited increased prevalence of respiratory infections when living in gas stove homes.	Speizer et al., 1980 Melia et al., 1979	age 0-5 17.2 million* age 5-13 36.6 million*
Asthmatics	Asthmatics reacted to lower levels of NO_2 than normal subjects in controlled human exposure studies.	Kerr et al., 1979 Orehek et al., 1976	6.0 million*
Chronic Bronchitics	Chronic bronchitics reacted to low levels of NO_2 in controlled human exposure studies.	Kerr et al., 1979 Von Nieding et al., 1971 Von Nieding et al., 1970	6.5 million*
Emphysematics	Emphysematics have significantly impaired respiratory systems. Because studies have shown that NO_2 impairs respiration by increasing airway resistance, it is reasonable to assume that emphysematics may be sensitive to NO_2.	Von Nieding et al., 1971 Beil and Ulmer, 1976 Orehek et al., 1976	1.3 million*
Persons with Tuberculosis, Pneumonia, Pleurisy, Hay Fever or Other Allergies	Studies have shown that NO_2 increases airway resistance. Persons who have or have had these conditions may be sufficiently impaired to be sensitive to low levels of NO_2.	Von Nieding et al., 1971 Beil and Ulmer, 1976 Orehek et al., 1976	unknown
Persons with Liver, Blood or Hormonal Disorders	NO_2 induces changes in liver drug metabolism, lung hormone metabolism, and blood biochemistry.	Menzel, 1980 Miller et al., 1980 Posin et al.., 1978	unknown

*1970 U.S. Bureau of Census and 1970 U.S. National Health Survey

**All subgroups listed are not necessarily sensitive to NO_2 exposure at low levels.

TABLE D.9. Effects on Pulmonary Function in Subjects Exposed to NO_2 and Other Pollutants (EPA 1982)

Concentration (ppm)	Exposure Duration	Study Population	Reported Effects	References
0.05 NO_2 + .11 SO_2 + 0.025 O_3	2-Hours	11 healthy subjects	Increased sensitivity to bronchoconstrictor as shown by increases in R_{aw}. No effect on A_2DO_2 or R_{aw} without bronchoconstrictor.	von Nieding et al., 1973
0.50 O_3; 0.50 O_3 + 0.29 NO_2; 0.50 O_3 + .29 NO_2 + 30 CO	4-Hours	4 healthy male subjects	Minimal change in pulmonary function caused by O_3 alone. Effects not caused by NO_2 or CO.	Hackney et al., 1975
0.25 O_3; 0.25 O_3 + 0.29 NO_2; 0.25 O_3 + 0.29 NO_2; + 30 CO	2-Hours	7 male subjects, some believed to be unusually reactive to irritants	Minimal change in pulmonary function caused by O_3 alone. Effects not increased by NO_2 or CO.	Hackney et al., 1975
50 CO + 5 SO_2; 4.8 NO_2 + 50 CO + 5 SO_2	-	3 subjects	Increase in dust retention from 50% to 76% after NO_2 was added to air containing SO_2 and CO.	Schlipkoter and Brockhaus, 1963
0.5 O_3; 0.5 O_3 + 0.5 NO_2 UNDER FOLLOWING CONDITIONS: 1) 25°C, 45% rh 2) 30°C, 85% rh 3) 35°C, 40% rh 4) 40°C, 50% rh	Rest-60 min. Exercise-30 min. Rest-30 min.	8 young adults	Response found only for O_3; no greater than additive effect or interaction between O_3 and NO_2 was observed.	Horvath and Folinspee, 1979

1) the uncertain health significance of altered sensitivity to bronchoconstrictors in healthy or sensitive subjects, 2) some uncertainties due to methodological differences between his techniques and those of other investigators, and 3) the lack of confirmation of the findings by other investigators. Because of these difficulties, the results of the Von Nieding study should not be used in determining the lowest concentration associated with adverse health effects. The study should be considered only as a factor in judging which standard(s) will provide an adequate margin of safety.

D.3.3 Community Epidemiology Studies

Community epidemiology studies of NO_2 are summarized in Table D.10. Because of the methodological approach (i.e., use of Jacob-Hochheiser method) with the Shy et al. (1970a, 1970b), Shy and Love (1979) and Pearlman et al. (1971) studies performed in Chattanooga, Tennessee, the health effects reported to be associated with NO_2 levels from these studies cannot be quantitatively assessed. Also, at the time of the studies, trying to sort out any health effects caused by NO_2 from effects caused by other pollutants found in the ambient air (e.g., zone, particulates, SO_2) was very difficult. These problems severely limit the usefulness of these studies for setting standards.

While the Kagawa and Toyama study (1975) shows some pulmonary function effects related to NO_2 concentrations, the results suggest that the observed respiratory effects are caused by a complex mixture of pollutants. Also, inadequate characterization of exposure to NO_2 prevents the drawing of any firm conclusions about the relationship between NO_2 exposure and resulting health effects.

