ENVIRONMENTAL ASSESSMENT

IN SUPPORT OF

PROPOSED INTERIM ENERGY CONSERVATION STANDARDS FOR NEW FEDERAL RESIDENTIAL BUILDINGS

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U.S. DEPARTMENT OF ENERGY

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FOREWORD

This environmental assessment is a study done in support of the Standards and Guidelines Program, of the Architectural and Engineering Systems Group, Building Systems Division. The Energy Conservation Standards Act of 1976, as amended, requires the Department of Energy (DOE) to issue performance standards for the design of new buildings. These standards are to be mandatory for the design of new Federal buildings and voluntary for all other buildings. DOE is to publish interim standards, conduct a demonstration study of the impact of the interim standard, report to Congress on the results, and promulgate a final standard. The DOE has divided the development of these standards into two parts, residential buildings and commercial buildings. The residential building portion has been further divided into Federal and non-Federal buildings due to the specialized nature of Federal residential buildings, which primarily house military personnel, and the method used to procure housing.

This environmental assessment supports the Federal Residential Buildings Energy Conservation Standard portion of that program. It specifically supports the issuance of a Notice of Proposed Rulemaking (NOPR) for the Federal Residential Building Standards, which is a step in developing the Interim Federal Residential Building Standards intended to permit the broadest public comment and input to the standard under development. This NOPR will have a minimum of a 90 day comment period during which public hearings will be scheduled for Washington, D.C., Chicago, IL, and San Francisco, CA. All comments will be carefully considered in developing the Interim Standards and in planning the subsequent demonstration study.

SUMMARY

Under Title III of the Energy Conservation and Production Act (the Act) (Pub. L. 94-385), as amended, the Secretary of Energy has the responsibility for developing voluntary performance standards for all new residential and commercial buildings. For the federal sector, the standard sets mandatory performance levels for the design of federal buildings. For the private sector, the standard is voluntary and serves as a guideline, providing technical information and examples of energy-efficient design practices. The director of each federal agency will be responsible for enacting regulations or procedures to ensure that all new federal residential building designs meet or exceed the proposed standard. Design professionals currently engaged in designing and constructing new non-federal residential buildings around the country are encouraged but not mandated to use it.

The U.S. Department of Energy (DOE) conducted this environmental assessment to address the possible incremental environmental effects of the proposed standards on residential buildings constructed for the federal sector. This assessment was mandated by 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). If promulgated by the DOE, the proposed standard would serve as an interim mandatory standard for federal sector construction of residential buildings and as voluntary guidelines for the private sector. The scope of this assessment is limited to the possible effects of implementing the proposed standard on the federal sector. The assessment does not examine impacts that the proposed standard could have as voluntary guidelines for the private sector because it would be virtually impossible to forecast what percentage of what types of private sector buildings would choose to comply with the voluntary standard. This environmental assessment also does not examine the environmental impacts of the proposed standard on commercial buildings. The commercial standard is assessed in a separate report entitled Final Environmental Assessment, Proposed Interim Conservation Standard for the Design of New Federal Commercial Buildings (DOE, 1986). The economic and socioeconomic impacts of the proposed residential standard have been analyzed in a separate document (Economic Analysis -- Proposed Interim Energy Conservation Standards for New

Federal Residential Buildings, DOE, October 1985) and are only summarized in this report.

To evaluate the impacts that the proposed standard would have on the environment, DOE reviewed current construction plans for federal residential housing and from this information identified nine types of residential units typical of current and expected construction from 1986 to 1990. For each type of residential unit, a design was selected and architecturally adjusted on paper to be fully typical of current design and building practices. Each of these nine "baseline" residential units was tested in a series of computer simulations to achieve the maximum practicable improvements in energy efficiency. This assessment included a life-cycle cost analysis. The energy-efficiency and life-cycle cost information was used to architecturally redesign each residential unit to meet the proposed standard. These architecturally redesigned residential units became the "proposed standard" units.

This analysis examines the incremental environmental consequences of the proposed standard. Differences between the design of the nine baseline residential units and the nine proposed standard units provide the bases for evaluating the incremental impacts of the proposed standard. This analysis of incremental environmental impacts emphasizes the possible alterations to a residence's indoor air quality.

The finding of this report is that the impact of the standard on building habitability, the outdoor environment, the economy, and federal institutions would be very small. Specific findings are summarized below.

HABITABILITY

In this assessment, habitability is expressed in terms of changes in various indoor air pollutant concentrations and concomitant occupant health and safety impacts that can be related to design changes attributed to the proposed standard. No significant adverse effects were found that relate to building habitability.

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 nine 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), and nitrogen dioxide (NO_2), radon and formaldehyde, and are shown in Table S.1. Also, the potential impact on indoor air quality of chemical compounds and microorganisms was assessed at a more qualitative level because the quantitative detail necessary for simulation modeling is not available.

Particulate Matter

Implementation of the proposed standard is expected to reduce the level of particulate matter slightly in all residences where electric cooking appliances replace gas cooking appliances and in residences where the exchange of outdoor and indoor air is increased from 0.7 to 1.0 air changes per hour.

Carbon Monoxide

Currently, computed indoor concentrations for CO from cooking and smoking are well below levels associated with health risk. The proposed standard would only reduce CO concentrations.

Carbon Dioxide

Residential units designed under the proposed standard are expected to maintain low concentration levels of CO_2. The health risk from indoor CO_2 concentrations would not increase.

TABLE S.1. Summary of Incremental Changes in Indoor Air Quality from the Proposed Standard for Federal Residential Buildings[a]

Residential Unit Abbreviation[b]	Fuel		Particulate Matter ($\mu g/m^3$)		Carbon Monoxide (mg/m^3)		Carbon Dioxide (mg/m^3)		Nitrogen Dioxide ($\mu g/m^3$)		Radon (pCi/ℓ)		Formaldehyde ($\mu g/m^3$)	
	Heat	Cook	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case
SFR-1S	NG[c]	NG	0	0	0	0	0	0	0	0	0	0	-3.8	-10.9
SFR-2S	NG	NG	0	0	0	0	0	0	0	0	0	0	-2.2	-6.4
TH-MU	NG	NG	0	0	0	0	0	0	0	0	0	0	-0.7	-2.0
TH-EU	NG	NG	0	0	0	0	0	0	0	0	0	0	-1.9	-5.5
APT-MU-U	NG	NG	0	0	0	0	0	0	0	0	0	0	-3.8	-10.8
APT-MU-D	NG	NG	0	0	0	0	0	0	0	0	0	0	0	0
APT-EU-U	NG	NG	0	0	0	0	0	0	0	0	0	0	-3.8	-10.8
APT-EU-D	NG	NG	0	0	0	0	0	0	0	0	0	0	0	0
MH-MS	NG	NG	0	0	0	0	0	0	0	0	0	0.012	-4.5	0
SFR-1S	E-HP[d]	Elec.	-21	-36	-0.45	-1.21	-281	-400	-22	-56	-0.053	-0.709	-28.2	-231.5
SFR-2S	E-HP	Elec.	-22	-38	-0.47	-1.28	-297	-422	-24	-59	-0.028	-0.369	-35.0	-382.2
TH-MU	E-HP	Elec.	-3	-10	-0.33	-1.09	-118	-248	-24	-61	0	0	-5.2	-11.1
TH-EU	E-HP	Elec.	-27	-47	-0.58	-1.57	-320	-474	-29	-73	-0.029	-0.369	-36.8	-360.3
APT-MU-U	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-10.6	-24.5
APT-MU-D	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-6.8	-13.7
APT-EU-U	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-10.6	-24.5
APT-EU-D	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-6.8	-13.7
MH-MS	E-HP	Elec.	-4	-14	-0.48	-1.57	-169	-357	-35	-88	0	0.012	-11.0	0

(a) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical and worst-case values.
(b) SFR-1S = Single-family residence, one story; SFR-2S = Single-family residence, 2 story; TH-MU = townhouse middle unit; TH-EU = townhouse, end unit; APT-MU-U = Apartment, middle unit (upstairs); APT-EU-D = apartment, middle unit (downstairs); APT-EU-U = apartment, end unit (upstairs); APT-EU-D = apartment, end unit (downstairs); MH-MS = mobile home, multisection.
(c) NG = natural gas.
(d) E-HP = electrical heat pump.

Nitrogen Dioxide

Release of NO_2 in residential indoor environments is small. The computed concentrations of NO_2 for the proposed standard residential units are either the same as the baseline residential units or are slightly lower.

Radon

Computed values for indoor air concentrations of radon indicate that for site-built residential units, indoor concentrations levels between the baseline and the proposed standard residential units would be either the same or slightly reduced where the proposed standard units have an increased air exchange rate. The mobile homes designed to meet the proposed standard have a two-inch reduction in floor insulation at one of the four climates evaluated. This reduction could have a very small impact on the infiltration of radon from soil into the residential unit.

Formaldehyde

The proposed standard is expected to reduce the level of formaldehyde concentrations. The reduction could benefit certain sensitive individuals who have a very low threshold to formaldehyde.