At best we can only conclude that the findings of Shy et al. (1970a, 1970b), Shy and Love (1979), Pearlman et al. (1971), and Kagawa and Toyama (1975) are not inconsistent with the hypothesis that NO_2, in a complex mix with other pollutants in the ambient air, adversely affects respiratory function and may cause illness in children. That is, although these studies do not provide clear evidence for positive associations between health effects and ambient exposures to NO_2, neither do they suggest that negative or no associations

TABLE D.10. Effects of Exposure to NO_2 on Pulmonary Function in Community Epidemiology Studies (EPA 1982)

Exposure Concentrations (ppm)	Study Population	Reported Effects	References
Median hourly 0.07 NO_2 Median hourly 0.15 O_x Median hourly 0.35 NO_2 Median hourly 0.02 O_x	205 office workers in L.A. 439 office workers in San Francisco	No differences in most tests. Smokers in both cities showed greater changes in pulmonary function than non-smokers.	Linn et al., 1976
High exposure area: 24 hr high 0.055 NO_2 .035 NO_2 1-hr mean High exposure area 0.14 NO_2 to 0.30 NO_2 Low exposure area 0.06 NO_2 to 0.09 NO_2	128 traffic policemen in urban Boston and 140 patrol officers in nearby suburbs	No difference in various pulmonary function tests	Speizer and Ferris, 1973, Burgess et al., 1973
High exposure group: Estimated 1-hr max 0.25 to 0.51 NO_2 Annual mean 24-hr 0.051 NO_2 Low Exposure groups: Estimated 1 hr max 0.12 to 0.23 NO_2 Annual mean 24 hr 0.01 NO_2	Nonsmokers in L.A. (adult)	No differences found in several ventilatory measurements including spirometry and flow volume curves	Cohen et al., 1972
1 hr conc. at time of testing (1:00 p.m.) 0.02 to 0.19 NO_2	20 school age children 11 years of age	During warmer part of year, NO_2, SO_2 and TSP significantly correlated with V_{max} at 25% & 50% FVC specific airway conductance. Significant correlation between each of four pollutants (NO_2, NO, SO_2 and TSP) and V_{max} at 25% and 50% FVC; but no clear delineation of specific pollutant concentrations at which effects occur.	Kagawa and Toyama, 1975

exist between such variables. Little or no evidence of health effects at ambient concentrations of NO_2 is provided by other community epidemiological studies.

It should be recognized that the community epidemiology studies cited and discussed above did not take into account exposure to, and effects of, indoor air pollutants such as NO_2 generated by the use of gas stoves.

D.3.4 Community Studies Involving Gas Stoves

Table D.11 summarizes reported effects of exposure to NO_2 in the home in community studies involving gas stoves. In evaluating the evidence from the Melia et al. (1977), Melia, du V. Florey and Chinn (1979), and Speizer et al. (1980) studies, the major uncertainties are what agent(s) caused the reported health effects and, if those agents are NO_2, then what exposure levels and patterns (concentration, averaging time, and frequency) are associated with the reported effects. Possible confounding and covarying factors which may be related to the increased prevalence rate of respiratory illness and symptoms observed in children in homes with gas stoves include humidity, socioeconomic status, and pollutants other than NO_2, such as carbon monoxide and hydrogen cyanide, which are emitted when gas combustion occurs. However, there is no evidence that carbon monoxide or hydrogen cyanide is given off in dangerous quantities by gas stove combustion, and there is also no evidence that these pollutants cause effects such as increased respiratory symptoms or illness. The contribution, if any, to increased respiratory symptoms or illness due to increased humidity or water vapor in gas stove homes requires further research.

Other factors, such as outdoor pollution levels and exposure to parental smoking, may have contributed to the overall effect observed in the Melia et al. (1977), Melia, du V. Florey and Chinn (1979), and Speizer et al. (1980) studies. There is, however, no evidence in the studies to suggest that these factors differ for children living in homes with electric versus gas stoves.

It should be noted that, while the animal studies provide some evidence that NO_2 impairs respiratory defense mechanisms, these studies are conducted at NO_2 exposure levels believed to be considerably higher than those experienced in the gas stove homes.