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. The proposed 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 indoor microorganism pollution problems result from growth of organisms on a damp surface or on stagnant water reservoir within the residential unit. The principal building design

change affecting the residential building's ability to shed moisture-laden air is the use of air-to-air heat exchangers in selected apartment units designed to meet the proposed standard. Moisture condensation is expected as warm moisture-laden air is exhausted through the heat exchanger. Condensed moisture, if not effectively collected and disposed of over the entire life of the operating unit, can eventually create host areas for microorganisms. The use of air-to-air heat exchangers in large numbers is a relatively new phenomenon in the U.S. To date, equipment research and use have not proven that air-to-air heat exchanger ventilation systems over the long term will always be operated and maintained as intended. Thus, the impacts of air-to-air heat exchangers on microorganism growth and distribution are of concern over the long term.

OUTDOOR ENVIRONMENTAL IMPACTS

On a national basis, the net improvement in outdoor environmental quality from reduced fuel usage and reduced insulation production is so small that the general magnitude of airborne pollutants does not change. Although changes in outdoor environmental quality were not measured, they are likely to be positive.

ECONOMIC IMPACTS

The primary national impacts of adopting the proposed standard by federal agencies, cumulated over 5 years, would be to reduce federal government expenditures over the life cycle of these residential buildings by about $27 million (1985 dollars). This $27 million savings is comprised of fuel savings of approximately $53 million, offset by increased capital costs of about $26 million. Regional impacts are also expected to be small. No discernible sectoral or industry impacts would result from adopting the proposed standard, nor would there be any adverse impacts on small business. Some modest nonquantifiable impacts could be associated with a change in the procedures that result from adopting the proposed standard, but these also are expected to be very small.

IMPACTS ON INSTITUTIONS

The proposed standard is not radically different from standards already being used by the federal government or by the private sector. It does, however, require computer algorithms to be used in assessing compliance. Offsetting this would be a reduction in the amount of paperwork currently required to assure compliance.

CONTENTS

TABLES

1.0 INTRODUCTION

The objective of this environmental assessment (EA) is to identify the potential environmental impacts that may result from implementing the proposed standard on federal sector construction of new residential buildings. The EA does not examine the effects that the proposed standard could have as voluntary guidelines for the private sector, nor does it examine the environmental impacts of the proposed standard for commercial buildings. In this chapter, background information and statutory requirements that lead to the proposed standard and the EA are presented, followed by a discussion of the assessment's scope, objectives and approach. The report's contents are also briefly outlined.

1.1 BACKGROUND AND STATUTORY REQUIREMENTS

The Energy Conservation Standards for New Building Act of 1976 (the Act), as amended, 42 U.S.C. Sec. 6831 et seq., requires the Department of Energy (DOE) to issue voluntary performance standards for the design of new residential and commercial buildings. Federal agencies are required to comply with the residential and commercial building standards for the design of new federal buildings. For nonfederal buildings, compliance is voluntary and the standards are only voluntary guidelines.

As originally enacted, Title III of the Energy Conservation and Production Act, Pub. L. 94-385, 90 Stat. 1144 et seq., requires the Department of Housing and Urban Development (HUD) to develop, promulgate, implement and enforce compliance of the performance standards. On August 4, 1977, the Act was amended by Section 304(a), 42 U.S.C. Sec. 7154, of the Department of Energy Organization Act, Pub. L. 95-91, which transferred from HUD to DOE the responsibility for developing and promulgating the standards. HUD retained its implementation responsibilities.

On November 28, 1979, DOE published proposed performance standards in the Federal Register, 44 FR 68120, et seq. The notice was controversial and generated over 1,800 comments. The comments included technical and other substantive criticisms of the proposed standards. Many commenters expressed concern

that the proposed standards were not technically feasible or economically achievable. Furthermore, many commenters stated that the proposed standards placed too great a reliance on the use of a complex computer program that they neither understood nor could afford to use.

Less than a year after the proposed standards were published, the Act was again amended, by Section 326 of the Housing and Community Development Act of 1980, Pub. L. 96-399 (October 8, 1980). This amendment required that DOE promulgate interim residential and commercial standards by August 1, 1981, and extended the date for promulgation of a final rule to April 1, 1983. These interim standards were only to apply to new federal buildings. In addition, the Act required demonstration projects in at least two geographical areas.

In August, 1981, Congress again amended the Act and also deferred the appropriation for the program from fiscal year 1981 to fiscal year 1982. Subtitle D of Title 10 of the Omnibus Reconciliation Act of 1981, Pub. L. 97-35 (August 13, 1981), amended the Act to again create "voluntary performance standards" and provided 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." The deadlines for reporting requirements also were extended.

The legislative changes that have occurred since the Act was enacted in 1976 required a fundamental change in focus. DOE retains the responsibility for developing performance standards for all new buildings, but these standards now serve a dual purpose. The performance standard serves one purpose for the federal sector, where the standards set required performance levels for the design of federal buildings. The Act specifically directs that, except for federal buildings, voluntary performance standards "...shall be developed solely as guidelines for the purpose of providing technical assistance for the design and construction of energy-efficient buildings" (Section 304(a)(4)). Accordingly, the proposed residential standard serves a second purpose by providing sound technical information and examples of energy-efficient design practices for private sector guidelines.

As defined by the Act, the proposed standard serves as a guideline for the design stage; it does not apply to the operation, maintenance or energy

consumption of a building once it is built. The proposed standard operates by setting an energy consumption goal for a building (i.e., a quantified target of energy consumption at the design stage) and a method to calculate whether the design meets the energy consumption goal.

1.2 SCOPE AND OBJECTIVES OF THE ASSESSMENT

As discussed above, the proposed residential building standard sets required performance levels to be applied during the design stage for federal buildings. The proposed standard encourages the fine-tuning of existing design approaches and in most cases, it is not expected to result in radical residential building design approaches. This assessment addresses the incremental environmental impacts attributable to the application of the proposed performance standard. Those impacts were determined by comparing "case-study" residences designed first to current design practices and then redesigned to meet the proposed standard. Various quantified and unquantified environmental consequences attributed to increasing energy conservation in residential buildings are discussed in this report. However, the emphasis of this analysis is directed toward the incremental changes that could occur from the baseline to the proposed standard, insofar as they can be identified. Thus, this assessment is intended to address the potential for adverse environmental impacts resulting from implementing the proposed standard to the design of federal residential buildings, and to determine whether an Environmental Impact Statement should be prepared.

If promulgated by the DOE, the proposed standard would serve as an interim mandatory standard for federal sector residential construction of residential buildings and as voluntary guidelines for the private sector. A separate environmental assessment is being prepared which addresses a proposed standard for commercial buildings. The scope of this assessment is limited to the possible impacts of implementing the proposed standard on the federal sector. The assessment does not examine effects that the proposed standard may have as voluntary guidelines for the private sector because it would be virtually

impossible to forecast what percentage of what types of private sector buildings would choose to comply with the voluntary standard.

1.3 APPROACH USED IN THE ASSESSMENT

The potential impacts of applying the proposed standard to federal construction of new residential buildings were examined through nine case-study residential buildings (one for each functional building category, e.g., mobile home, single-family detached, etc.). Each of the nine case-study residences was "modified" on paper by an architectural/engineer firm to meet first the existing design (baseline) practices and then the proposed standard. This process allowed real residential structures to be used and detailed actual and simulated residential characteristics.

This approach is felt to provide a defensible analytical base. A building performance standard that epitomizes flexibility of design and construction therefore provides many options for satisfying the standard. To address the broad array of potential impacts, each test building included design changes that would be required in five separate climate zones. The potential impacts identified in this report are based on minimum, typical, and maximum values of indoor pollutant concentrations and thus bracket a full range of effects. Air quality/human health impacts are based on the best health risk information available.

1.4 ORGANIZATION OF THE REPORT

The remainder of this assessment is organized as follows. Chapter 2 describes the proposed standard and the major alternative considered in the environmental assessment. Chapter 3 discusses in detail the general approach used in the assessment, followed by specific analyses of indoor air quality changes, human health impacts, outdoor environmental impacts, socioeconomic impacts (by reference), and institutional impacts. Each of these specific analyses includes background information, the methodology used, and the results of the analyses.

Appendix A contains detailed descriptions of the nine case-study residences used for the case-study analyses. Appendix B describes the indoor

air-quality monitoring experiment that was used to confirm the reasonableness of the computed indoor air-quality values, while Appendix C provides a detailed description of the inputs, assumptions and limitations of the model used to make the computations. Appendix D documents the information used to evaluate human health impacts.

2.0 DESCRIPTIONS OF THE PROPOSED STANDARD AND ALTERNATIVES

In developing the proposed residential building energy standard, DOE considered several different levels of stringency for elements of the standard. For example, greater and lesser levels of strigency were considered for the building envelope and equipment subsystems. The proposed standard reflects the maximum feasible levels of energy conservation based on a technological and professional assessment at the time of preparation. Development of a more stringency standard therefore was not considered economically feasible, and the development of a significantly less stringent standard was not considered because it was inconsistent with the statutory mandate, which stipulates that DOE promulgate a standard that requires the maximum energy savings to the extent practicable.

The no-action alternative, defined as a continuation of current practices represents a less stringent alternative than the proposed standard. However, because additional variations in stringencies from those proposed were not considered practical or reasonable, the only alternative to the proposed standard that is analyzed in this environmental is that of no action.