TABLE D.11. Community Studies of Nitrogen Dioxide Involving Gas Stoves (EPA 1982)[a]

NO_2 Concentration (ppm)	Study Population	Reported Effects[b]	References
95th percentile of 24 hr avg in activity room 0.02 - 0.06 (gas) 0.01 - 0.05 (elec.) Frequent peaks in 1 home of 0.4 - 0.6 (gas) Maximum peak 1.0 (gas)	8,120 children, ages 6-10, 6 different cities, data also collected on history of illness before age 2	Significant association between history of serious respiratory illness before age 2 and use of gas stoves ($p \sim .01$). Also, small but statistically significant decreases in pulmonary function (FEV_1 and FVC) in children from gas stove homes.	Speizer et al., 1980
NO_2 concentrations not measured at time of study.	2,554 children from homes using gas to cook compared to 3,204 children from homes using electricity, ages 6-11	Proportion of children with one or more respiratory symptoms or disease (bronchitis, day or night cough, morning cough, cold going to chest, wheeze asthma) increased in homes with gas stoves vs. electric stove homes (for girls $p \sim 0.10$; boys not sig.) after controlling for confounding factors.	Melia et al., 1977
NO_2 concentrations not measured in some homes studied for health effects.	4827 children, ages 5-10	Higher incidence of respiratory symptoms and disease associated with gas stoves (for boys $p \sim 0.02$; girls $p \sim 0.15$ for residences in urban but not rural areas, after controlling for confounding factors.	Melia et al., 1979
Kitchens (weekly avg.): 0.005 - 0.317 (gas) 0.006 - 0.188 (elec.) Bedrooms (weekly avg.): 0.004 - 0.169 (gas) 0.003 - 0.037 (elec.)	808 children, ages 6-7	Higher incidence of respiratory illness in gas-stove homes ($p \simeq 0.10$). Prevalence not related to kitchen NO_2 levels, but increased with NO_2 levels in bedrooms of children in gas-stove homes. Lung function not related to NO_2 levels in kitchen or bedroom.	Florey et al., 1979 and Goldstein et al., 1979 (both are companion papers to Melia et al., 1979)
Sample of households 24 hr. avg: 0.005 - 0.11 (gas) 0 - 0.06 (elec.) 0.015 - 0.05 (outdoors)	128 children, ages 0-5 346 children, ages 6-10 421 children, ages 11-15	No significant difference in reported respiratory illness between homes with gas and electric stoves in children from birth to 12 years.	Mitchell et al., 1974 See also Keller et al., 1979
Sample of household same as reported above but in no new monitoring reported.	174 children under 12	No evidence that cooking mode is associated with the incidence of acute respiratory illness.	Keller et al., 1979
See above for monitoring.	Housewives cooking with gas stoves, compared to those cooking with electric stoves. 146 households.	No evidence that cooking with gas associated with an an increase in respiratory disease.	Keller et al., 1979
See above for monitoring.	Members of 441 households	No significant difference in reported respiratory illness among adults in gas vs electric cooking homes	Mitchell et al., 1974 See also Keller et al., 1979
Preliminary measurements peak hourly .25 - 0.50, max 1.0	Housewives cooking with gas stoves, compared to those cooking with electric stoves	No increased respiratory illness associated with gas stove usage.	U.S., EPA, 1976

[a] Exposures in gas stove homes were to NO_2 plus other gas combustion products.

[b] Effects reported in published references are summarized here. However, the Criteria Document warns that considerable caution should be used in drawing firm conclusions from these studies.

The authors of the Speizer et al. (1980) study have hypothesized that repeated peak values are probably the most important exposures in causing the effects observed in the gas stove homes. Their judgment is in part based on the fact that there are no intermittent short-term (1/2 hour-2 hour) NO_2 peak concentrations in electric stove homes and that long-term (24-hour or longer) concentrations in gas stove homes are not that much higher than in electric stove homes.

The daily peak 2-hour NO_2 levels observed in 3 homes monitored by Cote, Wade and Yocom (1974) provide the best, although rough, estimate of the short-term (1-2 hour) levels that may have occurred in the gas stove homes in the Speizer et al. (1980) study. It is recognized that short-term levels in particular homes in the Six-City Study may have varied considerably in magnitude or frequency of peak levels from the homes in the Cote, Wade and Yocom (1974) study due to variation in gas stove usage, ventilation conditions, and designs of homes.

D.3.5 Recommended Standard for Nitrogen Dioxide

Based on best available scientific information presented earlier, the EPA staff has made the following recommendations on the national ambient air quality standard for NO_2 (EPA 1982):

- A 1-hour average NO_2 standard could be established at some level below 0.5 ppm, or at the range of 0.15 ppm to 0.30 ppm, which would have to be met for a specified number of days in the calendar year.
- An annual standard ranging from 0.05 to 0.08 ppm is recommended as an alternative to establishing the above short-term standard.

An annual standard in the range of 0.05 to 0.08 ppm (90 to 150 $\mu g/m^3$) would appear to provide adequate protection against the potential and uncertain health effects that may be associated with exposure to short-term NO_2 levels. Such a standard could be used as a surrogate for a short-term standard. An annual standard also would provide some, although unquantifiable, protection against possible adverse health effects from long-term exposure.