2.1 NO-ACTION ALTERNATIVE (CURRENT PRACTICES IN FEDERAL RESIDENTIAL BUILDINGS)

The Federal Energy Management Program (FEMP), administered by DOE, requires that alternative building systems be cost-effective over its life cycle. The requirement has been applied to building measures such as passive and active solar systems, but not to refinements in the level of energy conservation in typical construction, such as the thermal resistance to conductive heat flow (R-value) of insulation in a wall. Currently, no building performance standard exists for energy conservation in federal residential buildings.

The military purchases 95% of federal residential buildings, so the practices used in actual construction of military housing have been used to define typical current (baseline) practice for comparison to the proposed standard. Current practice in military residential building design tends to follow private sector practices for moderately energy-efficient buildings in that

location. The procedure used to identify typical practice in military family-housing activities is discussed in Appendix A, along with typical current insulation designs in four representative climate zones of the United States.

2.2 THE PROPOSED STANDARD

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

The standard relies on a minimum life-cycle cost analysis using energy, cost, climate, and other data. The operation of the standard has been mechanized through the development of a computer program; operation of the program is documented in Conservation Optimization Standard for Savings in Federal Residences (COSTSAFR)--User's Manual.[a] Several documents provide information about the technical information that was used in developing the standard. Previous DOE research produced Affordable Housing Through Energy Conservation, Technical Support Document (Lawrence Berkeley Laboratory Undated) and Affordable Manufactured Housing Through Energy Conservation, Technical Support Document (Steven Winter Associates, Inc. 1983). The new technical information generated for this standard and the underlying methodology are described in Proposed Interim Energy Conservation Standard for Federally Procured Residential Buildings, Technical Support Document.[b] The economic analysis conducted

(a) Draft report prepared by Pacific Northwest Laboratory, Richland, Washington.
(b) Draft report prepared by Steven Winter Associates, Inc., and Wright Associates for Pacific Northwest Laboratory, Richland, Washington.

for regulatory purposes is presented in Economic Analysis--Proposed Interim Energy Conservation Standard for Design of New Federal Residential Buildings.[a]

The proposed standard sets forth requirements for the energy performance of new residential buildings constructed for the federal government. It is a whole-building performance-based standard implemented by a microcomputer program that provides a point system for demonstrating compliance. The standard is the procedure used to develop an optimized energy budget for the building, while the software provides an easy-to-use compliance path. The standard covers building envelope measures such as insulation levels, window (amount, glazing, sash type), infiltration control measures, and heating and cooling equipment efficiencies. Water heaters and refrigerators are included in the energy budget at the option of the official implementing the standard.

The standard requires that, to the extent practicable, energy conservation measures that have a life-cycle energy cost equal to or less than the optimum life-cycle energy cost will be incorporated into federally purchased residential buildings. The optimum life-cycle energy cost is the energy cost of the fuel type and the set of energy conservation measures that has a minimum total 25-year life-cycle cost (including construction, maintenance, operation, and energy), given local construction, maintenance and operation costs; available fuels and fuel costs; fuel price projections of the Federal Energy Management Program (FEMP); local weather; the residential slide-rule data base[b] with equipment performance data; and appliance performance data. The set of energy conservation measures to be considered when determining the optimum set of measures is provided in the documentation of the standard.[c] The standard

(a) Roop, J. M., and R. G. Pratt. To be published in 1986. Pacific Northwest Laboratory, Richland, Washington.

(b) This DOE-developed tool is based on thousands of computer entries and puts information into a useful format allowing manufacturers and retailers to calculate how much energy can be saved by features such as additional insulation and glazing, energy-efficient appliances, night setback thermostats, reflective glazing, and solar hot water heaters.

(c) Steven Winter Associates, Inc., and Wright Associates. 1985 (Draft). Proposed Interim Energy Conservation Standard for Federally Procured Residential Buildings, Technical Support Document. Prepared for Pacific Northwest Laboratory, Richland, Washington.

applies to residential buildings purchased by the federal government which are less than three stories in height and designed with each living unit having a full kitchen and at least one full bathroom. A three-step procedure determines if a proposed building design is in compliance:

- Step 1 - Select from the list of available building prototypes the residential housing units that most closely corresponds to the types to be constructed.
- Step 2 - Using local construction, maintenance, and operation costs; available fuels and local fuel costs; regional FEMP fuel price forecasts and discount rates; equipment and appliance performance data, climate location multiplier data (all provided by the appropriate agency's director for regional housing); and the residential slide-rule energy data base, determine the fuel type and energy conservation measures from the set of basic measures which provide the minimum total 25-year life-cycle cost for the prototype building. The set of basic measures to be considered is provided in the documentation of the standard.[a] The 25-year life-cycle energy cost of the set of measures includes construction, maintenance, operation, replacement and energy costs; the set with the minimum total cost determines the optimum life-cycle energy cost.
- Step 3 - Demonstrate that the energy conservation measures of the proposed building provide 25-year life-cycle energy costs less than or equal to the optimum life-cycle energy costs 1) using the local fuel cost data, the regional FEMP fuel price forecasts and discount rates, and the local maintenance costs provided by the implementing official, and 2) applying the energy conservation measures to be used in the building under the proposed standard to the corresponding housing unit determined in Step 1. The demonstration may be accomplished using the slide rule data base, the DOE-2 building energy

(a) Steven Winter Associates, Inc., and Wright Associates. 1985 (Draft). Proposed Interim Energy Conservation Standard for Federally Procured Residential Buildings, Technical Support Document. Prepared for Pacific Northwest Laboratory, Richland, Washington.

simulation program, or alternative procedures approved by DOE. The fuel type(s) and manufacturers' data for the actual equipment and appliances to be installed are to be used in the computations.

The standard has been computerized in a form designed to provide easy use by the implementing official in developing the energy budget and by the builder in demonstrating compliance. The software, called COSTSAFR, is designed to allow input of local fuel costs, the corresponding residential unit, modifiers for inflation and adjustment of local construction costs, and the selection of the climatic location multiplier for the building or building project. The software includes the residential slide-rule energy data base and a construction cost data base that includes replacement and maintenance costs. The construction cost data base can be updated by the implementing official using the software.

The software performs the life-cycle-cost optimization of the basic set of measures and determines the energy cost for the optimum set of measures. It then prints out a point system for demonstrating compliance for the building using the residential slide-rule data base to determine the energy savings for the various energy conservation measures it contains. The point system allows tradeoffs among all the measures in the data base as well as heating/cooling equipment efficiencies and appliance efficiencies.

The proposed standard would generally result in buildings which save more energy than buildings designed with current practices. It would also result in building designs that have annual energy costs equal to or less than the annual energy cost of the optimum set of energy conservation measures. In a very few cases current construction practices that have been identified as typical are noted as not cost effective; i.e., they save more energy but cost more than is practical from a life-cycle-cost standpoint. In these cases, construction cost savings would more than compensate for the additional energy costs.

The standard does not require specific levels of insulation or efficiency on a component-by-component basis. Instead, it requires that the annual energy cost be less than or equal to the economically optimum annual energy cost. Impacts may be judged only on the basis of likely means of compliance selected

by building construction proposers. The analysis of impacts of the standard contained herein assumes that proposers will use the least expensive set of measures for compliance.

Two levels of fuel prices were used to evaluate impacts of the standard. Base procurement officials provided actual prices paid for military family housing activities. These prices tend to be lower than the FEMP averages, particularly for electricity. Electricity prices are low because of base-wide purchases at bulk rates. To estimate the impact of the standard in cases of higher fuel prices, the regional average FEMP prices were also used.

The standard would affect building envelope measures in three primary areas: levels of insulation, equipment efficiencies and the selection of fuel, and the use of air-to-air heat exchangers. Levels of insulation in ceilings would be reduced in many cases, usually by one level, i.e., from R-38 to R-30 or from R-30 to R-19. Wall insulation levels, on the other hand, often would increase from R-19 to R-26 in cold climates. Slab foundation insulation for site-built homes would be used in hot climates, while under current typical practice, it is not. The level of flow insulation in mobile homes is reduced in the hot humid climate from R-14 to R-11.

The second major impact of the standard would be on equipment efficiencies and the selection of fuels. In general, heating and cooling equipment efficiencies would be increased above the levels of current practice. Much of the fuel savings produced by the standard would be attributable to this measure. Similarly, where multiple fuel types are available for heating, the standard would encourage use of the most cost-effective selection available. In many cases this is electric heat pump heating, particularly where bulk purchases of electricity by a military base result in lower-than-average electric rates.

Finally, the standard would tend to increase the use of air-to-air heat exchangers to recover heat from ventilation air in very tightly constructed houses having low infiltration rates. The nominal exchange of outdoor and indoor air for houses built under current practice was identified as 0.7 air changes per hour (ACH). With an air-to-air heat exchanger and other infiltration-reducing measures in place, the natural air exchange rate would be reduced to 0.2 ACH. The overall air exchange rate would be maintained at 0.7 ACH using

the heat exchanger to recover heat from the exhaust air stream. Nominal air change rates are used in the standard for both energy and indoor air quality analyses, although it is recognized that air change rates are influenced by climatic variables such as outdoor temperature, wind velocities, and occupancy practices. While further research needs to be done in this area, the literature on measured air change rates indicates that climatic influences are less than anticipated by current models. For this reason, the nominal air change rates of 1.0 ACH for average, 0.7 ACH for tight, and 0.7 ACH with heat recovery for very tight construction practices are used.