The lack of scientifically demonstrated health effects in humans from NO_2 exposure in concentrations below 0.5 ppm could be interpreted to mean that there is no need for an NO_2 National Ambient Air Quality Standard. However, such an interpretation would ignore the cumulative evidence from controlled animal and human exposure studies, and community indoor studies, which strongly suggest that NO_2 may cause adverse health effects in sensitive population groups exposed to NO_2 levels at or near existing ambient levels (EPA 1982).

D.4 FORMALDEHYDE

In this section, human sensitivity to formaldehyde, its short- and long-term effects, and indoor concentrations of formaldehyde are discussed.

D.4.1 Human Sensitivity to Formaldehyde

The effects on humans of exposure to low formaldehyde concentrations partially result from formaldehyde's properties as a sensitizer and strong irritant (Gupta 1982). Controlled exposure studies have reported effects on humans at concentrations as low as 10 $\mu g/m^3$ (Schuck, Stephens and Middleton 1966). Between 10 and 70 $\mu g/m^3$, humans reach thresholds for eye irritation and odor detection, as noted in Table D.12, which lists the effects of subjects exposed to various levels of formaldehyde for various durations. Controlled experimental conditions produced statistically significant irritant responses of the eye, nose, and throat at 240 $\mu g/m^3$ and above in healthy adults (Anderson 1979; Weber-Tschop, Fischer and Grandjean 1977; and Rader 1974). Although the odor threshold for formaldehyde is reported at 60 $\mu g/m^3$ by some subjects, it is most commonly detected at 1.2 mg/m^3 (National Academy of Sciences 1981). Gupta, Ulsamer and Preuss (1982) note that repeated exposure to formaldehyde can cause certain individuals to become sensitized and to exhibit allergic dermatitis (Horsfall 1934; Pirila and Kilpio 1949; Hovding 1969) or mild to severe asthmatic reactions (Popa, Teculescu and Stanescu 1969; Alanko, Keskiner and Saarinen 1977; Hendrick and Lane 1977). These responses may increase in severity if the individuals have continued exposure to formaldehyde (Shellow and Altman 1966; Skogh 1959; Breysse 1977). These controlled studies indicated that the severity and number of subjects that respond to formaldehyde increases as the airborne concentration level increases.

TABLE D.12. Effects in Subjects Exposed to Formaldehyde

Concentration ($\mu g/m^3$)	Exposure Duration	Reported Effect	Reference
10	5 minutes	Eye irritation	Schuck, Stephens and Middleton (1966)
60-70	minutes	Odor threshold	Wahren (1980) Melekhina (1964)
80	minutes	Optical chronaxy threshold	Melekhina (1964)
100	minutes	Threshold to affect the functional state of cerebral cortex	Melekhina (1964)
240	1 hour	Eye, nose, and throat irritation	Rader (1974)
300	5 hours	Dryness of nose and throat, decrease in mucus flow rate	Anderson (1979)
1000	1 minute	Altered functional state of cerebral cortex	Feldman and Bonashevskaya (1971)
1000	10 minutes	Irritation of upper tract and eyes, accelerated breathing, EEG changes such as alpha rhythm enhancement, changes of automatic nervous system	Sgibnev (1968)
1700	1 minute	Eye sensitivity to light lowered in unacclimated group	Melekhina (1964)
5000	1 minute	Unbearable without respiratory protection	Wiley (1980)

D.4.2 Short-Term Impacts

The Consumer Product Safety Commission (CPSC) has received numerous complaints about formaldehyde concentrations in residential buildings. The CPSC reports that residential concentrations of 10 to 120 $\mu g/m^3$ have been identified as causing nausea, eye, nose and throat irritation, headaches, vomiting, and stomach cramps (Greisemer et al. 1980). The research information compiled by Gupta, Ulsamer and Preuss (1982) indicates that the human threshold for short-term exposure varies widely.

The National Academy of Sciences (NAS) concluded that there is no population threshold for the irritant effects of formaldehyde (NAS 1980). Persons sensitized to formaldehyde and persons with hyperactive airways may respond more severely (NAS 1981). The Academy has also estimated that 10% to 12% of the U.S. population may have hyperactive airways, which may make them more susceptible to the irritant effects of formaldehyde (NAS 1981).

D.4.3 Long-Term Impacts

The long-term concern over exposure to formaldehyde is based on the observation of nasal carcinogenisis in rats exposed to formaldehyde vapors (Gupta, Ulsamer and Preuss 1982). It is not clear, however, how this information relates to human risk. Gupta, Ulsamer and Preuss (1982) does conclude, as did the Federal Panel on Formaldehyde (Greisemer et al. 1980) that:

> "formaldehyde should be presumed to pose a carcinogenic risk to humans. ...that efforts should be made to reduce or eliminate human exposure to formaldehyde."

These conclusions are supported further by the deliberations of the International Agency for Research on Cancer, which concluded in October 1981 that (a) sufficient evidence indicates that formaldehyde gas is carcinogenic to rats; (b) the epidemiological studies are inadequate to assess the carcinogenicity of formaldehyde in humans; and (c) at present, formaldehyde gas should be considered, for practical purposes, as if it represented carcinogenic risk to humans (Gupta, Ulsamer and Preuss 1982).

D.4.4 Indoor Concentrations

Formaldehyde concentrations vary across a wide range of levels and are influenced by the type of residence and whether urea-formaldehyde foam insulaon (UFFI) was used as an insulation material. Neither the baseline or the proposed standard residence uses UFFI, so the values of formaldehyde concentration in residences, shown in Table D.13, are for residence, without UFFI. Table D.14 shows preliminary formaldehyde emission rates from materials found in residences as measured by the Inhalation Toxicology Research Institute (Gupta, Ulsamer and Preuss 1982). Indoor concentrations of formaldehyde can also result as a product of combustion. Table D.15 shows the average 24-hour formaldehyde contribution from gas stoves.

TABLE D.13. Formaldehyde Concentration in Residences (Gupta, Ulsamer and Preuss 1982)

Type of Residence	n	Formaldehyde Concentration ($\mu g/m^3$) Range	Average
Ambient	156	0-100	10
Homes	41	10-100	40
Mobile homes	431	10-3500	460

TABLE D.14 Formaldehyde Emission From Selected Products (Gupta, Ulsamer and Preuss 1982)

Product	Emission rate[a] ($\mu g/g$-day)
Particle board	0.4-8.1
Plywood	0.03-9.2
Paneling	0.84-2.1
Fiberglass insulations	0.3-2.3
Clothing	0.2-4.9
Drapery	ND[b]-3.0
Paper products	0.03-0.36
Carpet	ND[b]-0.06

(a) The emission range represents two or more tests, on three to five samples for each product category, using conditions closely resembling Japanese Desiccator Test.
(b) ND = not detectable.

D.5 RADON

The potential lung cancer risk from exposure to short-lived radioactive daughters of radon-222 in residential environments has become increasingly recognized. Surveys of radon daughters in residential structures have shown that radon in soil air is the primary source of indoor radon (Wilson 1984). The principal source of radon is the distribution of the radioactive elements uranium, thorium and potassium-40 in bedrock and other materials. These

TABLE D.15. Formaldehyde Contributions from Selected Combustion Sources (Hawthorne and Matthews 1985)

Source	Modeled Duty Cycle	Approximate Measured Emission Rate (mg/h)	Emission Average Over 24-h (mg/h)
Gas stove			
-burner	0.7 h/day	15	0.7
-oven	0.7 h/day	20	0.7
Kerosene heater			
-convective	8 h/day	1	0.3
-radiant	8 h/day	4	1.3
Cigarettes	10 cig/day	~1	0.6

elements occur, generally at very low concentrations, in all rock and soil types (Wilson 1984). Several important factors have been identified as controlling the level of radon gas that may accumulate in a residence. Those factors include the rate that indoor air is exchanged with outdoor air, the way the residence is coupled with the soil, the permeability of the soil layers under the residence, the radon content of the soil, and the amount of time and extent the residence is under negative pressure compared to the soil.

D.5.1 Exposure

Bale[a] and Harley (1953) were the first to note that the lung cancer hazard from exposure to radon and radon daughters was from the alpha dose delivered through lung deposition of the short-lived daughters of radon [^{218}Po(RaA), ^{214}Pb(RaB), ^{214}Bi(RaC) and ^{214}Po(Rac')] and not from the radon itself. Two alpha emitters, ^{218}Po(RaA) and ^{214}Po(RaC'), ultimately deliver the carcinogenic dose to tracheobronchial epithelium. The complexity in the dose estimates required to account for daughter deposition, radioactive buildup and decay, removal by physiological clearance processes, and physical dose calculations to specific cells in bronchial mucosa has been detailed by many authors and considered by various national and international organizations.

(a) Bale, W. F. 1951. "Hazards Associated with Radon and Thoron." Memo, March 14, 1951, Div. Biol. and Med., Atomic Energy Commission, Washington, D.C.

For more information on exposure, see Altshuler, Nelson and Kuschner 1964; Jacobi 1964, 1972, 1977; Haque 1966, 1967; Haque and Collinson 1967; Parker 1969; Walsh 1970, 1971, 1979; Harley and Pasternack 1972, 1981; Nelson et al. 1974; Fry 1977; McPherson 1979; Jacobi and Eisfeld 1980; James, Greenhalgh and Birchall 1980; James, Jacobi and Steinhausler 1981; Hofmann 1982; Wise 1982; United States Public Health Service (USPHS) 1957, 1961; Federal Radiation Council (FRC) 1967; Joint Committee on Atomic Energy (JCAE) 1967, 1969; International Commission on Radiological Protection (ICRP) 1977, 1981; United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 1972, 1977; National Institute for Occupational Safety and Health/National Institute of Environmental Health Sciences (NIOSH/NIEHS) 1971; and National Academy of Sciences (NAS) 1972, 1980.