3.0 ANALYSIS OF POTENTIAL IMPACTS

This chapter presents an assessment of the potential impacts of adopting the proposed standard for new federal sector residential buildings. For building materials and certain indoor air pollutants, the incremental differences between the proposed standard and current building practices (baseline) have been quantified wherever possible. For other areas, such as health and institutional impacts, quantification was not possible, so comparisons are in qualitative terms.

3.1 FOCUS OF THE ASSESSMENT

The proposed standard incorporates energy conservation measures that increase a residence's energy efficiency. These design changes could have some impact on the building's habitability (indoor environment), the outdoor environment, the nation's economy, and the affected federal agencies. Changes in the habitability of residential buildings include potential impacts on indoor air quality and the related human health impacts (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, Proposed Interim Energy Conservation Standard for Design of New Federal Residential Buildings)[a] and are only summarized in this report (Section 3.5). Adopting the proposed standard may also lead to certain institutional impacts for affected federal agencies, as discussed in Section 3.6.

This report does not address potential changes in aesthetic qualities because those are design choices that are not dictated by the performance standard.

(a) Roop, J. M., and R. G. Pratt. To be published in 1986. PNL-5637, Pacific Northwest Laboratory, Richland, Washington.

3.2 GENERAL METHODOLOGY

The proposed standard is a highly flexible approach to the energy-efficient design of residential buildings. This inherent flexibility makes it difficult to pinpoint aggregate differences between current design practices and design practices under the proposed standard. To best identify the design practice changes that may occur as the result of the proposed standard, a life-cycle cost analysis was conducted. That analysis allowed the combination of options that optimized energy savings and overall cost savings to be selected from a broad array of potential energy conservation measures. With this energy conservation measure information, residential structures as currently designed could be redesigned to meet the proposed standard.

This environmental assessment is based on nine residential case-studies. The case study residences each represent one of nine residences that are built for both the public and private sector. In selecting the case study residential units, a review was conducted of the type of residential units currently being constructed for military housing and the types of units anticipated to be constructed from 1986 to 1990. The nine case-study residential units selected for this analysis are listed in Table 3.1. Characteristics of the nine residential units are shown in Table 3.2. More detail on the case-study residential units is contained in Appendix A.

Building practices were identified for each baseline unit as it was relocated in each of the four sites representing different climate zones by examining current practice in military housing. The sites represent a broad climate diversity and are: New Orleans, LA (hot, humid); Barstow, CA (hot, dry); Washington, D.C. (moderate); and Sheridan, WY (cold). These locations bracket a wide range of climates and represent typical climate zones for military housing. Typical current insulation levels for the four sites are shown in Table 3.3. The air exchange rate for the occupied military housing is assumed to be 0.7 ACH. Section C.2.2.1 of Appendix C gives more details on air exchange rates.

The least expensive set of conservation measures that meet the requirements of the standard was determined by using the COSTSAFR residential building

TABLE 3.1. Residential Unit Case Studies

	Abbreviation
Site-Built Residences	
Detached	
1) Single-Family Residence, Single Story	(SFR-1S)
2) Single-Family Residence, 2 Story	(SFR-2S)
Attached	
3) Townhouse, Middle Unit	(TH-MU)
4) Townhouse, End Unit	(TH-EU)
5) Apartment, Middle Unit (Upstairs)	(APT-MU-U)
6) Apartment, Middle Unit (Downstairs)	(APT-MU-D)
7) Apartment, End Unit (Upstairs)	(APT-EU-U)
8) Apartment, End Unit (Downstairs)	(APT-EU-D)
Manufactured Residences	
9) Mobile Home, Multisection	(MH-MS)

TABLE 3.2. Residential Housing - Selected Unit-Dependent Characteristics

Item	SFR-1S	SFR-2S	TH-MU	TH-EU	APT-MU-U	APT-MU-D	APT-EU-U	APT-EU-D	MH-MS
Gross Square Feet	1746	1655	1436	1436	1073	1073	1073	1073	1344
Net Square Feet	1615	1418	1200	1200	949	949	949	949	1270
Bedrooms	4	4	3	3	2	2	2	2	3
Bathrooms	2	2 1/2	2 1/2	2 1/2	1	1	1	1	2
Heating	NG[a]	NG	NG	NG	NG	NG	NG	NG	NG
Cooling	Elec.	Elec.	Elec.	Elec.	Elec.	Elec.	Elec.	Elec.	Elec.
Hot Water Heating	NG	NG	NG	NG	NG	NG	NG	NG	NG
Cooking	NG	NG	NG	NG	NG	NG	NG	NG	NG
Occupancy	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)

(a) NG = natural gas
(b) 2 bedroom residence - 2 adults, 1 child; 3 bedroom residence - 2 adults, 2 children; 4 bedroom - 2 adults, 3 children.

energy analysis microcomputer program. The results of these calculations provided the design for the baseline and proposed standard residential unit at each site, shown in Table 3.4. These units were used to derive the incremental

TABLE 3.3. Location-Dependent Characteristics (baseline)

Insulation Location	Insulation Data			
	New Orleans, LA	Barstow, CA	Washington, D.C.	Sheridan, WY
Wall				
Type	Fiberglass[a]	Fiberglass	Fiberglass	Fiberglass
Thickness	3 1/2"	3 1/2"	5 1/2"	5 1/2"
Partition				
Type	Fiberglass	Fiberglass	Fiberglass	Fiberglass
Thickness[b]	3 1/2"	3 1/2"	3 1/2"	3 1/2"
Ceiling				
Type	Fiberglass	Fiberglass	Fiberglass	Fiberglass
Thickness	7"	7"	8 1/2"	10 1/2"
Floor[c]				
Type	Fiberglass	Fiberglass	Fiberglass	Fiberglass
Thickness	5 1/2"	5 1/2"	5 1/2"	5 1/2"
Slab Perimeter				
Type	N/A	N/A	Styrofoam	Styrofoam
Thickness			1"	2"
Depth			1 1/2'	3'

(a) Fiberglass batt.
(b) Partition insulation is two 3 1/2" layers; one layer is associated with each unit.
(c) Floor applicable to mobile home unit only.
N/A = Not Applicable.

changes between current design practices and the proposed standard. The projected impacts discussed in this chapter reflect the incremental changes identified for the nine case-study residential units. The case-study residential units represent a full range of typical house plans and materials for site-built and mobile homes for military housing.

Actual building material changes resulting from the proposed standard would be limited to the building's envelope, where the amount of insulation may be reduced for most residential units in all four climate zones. The potential effects on the indoor air quality and outdoor environment were therefore examined on the basis of these envelope changes.

TABLE 3.4. Location-Dependent Characteristics (proposed standard)

Building Prototype	Location	Building Characteristics[a]					Efficiency/SEER[b]	
		Ceiling	Foundation	Infiltration	Wall	Window	Heating[c]	Cooling
Multisection Manufactured Home	New Orleans, LA	R11	R14	Tight	R11	Dbl-Al	70	8.0
	Barstow, CA	R19	R19	Tight	R19	Dbl-Al	75	8.0
	Washington, DC	R19	R19	Tight	R19	Dbl-Al	75	7.0
	Sheridan, WY	R19	R19	Tight	R19	Dbl-Al	80	7.0
Ranch	New Orleans, LA	R19	R5-2'	Tight	R11	Dbl-Al	75	10.0
	Barstow, CA	R19	R5-4'	Tight	R19	Dbl-Al	80	9.0
	Washington, DC	R30	R5-4'	Tight	R26	Dbl-Al.	80	8.0
	Sheridan, WY	R30	R5-4'	Tight	R26	Dbl-Altb	85	7.0
Two-Story	New Orleans, LA	R19	R5-2'	Tight	R11	Dbl-Al	75	10.0
	Barstow, CA	R19	R5-4'	Tight	R19	Dbl-Al	70	9.0
	Washington, DC	R30	R5-4'	Tight	R26	Dbl-Al	85	8.0
	Sheridan, WY	R30	R5-4'	Tight	R26	Dbl-Altb	90	7.0
Townhouse Mid. Unit	New Orleans, LA	R19	R5-2'	Tight	R11	Dbl-Al	70	9.0
	Barstow, CA	R19	R5-4'	Tight	R19	Dbl-Al	70	8.0
	Washington, DC	R30	R5-4'	Tight	R26	Dbl-Altb	75	7.0
	Sheridan, WY	R30	R5-4'	Tight	R26	Dbl-Altb	80	7.0
Townhouse End Unit	New Orleans, LA	R19	R5-2'	Tight	R11	Dbl-Al	75	9.0
	Barstow, CA	R19	R5-4'	Tight	R19	Dbl-Al	70	8.0
	Washington, DC	R30	R5-4'	Tight	R26	Dbl-Altb	75	7.0
	Sheridan, WY	R30	R5-4'	Tight	R26	Dbl-Altb	80	7.0
Apartment Mid. Unit	New Orleans, LA	R19	R5-2'	Tight	R11	Dbl-Al	65	11.0
	Barstow, CA	R30	R5-2'	Tight	R19	Dbl-Al	65	10.0
	Washington, DC	R30	R5-2'	Tight	R19	Dbl-Atb	75	9.0
	Sheridan, WY	R30	R5-4'	Tight	R26	Dbl-Altb	75	7.0
Apartment End Unit	New Orleans, LA	R19	R5-2'	Tight	R11	Dbl-Al	70	11.0
	Barstow, CA	R30	R5-2'	Tight	R19	Dbl-Al	65	10.0
	Washington, DC	R30	R5-4'	Tight	R26	Dbl-Al	75	10.0
	Sheridan, WY	R30	R5-4'	Tight	R26	Dbl-Altb	80	7.0

(a) Insulation is resistance measures for ceiling, foundation and walls; R5-2' indicates that foundation insulation extends 2 feet below grade; infiltration rates are: avg: 1.0 ACH changes per hour (ACH); tight: 0.7-1.0 ACH; very tight: less than 0.7 ACH. Window identified as: Sngl-Al: single glazed aluminum frame; Dbl: double; Tb: thermal break.

(b) Cooling: Measure is Seasonal Energy Efficiency Rating (SEER);
Heating: Measure is efficiency in percent for all except heat pumps, which are measured in Heating Season Performance Factors (HSPF). Unit measure for both SEER and HSPF is Btu output/kWh input.

(c) Natural gas.

3.3 HABITABILITY IMPACTS

The following section examines the potential for changes in the habitability (indoor environment) of residential units constructed according to the current design practices and designs that meet the proposed standard. The discussion focuses on the projected impact on indoor air quality (IAQ) and related impacts on the health of the residential unit's occupants.

3.3.1 Approach to Indoor Air Quality Analysis

The IAQ analysis is based on a computer simulation of the generation, buildup and dissipation of various pollutants in occupied residential buildings and estimates of occupied building air exchange rates. Normal air exchange rates for occupied military housing is assumed to be 0.7 ACH for tight buildings using an air-to-air heat exchanger. (For more information on fresh air ventilation see Appendix C, Section C.2.2.1.) Because of the complex nature of indoor air quality studies, the information in this section presents only the major aspects of the approach to the analysis. More detailed information may be found in the appendices.

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. However, recent reviews indicated that for many pollutants there is a lack of a strong 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 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 based on the normal range of pollutant emissions. (See Table C.3 in Appendix C for a concise listing of the ranges used in the air-quality analysis.)

The predicted IAQ under the baseline and proposed standard was derived by using a computer modeling approach that has been used and accepted by many IAQ experts (e.g., Miksch, Hollowell and Schmidt 1982; Molhave 1982). Estimates of pollutant concentrations based on building materials and usage parameters have been derived by this method and have corresponded reasonably well with monitored IAQ.

Indoor air pollutant concentrations were estimated by computing concentration values for the baseline and for the proposed standard. Pollutant concentrations levels were then compared and the incremental change noted. The pollutants selected for evaluation [particulate matter, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), radon and formaldehyde] have suspected adverse effects on human health. A number of studies have been made of the release rates of the selected pollutants from various building materials. The emission rates used in the IAQ modeling effort were derived from these data sources. Although other pollutants are present inside buildings, most of the quantitative research to date has been focused on the above pollutants, and thus an extensive knowledge base exists. In the long-run the knowledge base of other pollutants, their sources, and emission rates will be large enough to support simulation modeling.

Long-term steady-state concentrations of average indoor pollutants were computed for the six pollutants for each of the nine case-study residential units. Average outdoor pollutant concentrations (from the air and underlying soils) were treated as background to which internally generated pollutant emissions were added. Concentrations for each pollutant were computed for three release rates: minimum (min), middle (typical) and maximum (max) (see Appendix C), based on information in available literature. Min is defined as lowest expected emission rate, and max is a worst-case emission rate. Together these numbers span the range of possible emission rates for pollutant sources expected to be found in the case-study residences. The type of material used and amount are dictated by each unit's design.

3.3.2 Indoor Air Pollutants

The proposed building standard could change the concentration of indoor pollutants in two major ways. First, the changes could increase or decrease the air exchange rate between indoor and outdoor air. Second, the new standard could change the sources of internally generated indoor pollutants. For example, designs that meet the proposed standard could change the amount and types of various building materials used, such as concrete and insulation.

Various pollutants are released within residential buildings continuously or intermittently. These pollutants can originate from furnishings within a

building (e.g., carpets or furniture), from building materials themselves (e.g., insulation material, particle board), or from the indoor activities of building occupants (e.g., smoking, cooking, painting).

Although it is known that indoor air quality depends mainly on factors such as the building design, materials, contents, and usage, the relationships for indoor pollution concentrations can be complex. An increase in the indoor-outdoor air exchange rate will reduce indoor-generated pollutant concentrations. However, if the source of pollutant is outside the envelope, such as radon, indoor pollution levels may increase if infiltration is increased from a crawl space where elevated radon concentrations exist.

Changes in the air exchange rate of the baseline and proposed standard design are expected to be minimal. The average air exchange rates will only change in four situations and in each case will increase (see Table 3.5). For all other case-study units, the air exchange rates remain at 0.7 ACH.

The floor plans for the baseline and proposed standard residences are essentially the same (see Appendix A). Appendix A also provides data on unit-dependent characteristics such as exterior and interior wall sheathing and finish. The eight site-built residences are all constructed slab-on-grade with wood-frame walls and trussed system roofs. The principal difference between the baseline and proposed standard residence is the tightness of the envelope and the location and amount of insulation placed in the building envelope. Table 3.6 shows the changes in insulation thicknesses between the baseline and

TABLE 3.5. Cases Where Residential Indoor/Outdoor Air Exchange Rate Changed

Category of Residence	Heating Site	Base Fuel	Baseline ACH	Proposed Standard ACH	Delta ACH
SFR-1S	New Orleans, LA	Heat pump	0.7	1.0	0.3
SFR-2S	New Orleans, LA	Heat pump	0.7	1.0	0.3
SFR-2S	Sheridan, WY	Heat Pump	0.7	1.0	0.3
TH-EU	New Orleans, LA	Heat pump	0.7	1.0	0.3

The macroeconomic effects of the proposed standard on Federal construction were estimated using the direct net benefits in an interindustry macroeconomic model of the United States. The entire discounted present value of the standard (over the 20 year period) was used to modify government expenditures in a single forecast year--1985.[3] If the annualized savings were imposed each year, the effect would be too small to be measurable by existing economic tools. The entire cumulative impact of the change in the standard was imposed in a single year, rather than having the effects distributed over the 20 years specified for this analysis, for one major reason: it allows measurement of the direction of effects. Conducting the analysis this way, it can also be argued, it
establishes an upper limit to the effects of imposing this standard on Federal construction, albeit an exaggerated one.

The direct effects of the proposed standard on Federal construction of commercial buildings are discussed in Sections 3.2.1. These consist primarily of energy savings. It comes as some surprise that in most regions, the capital costs of buildings under the proposed standard is less than it would be under the existing standard. This results from being able to downsize the heating and other equipment within the building, since peak energy loads have been reduced. The Federal adaption of the proposed standard would represents a resource savings over the 20 year period of analysis of about $165 million (present value, in 1982 terms). Thus the direct effects--the net benefits over costs--are the value of this resource savings.

Table 3.2 reports the levels and changes for selected macroeconomic variables for the base and proposed standard cases. All variables except employment are recorded in millions of 1972 dollars; employment is in thousands of workers. Structures and employment are reported in categories that correspond to the one-digit standard industrial classification (SIC) level. Government expenditures and total output are reported at the input-output

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[3] A recent forecast year was used to prevent the growth of the economy over time from minimizing the impact of the proposed standard.

TABLE 3.6 Changes in Insulation Thickness (from baseline to proposed standard)

Geographic Location	Insulation Location	Heating Fuel Type[b]	Residence[a] 1 SFR-1S	2 SFR-2S	3 TH-MU	4 TH-EU	5 APT-MU-U	6 APT-MU-D	7 APT-EU-U	8 APT-EU-D	9 MH-MS
New Orleans, LA	Wall	Gas	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
		Elec.-R	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
		-HP	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
	Partition	Gas	N/A[c]	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		Elec.-R	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		-HP	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
	Ceiling	Gas	-3 1/2"	-3 1/2"	-1 1/2"	-3 1/2"	-3 1/2"	-0-	-3 1/2"	-0-	-3 1/2"
		Elec.-R	-1 1/2"	-1 1/2"	-1 1/2"	-1 1/2"	-1 1/2"	-0-	-1 1/2"	-0-	-3 1/2"
		-HP	-3 1/2"	-3 1/2"	-1 1/2"	-3 1/2"	-3 1/2"	-0-	-3 1/2"	-0-	-3 1/2"
	Floor	Gas	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2"
		Elec.-R	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2"
		-HP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2"
	Foundation	Gas	1"/2'[d]	1"/2'	1"/2'	1"/2'	N/A	1"/2'	N/A	1"/2'	N/A
		Elec.-R	1"/2'	1"/2'	1"/2'	1"/2'	N/A	1"/2'	N/A	1"/2'	N/A
		-HP	1"/2'	1"/2'	1"/2'	1"/2'	N/A	1"/2'	N/A	1"/2'	N/A

(a) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(b) Elec.-R = Electric Resistance Heating; Elec.-HP = Electric Heat Pump Heating.
(c) N/A = not applicable.
(d) Foundation perimeter insulation thickness/depth.

proposed standard residence for all nine types of residential units located at the New Orleans, LA, site. Insulation changes for all four sites are given in Appendix C.