Historically, exposure is defined in terms of the air concentration of radon daughters in units of working level (WL). A working level is defined to be a concentration of short-lived radon daughters (through RaC') totaling 1.3×10^5 MeV of potential alpha energy per liter of air. A working level month (WLM) is an equivalent exposure to 1 WL for 173 hours. These definitions avoid the problems of disequilibrium of the daughters and avoid the need to determine whether the daughters are attached to a carrier aerosol or remain unattached. Attached radon daughters deposit with some finite probability to the lung surfaces; unattached radon daughters deposit in the respiratory tract with virtual 100% probability. Thus, the mix of attached and unattached radon daughters is an important consideration in assessing lung dosimetry. The unattachment fraction values found in the workplace and in the environment are reasonably constant and not sufficiently different to cause a large disparity in the radiological dose assessment of environmental and occupational exposures to radon daughters. The same can be said for the other parameters influencing radon daughter lung dose, such as differences in daughter product equilibrium, particle size distributions, breathing patterns, bronchial morphometry, and physiologic clearance processes.

D.5.2 Lung Dosimetry Models

The more recent lung dosimetry models for radon daughters are in substantial agreement with one another and place the bronchial epithelium exposure-to-dose conversion factor at about 0.5 rad/WLM for uranium miners. The dose per unit cumulative exposure has also been derived for environmental conditions (Harley and Pasternack 1981). Close agreement was found for the adult male (0.71 rad/WLM), adult female (0.64 rad/WLM), a 10-year-old child (1.2 rad/WLM), and a 1-year-old infant (0.64 rad/WLM). The small differences primarily reflect the reduced breathing rates during normal environmental exposures, lung morphometry, particle size differences, and the increased percentage of unattached RaA in ordinary atmospheres (~7% environmental vs. ~4% in mines). These conversion factors indicate that a cumulative exposure in the environment is somewhat more effective in delivering a radiation dose than exposures under working conditions in a mine. Certain home energy conservation practices could produce exposure-to-dose conversion factors even closer to those calculated for the miners as a result of lower RaA unattachment fractions from dustier home conditions. In some treatments of modeling of risk from radon daughter exposure, a tendency to artificially lower the cumulative exposure in the environment has been evident, presumably to account for decreased breathing rates under nonworking conditions.[a]

D.5.3 Radon Daughter Epidemiology Studies

The epidemiological data derived from many types of underground mining show a relatively consistent relationship between lung cancer incidence and exposure to radon daughters in WLM. This underlying consistency is probably related to the relatively narrow range of bronchial dose per WLM. Assessing the risk of attributable lung cancer through human epidemiological studies is difficult because the detailed information required is not available. In the ideal case, the exposure of each miner as a function of time would be long enough and the followup period would be long enough for all of the group to have died from lung cancer or other causes. In addition, separating attributable lung cancers from those arising spontaneously or from cigarette smoking

(a) Environmental Protection Agency (EPA). 1980 (Draft). Draft Environmental Impact Statement (DEIS) for Remedial Action Standards for Inactive Uranium Processing Sites. EPA 52014-80-011, Environmental Protection Agency, Research Triangle Park, North Carolina.

would be possible. The cumulative exposure, person-years at risk, and the number of attributable lung cancers would allow a risk factor to be calculated exactly.

The present data do not fulfill the above requirements because exposures are only estimates and the followup periods are not long enough. Nevertheless, by recognizing the limitations of the data, we can estimate a mean risk factor based on the available epidemiological data.

Human data are now available from several groups of underground metal ore miners: the U.S., Canadian, and Czechoslovakian uranium miners; Swedish and British iron miners; Swedish lead and zinc miners; and Newfoundland fluorspar miners. Although other potential carcinogens such as diesel smoke, traces of arsenic or nickel and iron ore are found in these mines, the lung cancer response appears to be predictably based on radon daughter exposure. Some of these studies have divided the workers into subgroups on the basis of exposure. Eighteen of these subgroups were selected as being most suitable (considering both epidemiological and environmental data) for quantitative treatment of the lower exposure levels (Archer, Radford and Axelson 1979). In addition to this treatment, these mining populations have been reviewed by other authors and organizations (NIOSH/NIEHS 1971; NAS 1972, 1980; Sevc, Kunz and Placek 1976; Jorgensen 1973; Axelson and Sundell 1978; Snihs 1973, 1974; Renard 1974; DeVilliers and Windish 1964; Wright and Couves 1977; McCullough, Stocker and Makepeace 1979; UNSCEAR 1977; Evans et al. 1981; and Radford 1981a).