Combustion pollutants are primarily related to activities within the residential unit. Combustion emission rates therefore are not affected by the design standard or building material used. The concentrations estimated for particulate matter, CO, CO_2 and NO_2 include a certain amount from background, or ambient, outdoor sources.

Within a residential building, cigarette smoking, stoves and ovens are the main sources of combustion products. In addition, strong sources from outside the building (particularly vehicle exhaust) can be drawn into the residence. 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 organic and inorganic constituents have also been identified [National Research Council (NRC) 1981a], but indoor concentration levels of these pollutants are not computed.

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

- 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 (medium 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 2 hours per day. Gas ovens are used an average 1 hour per day.
- Gas furnaces and hot water heaters are vented directly to the outdoors.

The discussion of specific pollutants begins with a brief review of the character of the pollutant, followed by information on health impacts associated with the pollutant. The indoor concentrations computed by the IAQ model for each of the nine residential units are then presented. Each subsection ends with findings of IAQ impacts based on the computed values for indoor pollutant concentrations.

Particulate Matter

The discussion of particulates in this section 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 (TSP) levels can be examined in an analysis such as this, or only the respirable 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.

RSP emission rates 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, allows for the number of occupancy hours per day and assumes a smoker population of 0, 1 or 2.

Health Impacts. The health impacts caused by particulate matter depend to some extent on the sensitivity of the individual exposed. 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 Standard. Table 3.7 shows the computed concentration levels of particulate matter based on 0, 1 or 2 smokers in the residence and with either a gas-fueled cook stove and oven or an electric stove and oven. For the residential units with a gas stove and oven, the incremental impact of the proposed standard is a slight reduction in particulate matter for cases where the air exchange rate increases from 0.7 to 1.0 ACH. In residences where the cook stove and oven is electrically heated instead of gas-fueled, the incremental impact of the proposed standard is a slight reduction in the long-term level of particulate concentration in the residential unit.

Findings. The indoor particulate matter concentration computed on the basis of smoking and cooking sources are expected to be below 55 $\mu g/m^3$ in residences where smoking does not occur (55 $\mu g/m^3$ is the level considered to be low enough that health effects do not occur). Implementation of the proposed standard is expected to reduce the level of particulate matter in all residences where electric cooking appliances are used and in residences where the indoor/outdoor air exchange rate is increased from 0.7 to 1.0 ACH. However, the reduction in particulate matter due to the change in ACH and cooking appliances would not measurably reduce the particulate matter concentration in residential units where smoking occurs regularly by either one or two smokers. The proposed standard thus would have a very small but positive effect on health risks related to particulate matter.

TABLE 3.7. Computed Indoor Particulate Concentrations[a,b] ($\mu g/m^3$)

Residential Unit Abbreviation[c]	Baseline Fuel		Baseline Min. Value	Baseline Typical Value	Baseline Max. Value	Proposed Standard Fuel		Proposed Standard Min. Value	Proposed Standard Typical Value	Proposed Standard Max. Value	Increment Min.	Increment Typical	Increment Max.
	Heat	Cook				Heat	Cook						
SFR-1S	NG[d]	NG	1	64	99	NG	NG	1	64	99	0	0	0
SFR-2S	NG	NG	1	67	104	NG	NG	1	67	104	0	0	0
TH-MU	NG	NG	1	70	109	NG	NG	1	70	109	0	0	0
TH-EU	NG	NG	1	83	129	NG	NG	1	83	129	0	0	0
APT-MU-U	NG	NG	1	105	163	NG	NG	1	105	163	0	0	0
APT-MU-D	NG	NG	1	105	163	NG	NG	1	105	163	0	0	0
APT-EU-U	NG	NG	1	105	163	NG	NG	1	105	163	0	0	0
APT-EU-D	NG	NG	1	105	163	NG	NG	1	105	163	0	0	0
MH-MS	NG	NG	1	101	156	NG	NG	1	101	156	0	0	0
SFR-1S	NG	NG	1	64	99	E-HP[e]	Elec.	0	43	63	-1	-21	-36
SFR-2S	NG	NG	1	67	104	E-HP	Elec.	0	45	66	-1	-22	-38
TH-MU	NG	NG	1	70	109	E-HP	Elec.	0	67	99	-1	-3	-10
TH-EU	NG	NG	1	83	129	E-HP	Elec.	0	56	82	-1	-27	-47
APT-MU-U	NG	NG	1	105	163	E-HP	Elec.	0	101	149	-1	-4	-15
APT-MU-D	NG	NG	1	105	163	E-HP	Elec.	0	101	149	-1	-4	-15
APT-EU-U	NG	NG	1	105	163	E-HP	Elec.	0	101	149	-1	-4	-15
APT-EU-D	NG	NG	1	105	163	E-HP	Elec.	0	101	149	-1	-4	-15
MH-MS	NG	NG	1	101	156	E-HP	Elec.	0	97	142	-1	-4	-14

(a) Background = 0.
(b) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical values.
(c) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(d) NG = natural gas.
(e) E-HP = electric heat pump.

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 hours per day and the oven is assumed to be used 1 hour 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 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 their 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 health risk information 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-hour average (see Appendix D for details).

Expected Impact of the Proposed Standard. Table 3.8 shows the computed indoor concentrations of CO for the baseline and for the proposed standard, and the incremental difference between the two. In the residential units where the unit's ACH is increased as a result of the proposed standard, CO levels would decline slightly. Reduction in smoking levels and the use of electric cooking appliances instead of gas would also reduce the calculated concentration of indoor CO slightly.

TABLE 3.8. Computed Indoor Carbon Monoxide Concentrations[a,b] (mg/m^3)

Residential Unit Abbreviation[c]	Baseline Fuel		Baseline Min. Value	Baseline Typical Value	Baseline Max. Value	Proposed Standard Fuel		Proposed Standard Min. Value	Proposed Standard Typical Value	Proposed Standard Max. Value	Increment Min.	Increment Typical	Increment Max.
	Heat	Cook				Heat	Cook						
SFR-1S	NG[d]	NG	0.06	0.79	1.71	NG	NG	0.06	0.79	1.71	0.00	0.00	0.00
SFR-2S	NG	NG	0.07	0.83	1.80	NG	NG	0.07	0.83	1.80	0.00	0.00	0.00
TH-MU	NG	NG	0.07	0.87	1.88	NG	NG	0.07	0.87	1.88	0.00	0.00	0.00
TH-EU	NG	NG	0.08	1.02	2.22	NG	NG	0.08	1.02	2.22	0.00	0.00	0.00
APT-MU-U	NG	NG	0.11	1.30	2.82	NG	NG	0.11	1.30	2.82	0.00	0.00	0.00
APT-MU-D	NG	NG	0.11	1.30	2.82	NG	NG	0.11	1.30	2.82	0.00	0.00	0.00
APT-EU-U	NG	NG	0.11	1.30	2.82	NG	NG	0.11	1.30	2.82	0.00	0.00	0.00
APT-EU-D	NG	NG	0.11	1.30	2.82	NG	NG	0.11	1.30	2.82	0.00	0.00	0.00
MH-MS	NG	NG	0.10	1.25	2.70	NG	NG	0.10	1.25	2.70	0.00	0.00	0.00
SFR-1S	NG	NG	0.06	0.79	1.71	E-HP[e]	Elec.	0.00	0.34	0.50	-0.06	-0.45	-1.21
SFR-2S	NG	NG	0.07	0.83	1.80	E-HP	Elec.	0.00	0.36	0.53	-0.07	-0.47	-1.28
TH-MU	NG	NG	0.07	0.87	1.88	E-HP	Elec.	0.00	0.54	0.79	-0.07	-0.33	-1.09
TH-EU	NG	NG	0.08	1.02	2.22	E-HP	Elec.	0.00	0.44	0.65	-0.08	-0.58	-1.57
APT-MU-U	NG	NG	0.11	1.30	2.82	E-HP	Elec.	0.00	0.81	1.18	-0.11	-0.50	-1.64
APT-MU-D	NG	NG	0.11	1.30	2.82	E-HP	Elec.	0.00	0.81	1.18	-0.11	-0.50	-1.64
APT-EU-U	NG	NG	0.11	1.30	2.82	E-HP	Elec.	0.00	0.81	1.18	-0.11	-0.50	-1.64
APT-EU-D	NG	NG	0.11	1.30	2.82	E-HP	Elec.	0.00	0.81	1.18	-0.11	-0.50	-1.64
MH-MS	NG	NG	0.10	1.25	2.70	E-HP	Elec.	0.00	0.77	1.13	-0.10	-0.48	-1.57

(a) Background = 0.
(b) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical values.
(c) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(d) NG = natural gas.
(e) E-HP = electric heat pump.

Findings. The computed indoor concentration of CO from cooking and smoking are well below levels currently associated with health risks. The proposed standard will only reduce indoor concentrations of CO even further from the 10 mg/m concentration level (8-hour average) where health risks may begin to occur.