The data thus far suggest that an absolute threshold exposure for lung cancer induction is highly unlikely. This is consistent with current views of radiation biology and radiation protection that radiation-induced cancer is a stochastic process. Some argue that the lung cancer mortality data at the lowest reported exposures are not statistically different from expected (Evans 1967; Stranden 1980) and that at least a "practical" threshold for radon daughter carcinogenesis may exist. Archer, Radford and Axelson (1979) conclude from their analysis of the 18 subgroups that if a threshold exists, it is below 20 to 30 WLM. Snihs (1973, 1974) considers the lowest underground exposure resulting in an apparent increase in lung cancer deaths in Swedish miners to be about 15 WLM, although he states that drawing conclusions about the exposure-response relationship below 100 WLM is impossible. Hewitt (1979) concludes from the analysis of Canadian uranium miners that if a threshold exists, it is below 60 WLM. Thus, the possibility exists that environmental radon daughters do not induce lung cancer.

The incidence of lung cancer attributable to radon daughter exposure observed in the various mining subgroups ranges overall from about 1.5 to 50 cases per WLM/year/10^6 persons, with a reasonable average value of 10 x 10^{-6} per person per year per WLM. This average value has been accepted in the lung cancer estimation model of Harley and Pasternack (1981) as being reasonably realistic when predictive data are compared to background (normally occurring) lung cancer incidence in nonsmokers from environmental exposure to radon.

In estimating the effect of radon daughter exposure at environmental levels (normally less than about 20 WLM per lifetime), the attributable risk at high exposures must somehow be extrapolated to the low exposure region. With the conventional method, the extrapolation is linear, even though some studies suggest that exposures may be even more efficient in inducing lung cancer as the exposure rate approaches background levels (Archer 1978).

D.5.4 Influence of Cigarette Smoke

The effect of cigarette smoke on radiation-induced cancer probabilities is still unresolved. During periods of relatively short followup (15 to 25 years), cigarette smoking is associated with a markedly increased incidence of lung cancer in miners. During periods of followup that are 30 to 60 years after initial exposure, lung cancer incidence is reported to be either somewhat greater among nonsmokers than smokers (Axelson and Edding 1980) or about the same (Radford 1981b). The human evidence has been confirmed in studies with beagle dogs; in those studies, dogs that smoked had fewer respiratory tract tumors than dogs that did not smoke, but they had comparable radon daughter exposures (Cross et al. 1978). The data on cigarette smoking suggest that smoking's principal role in lung cancer among uranium miners is to accelerate the appearance of cancers induced by radiation. The role of smoking at reduced radon levels is unknown.

D.5.5 Animal Studies

Animal studies were conducted several decades ago in initial attempts to identify the nature and levels of uranium mine air contaminants that were responsible for producing the lung cancers observed among uranium mining populations. Many of these studies were concerned with early effects or short-term pathologic changes (Jansen and Schultzer 1926; Read and Mottram 1939; Jackson 1940). In these studies also, exposures were primarily based on radon gas concentrations, thus leaving little or no information on the radon daughter concentrations that subsequently have been shown to contribute the greatest radiation dose to the lung. The earlier studies in which lung tumors were produced were methodologically or statistically inadequate to show an unequivocal association of lung tumors after exposure to radon or radon daughters (Huech 1939; Rajewsky, Shraub and Shraub 1942a, 1942b; Kushneva 1959).

Beginning in the 1950s, a growing concern emerged that the increased incidence of respiratory cancer observed in the European uranium mining population would also be found in the U.S. mining population (Seven State Uranium Mining Conference 1955; Wagoner et al. 1964). Systematic studies were subsequently begun in this country to identify the agents responsible for the excess lung cancer and to develop exposure-response relationships with animals. The importance of accurately determining the levels of radon daughter radionuclides in mine air was also noted by several investigators (Bale and Shapiro 1956; Harley 1953). Researchers at the University of Rochester began to focus attention on the biological and physical behavior of radon daughters as well as their contribution to the radiation dose of the respiratory tract (Harris 1954; Morken 1955).[a] Shapiro (1954) exposed rats and dogs to several levels of radon alone and in the presence of radon daughters attached to "room dust" aerosols. He showed that the degree of attachment of radon daughters to carrier dust particles was a primary factor influencing the radiation dose to

(a) Also Bale, W. J. 1951. "Hazards Associated with Radon and Thoron." Memo, March 14, 1951, Div. Biol. and Med., Atomic Energy Commission, Washington, D.C.

the airway epithelium and demonstrated that this dose was due primarily (>95%) to the short-lived radon daughters RaA (^{218}Po) and RaC' (^{214}Po), rather than to the parent radon.

Cohn, Skow and Gong (1953) reported relative levels of radioactivity found in the nasal passages, trachea, plus major bronchi, and the remainder of rat lungs after exposure to radon and radon daughter products. The respiratory tracts of animals that inhaled radon plus its decay products contained 125 times more activity compared with those of animals that inhaled radon alone.

Beginning in the mid-1950s, Morken initiated a pioneering series of experiments to evaluate the biological effects of inhaled radon and radon daughters in mice, with later experiments using rats, as well as beagle dogs (Morken and Scott 1966; Morken 1973a, 1973b). The essentially negative character of the biological results shown in these studies suggested that α-irradiation is inefficient in producing radiation-specific tumors in the respiratory system. The only apparent late and permanent changes occurred in the alveolar and respiratory bronchial regions of the lung for a wide range of exposure levels and for observation times of three years in the dog and one and two years in the rat and mouse. Injury was produced in the bronchial tissue, but it was quickly repaired after irradiation ceased.

In the late 1960s and early 1970s, France and the U.S. initiated studies in which lung tumors were successfully produced from inhaled radon daughters (Perraud et al. 1970; Chameaud et al. 1974, 1980; Cross et al. 1978). At an average estimated lung dose of about 3000 rad from radon daughters, following prior lung stressing with stable cerium, 73 of the rats in the French studies developed malignant tumors (Perraud et al. 1970). In subsequent French studies, rats exposed either to radon daughters alone or in combination with uranium ore dust and cigarette smoke also produced tumors in the lung (Chameaud et al. 1974, 1980). The U.S. studies were designed to systematically determine the pathogenic role of radon daughters, uranium ore dust, diesel engine exhaust fumes, and cigarette smoke, alone or in various combinations. These studies involved life-span exposures of beagle dogs and Syrian golden hamsters (Cross et al. 1978). Followup studies are currently being conducted with rats. In the later U.S. studies, tumors also were produced in the respiratory tracts of the animals.

The animal studies have supported the human epidemiology studies. Noted similarities are as follows:

1. Tumor production per WLM at very high exposures is lower than at moderate exposures. This has been tested primarily in rats (Cross et al. 1980; Chameaud et al. 1980). The lowest attributable lung cancer rates per unit exposure were observed in the U.S. uranium miners and Canadian fluorspar miners, where radon daughter levels were the highest of all the underground mines.

2. Tumor production appears to increase with a decrease in exposure rate (Cross et al. 1980). This is suggested in both the human and animal studies although exposure rate is considered to be of less importance than cumulative exposure.

3. A lower lifetime incidence of lung cancer is observed in dogs exposed to cigarette smoke in succession with radon daughters and uranium ore dust than to radon daughters and uranium ore dust without cigarette smoke (Cross et al. 1978). This effect was also observed in a small group of Swedish zinc-lead miners and is tentatively ascribed to the protective effect of increased mucus production from smoking (Axelson and Sundell 1978) or of the thickened mucosa resulting from smoker's bronchitis. Tobacco smoke has been found to be cocarcinogenic with radon daughters when given to rats following their cumulative exposure to the daughters (Chameaud et al. 1980). This effect is not observed, however, when smoking precedes the radon daughters (Chameaud et al. 1981). This may partially explain the discrepancies observed in the interpretation of epidemiological data.

4. Emphysema can be attributed to radon daughter exposure in both animals (hamsters, rats, and dogs) and underground miners. The simultaneous presence of ore dust or diesel fumes does not appear to

increase the number of tumors produced by exposure to radon daughters (Cross et al. 1978, 1980; Chameaud et al. 1981).

5. For equal cumulative exposures, the older the age at the start of exposure, the shorter the latency period and, within limits, the higher the associated risk (Chameaud et al. 1981). In humans, the highest risk coefficient calculated, 50×10^{-6} lung cancers per year per WLM, is for persons first exposed later in life (over 40 years of age).

6. The estimates made by the various dosimetric models appear to be borne out in the various species. The tumors induced in experiments with hamsters and rats, which have similar lung morphometry, occur in the distal portion of the conducting airways or in the pulmonary region. These regions receive the highest dose, based on calculations (Desrosiers, Kennedy and Little 1978). Human tumors appear almost exclusively in the upper generations of the bronchial tree. Absorbed dose calculations show that basal cells in the upper airways at about the segmental bronchi receive the highest dose from radon daughters (Harley and Pasternack 1972).

7. Lifetime risk coefficients are similar in both the animals and humans. The rat data appear to range between 1 and 4×10^{-4} per WLM for all tumors (benign and malignant) at cumulative exposures less than 5000 WLM (Chameaud et al. 1981).[a] At exposures where life-span does not appear to be significantly shortened (<500 WLM), the lifetime risk coefficient appears to be about 2×10^{-4} per WLM for malignancies and ranges between 2 to 4×10^{-4} for all tumors. As yet, data are insufficient to determine the value below 100 WLM exposures.

(a) F. T. Cross, et al. Unpublished data from draft report, An Overview of the PNL Experiments With Reference to Epidemiology Data. Pacific Northwest Laboratory, Richland, Washington.

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