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-hour), and gas ovens (383,000 to 400,000 mg/burner-hour). Occupancy for the baseline and proposed standard residences is assumed to be directly related to the number of bedrooms the residential unit contains. Two bedroom residential units are assumed to be occupied by 3 persons (2 adults and 1 child), three bedroom units by 4 persons (2 adults and 2 children), and four bedroom units by 5 persons (2 adults and 3 children). Occupant smoking is based on the number of smokers (0, 1 or 2 smokers per household). Cooking appliances are expected to be used an average of 2 hours per day for the range top burner and 1 hour per day for the oven.

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). Currently, no state or federal indoor standards for CO_2 are applied to military housing. The Occupational Safety and Health Administration (OSHA) has a CO_2 standard for the workplace of 9,000 mg/m^3. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) has a recommended guideline for the nonworkplace of 4,500 mg/m^3 continuous (24-hour 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 Standard. Table 3.9 shows computed concentrations of CO_2 for the baseline and proposed standard units, and the incremental difference between the two. CO_2 concentrations are reduced slightly

TABLE 3.9. Computed Indoor Carbon Dioxide Concentrations[a,b] (mg/m^3)

Residential Unit Abbreviation[c]	Baseline Fuel		Baseline Min. Value	Baseline Typical Value	Baseline Max. Value	Proposed Standard Fuel		Proposed Standard Min. Value	Proposed Standard Typical Value	Proposed Standard Max. Value	Increment Min.	Increment Typical	Increment Max.
	Heat	Cook				Heat	Cook						
SFR-1S	NG[d]	NG	1350	1407	1526	NG	NG	1350	1407	1526	0	0	0
SFR-2S	NG	NG	1385	1445	1571	NG	NG	1385	1445	1571	0	0	0
TH-MU	NG	NG	1286	1348	1479	NG	NG	1286	1348	1479	0	0	0
TH-EU	NG	NG	1388	1462	1616	NG	NG	1388	1462	1616	0	0	0
APT-MU-U	NG	NG	1378	1472	1668	NG	NG	1378	1472	1668	0	0	0
APT-MU-D	NG	NG	1378	1472	1668	NG	NG	1378	1472	1668	0	0	0
APT-EU-U	NG	NG	1378	1472	1668	NG	NG	1378	1472	1668	0	0	0
APT-EU-D	NG	NG	1378	1472	1668	NG	NG	1378	1472	1668	0	0	0
MH-MS	NG	NG	1533	1622	1810	NG	NG	1533	1622	1810	0	0	0
SFR-1S	NG	NG	1350	1407	1526	E-HP[e]	Elec.	1126	1126	1126	-225	-281	-400
SFR-2S	NG	NG	1385	1445	1571	E-HP	Elec.	1148	1149	1149	-237	-297	-422
TH-MU	NG	NG	1286	1348	1479	E-HP	Elec.	1230	1230	1230	-56	-118	-248
TH-EU	NG	NG	1388	1462	1616	E-HP	Elec.	1142	1142	1142	-247	-320	-474
APT-MU-U	NG	NG	1378	1472	1668	E-HP	Elec.	1294	1295	1295	-84	-177	-373
APT-MU-D	NG	NG	1378	1472	1668	E-HP	Elec.	1294	1295	1295	-84	-177	-373
APT-EU-U	NG	NG	1378	1472	1668	E-HP	Elec.	1294	1295	1295	-84	-177	-373
APT-EU-D	NG	NG	1378	1472	1668	E-HP	Elec.	1294	1295	1295	-84	-177	-373
MH-MS	NG	NG	1533	1622	1810	E-HP	Elec.	1452	1453	1454	-80	-169	-357

(a) Background = 720.
(b) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical values.
(c) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(d) NG = natural gas.
(e) E-HP = electric heat pump.

where residential ACH rates are increased and where electric cooking appliances are used. Reduced smoking levels also help to reduce indoor CO_2 concentrations.

Findings. Computed concentrations for CO_2 from respiration, cooking and smoking are well below the ASHRAE recommended guideline of 4,500 mg/m^3 and somewhat below the Japanese standard of 1,800 mg/m^3. Residential units designed under the proposed standard are expected to maintain low concentrations of CO_2 so that health risks from indoor CO_2 concentrations are not increased.

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-hour of operation. Gas ovens release rates between 80 and 130 mg/oven-hour 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, 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 Standard. Table 3.10 shows the computed concentration of NO_2 based on release of NO_2 from gas cooking appliances and smoking. The expected NO_2 concentrations in the proposed standard units are expected to be slightly below units designed under current practices because of

TABLE 3.10. Computed Indoor Nitrogen Dioxide Concentrations[a,b] ($\mu g/m^3$)

Residential Unit Abbreviation[c]	Baseline					Proposed Standard					Increment		
	Fuel		Min. Value	Typical Value	Max. Value	Fuel		Min. Value	Typical Value	Max. Value	Min.	Typical	Max.
	Heat	Cook				Heat	Cook						
SFR-1S	NG[d]	NG	8	23	56	NG	NG	8	23	56	0	0	0
SFR-2S	NG	NG	9	24	59	NG	NG	9	24	59	0	0	0
TH-MU	NG	NG	9	25	62	NG	NG	9	25	62	0	0	0
TH-EU	NG	NG	11	29	73	NG	NG	11	29	73	0	0	0
APT-MU-U	NG	NG	14	37	93	NG	NG	14	37	93	0	0	0
APT-MU-D	NG	NG	14	37	93	NG	NG	14	37	93	0	0	0
APT-EU-U	NG	NG	14	37	93	NG	NG	14	37	93	0	0	0
APT-EU-D	NG	NG	14	37	93	NG	NG	14	37	93	0	0	0
MH-MS	NG	NG	13	36	89	NG	NG	13	36	89	0	0	0
SFR-1S	NG	NG	8	23	56	E-HP[e]	Elec.	0	0	0	-8	-22	-56
SFR-2S	NG	NG	9	24	59	E-HP	Elec.	0	0	0	-9	-24	-59
TH-MU	NG	NG	9	25	62	E-HP	Elec.	0	0	1	-9	-24	-61
TH-EU	NG	NG	11	29	73	E-HP	Elec.	0	0	0	-11	-29	-73
APT-MU-U	NG	NG	14	37	93	E-HP	Elec.	0	1	1	-14	-37	-92
APT-MU-D	NG	NG	14	37	93	E-HP	Elec.	0	1	1	-14	-37	-92
APT-EU-U	NG	NG	14	37	93	E-HP	Elec.	0	1	1	-14	-37	-92
APT-EU-D	NG	NG	14	37	93	E-HP	Elec.	0	1	1	-14	-37	-92
MH-MS	NG	NG	13	36	89	E-HP	Elec.	0	1	1	-13	-35	-88

(a) Background = 0.
(b) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical values.
(c) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(d) NG = natural gas.
(e) E-HP = electric heat pump.

1) an increase in the indoor/outdoor air exchange rate for some residences using electric heat pump furnaces, and 2) residences using electric cooking appliances.

Findings. Release of NO_2 from cooking appliances and tobacco smoking is small. The computed concentrations for NO_2 for the proposed standard are either the same or lower than those computed for the baseline residences. Thus, the proposed standard could only further reduce the annual NO_2 levels in residential structures from the 90 $\mu g/m^3$ level identified as adequate to protect against health risk.

Radon

The greatest single source of radon is from the soil. Source terms from the soil range from 0.1 to 1 pico curies per square meter 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 of the concrete as well as cracks and holes. An intact concrete slab without cracks or leaks through pipes will reduce flux by a factor of about 10 (Bruno 1981); a vented crawl space can further reduce flux, but crawl spaces were absent in all the site-built residences analyzed here. 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. Exterior walls of all case-study site-built residences are assumed to be 50% brick and 50% wood (typical for military housing). Another major source of indoor radon is water. Water radon emission rates were selected to cover the expected range supplied by 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 typical background value of 0.25 pico curies per liter (pCi/ℓ) was chosen for this computation. The water supplies for the residential buildings were assumed to be from base-wide supply systems.

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 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, 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 Standard. Radon concentrations were computed for each of the nine case-study residences. Concentration values for residences representing current design practice and for those that might be constructed under the proposed standard are presented in Table 3.11. The minimum (min), typical, and maximum (max) values are derived from the source-term assumptions discussed above. Background or ambient outdoor concentrations are assumed to be 0.25 pCi/ℓ.

The design changes related to the proposed standard could affect indoor radon concentrations in two ways: 1) in residential units where the indoor/outdoor air exchange rate is increased, radon concentrations would be reduced proportionately; 2) in the mobile home units where floor insulation is reduced,

TABLE 3.11. Computed Indoor Radon Concentrations[a,b] (pCi/ℓ)

Residential Unit Abbreviation[c]	Baseline Fuel		Baseline Min. Value	Baseline Typical Value	Baseline Max. Value	Proposed Standard Fuel		Proposed Standard Min. Value	Proposed Standard Typical Value	Proposed Standard Max. Value	Increment Min.	Increment Typical	Increment Max.
	Heat	Cook				Heat	Cook						
SFR-1S	NG[d]	NG	0.330	0.425	2.612	NG	NG	0.330	0.425	2.612	0.000	0.000	0.000
SFR-2S	NG	NG	0.292	0.344	1.480	NG	NG	0.292	0.344	1.480	0.000	0.000	0.000
TH-MU	NG	NG	0.289	0.340	1.463	NG	NG	0.289	0.340	1.463	0.000	0.000	0.000
TH-EU	NG	NG	0.293	0.345	1.480	NG	NG	0.293	0.345	1.480	0.000	0.000	0.000
APT-MU-U	NG	NG	0.311	0.371	1.027	NG	NG	0.311	0.371	1.027	0.000	0.000	0.000
APT-MU-D	NG	NG	0.338	0.433	2.619	NG	NG	0.338	0.433	2.619	0.000	0.000	0.000
APT-EU-U	NG	NG	0.311	0.371	1.027	NG	NG	0.311	0.371	1.027	0.000	0.000	0.000
APT-EU-D	NG	NG	0.338	0.433	2.619	NG	NG	0.338	0.433	2.619	0.000	0.000	0.000
MH-MS[e]	NG	NG	0.379	0.488	0.975	NG	NG	0.379	0.488	0.987	0.000	0.000	0.012
SFR-1S	NG	NG	0.330	0.425	2.612	E-HP[f]	Elec.	0.306	0.373	1.904	-0.024	-0.053	-0.709
SFR-2S	NG	NG	0.292	0.344	1.480	E-HP	Elec.	0.279	0.316	1.111	-0.013	-0.028	-0.369
TH-MU	NG	NG	0.289	0.340	1.463	E-HP	Elec.	0.289	0.340	1.463	0.000	0.000	0.000
TH-EU	NG	NG	0.293	0.345	1.480	E-HP	Elec.	0.280	0.317	1.111	-0.013	-0.029	-0.369
APT-MU-U	NG	NG	0.311	0.371	1.027	E-HP	Elec.	0.311	0.371	1.027	0.000	0.000	0.000
APT-MU-D	NG	NG	0.338	0.433	2.619	E-HP	Elec.	0.338	0.433	2.619	0.000	0.000	0.000
APT-EU-U	NG	NG	0.311	0.371	1.027	E-HP	Elec.	0.311	0.371	1.027	0.000	0.000	0.000
APT-EU-D	NG	NG	0.338	0.433	2.619	E-HP	Elec.	0.338	0.433	2.619	0.000	0.000	0.000
MH-MS[e]	NG	NG	0.379	0.488	0.975	E-HP	Elec.	0.379	0.488	0.987	0.000	0.000	0.012

(a) Background = 0.25 pCi/ℓ.
(b) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical values.
(c) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(d) NG = natural gas.
(e) With ventilated crawl space.
(f) E-HP = electric heat pump.

it is assumed that infiltration from the crawl space would be increased slightly, increasing the level of indoor radon.

Computed radon concentrations vary from slightly over background levels to 2.6 pCi/ℓ.

Findings. In some cases the proposed standard could affect indoor radon concentrations by either decreasing or increasing the indoor concentration very slightly. Decreases in indoor concentrations of radon would occur as a result of increasing the residential units' indoor/outdoor air exchange rate. A small increase would occur in mobile homes where the amount of floor insulation is reduced. (See Appendix C, Table C.4 for a listing of how mobile home floor insulation varies by location.)

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 clearly indicates that only a very slight shift, if any, would occur as a result of the proposed standard. Thus, the change in health risk from indoor radon concentrations would be negligible. Note that radon release from soil, water and building materials varies greatly from site to site and should remain a major health risk concern until determined for that site not to be present at elevated levels.

Formaldehyde

Formaldehyde is a substance used in the manufacture of many building materials. 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-hour for range-top burners to 25 mg/oven-hour for ovens. Formaldehyde is also a component of sidestream 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 formaldehyde accumulation. For manufactured homes, the Department of Housing and Urban Development has established standards limiting permissible amounts of formaldehyde emissions from plywood and particleboard in support of limiting indoor formaldehyde concentrations to 0.4 ppm ("Manufactured Home Construction and Safety Standards" 1984).

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 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).

Expected Impact of the Proposed Standard. The computed indoor concentrations of formaldehyde from building materials, gas cooking appliances and smoking for the baseline and the proposed standard, and the incremental difference between the two are shown in Table 3.12. Building materials are assumed to be new. Emission rates would drop as the material ages. The reduction in insulation in both the gas furnace and electric heat pump designs would reduce formaldehyde levels. Formaldehyde concentrations also would decrease in cases where the designs under the proposed standard would increase the residential unit's indoor/outdoor ACH, and where electric cooking appliances would be used instead of gas appliances. In general, the incremental impact of the proposed standard would be to reduce formaldehyde concentrations slightly.

Findings. The level of formaldehyde concentrations is expected to be reduced slightly as the result of residential designs meeting the proposed standard. Although the reduction in formaldehyde concentrations would be small, it could benefit certain sensitive individuals having a very low threshold to formaldehyde.

Summary of Computed Incremental Changes in IAQ

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 nine case-study residences, based on baseline conditions and on the proposed standard. Incremental pollutant concentrations were calculated for particulate matter, CO, CO_2, NO_2, radon and formaldehyde and are shown in Table 3.13. Chemical compounds and microorganism are qualitatively discussed in the following sections.

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 levels present in indoor air. This assessment has

TABLE 3.12. Computed Indoor Formaldehyde Concentrations[a,b] ($\mu g/m^3$)

Residential Unit Abbreviation[c]	Baseline Fuel		Baseline Min. Value	Baseline Typical Value	Baseline Max. Value	Proposed Standard Fuel		Proposed Standard Min. Value	Proposed Standard Typical Value	Proposed Standard Max. Value	Increment Min.	Increment Typical	Increment Max.
	Heat	Cook				Heat	Cook						
SFR-1S	NG[d]	NG	14.8	75.5	727.0	NG	NG	13.4	71.7	716.1	-1.4	-3.8	-10.9
SFR-2S	NG	NG	16.1	101.4	1238.8	NG	NG	15.3	99.2	1232.4	-0.8	-2.2	-6.4
TH-MU	NG	NG	15.7	84.4	890.4	NG	NG	15.4	83.7	888.4	-0.3	-0.7	-2.0
TH-EU	NG	NG	18.9	105.8	1163.1	NG	NG	18.2	103.9	1157.6	-0.7	-1.9	-5.5
APT-MU-U	NG	NG	18.9	120.1	1434.8	NG	NG	17.5	116.4	1424.1	-1.4	-3.8	-10.8
APT-MU-D	NG	NG	13.6	69.7	622.6	NG	NG	13.6	69.7	622.6	0.0	0.0	0.0
APT-EU-U	NG	NG	19.3	126.2	1547.5	NG	NG	17.9	122.5	1536.7	1.4	-3.8	-10.8
APT-EU-D	NG	NG	14.0	76.6	749.3	NG	NG	14.0	76.6	749.3	0.0	0.0	0.0
MH-MS	NG	NG	99.7	425.6	492.0	NG	NG	98.0	421.1	492.0	-1.7	-4.5	0.0
SFR-1S	NG	NG	14.8	75.5	727.0	E-HP[e]	Elec.	7.9	47.3	495.5	-6.9	-28.2	-231.5
SFR-2S	NG	NG	16.1	101.4	1238.8	E-HP	Elec.	9.2	66.4	856.5	-6.9	-35.0	-382.2
TH-MU	NG	NG	15.7	84.4	890.4	E-HP	Elec.	13.1	79.1	879.3	-2.5	-5.2	-11.1
TH-EU	NG	NG	18.9	105.8	1163.1	E-HP	Elec.	10.9	69.0	802.8	-8.1	-36.8	-360.3
APT-MU-U	NG	NG	18.9	120.1	1434.8	E-HP	Elec.	14.1	109.5	1410.4	-4.8	-10.6	-24.5
APT-MU-D	NG	NG	13.6	69.7	622.6	E-HP	Elec.	10.1	62.9	608.9	-3.4	-6.8	-13.7
APT-EU-U	NG	NG	19.3	126.2	1547.5	E-HP	Elec.	14.5	115.6	1523.0	-4.8	-10.6	-24.5
APT-EU-D	NG	NG	14.0	76.6	749.3	E-HP	Elec.	10.6	69.8	735.6	-3.4	-6.8	-13.7
MH-MS	NG	NG	99.7	425.6	492.0	E-HP	Elec.	94.8	414.5	492.0	-4.9	-11.0	0.0

(a) Background = 0.
(b) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical values.
(c) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = manufactured home, multisection.
(d) NG = natural gas.
(e) E-HP = electric heat pump.

TABLE 3.13. Summary of Incremental Changes in Indoor Air Quality from the Proposed Standard for Federal Residential Buildings[a]

Residential Unit Abbreviation[b]	Fuel		Particulate Matter ($\mu g/m^3$)		Carbon Monoxide (mg/m^3)		Carbon Dioxide (mg/m^3)		Nitrogen Dioxide ($\mu g/m^3$)		Radon (pCi/ℓ)		Formaldehyde ($\mu g/m^3$)	
	Heat	Cook	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case	Typical	Worst Case
SFR-1S	NG[c]	NG	0	0	0	0	0	0	0	0	0	0	-3.8	-10.9
SFR-2S	NG	NG	0	0	0	0	0	0	0	0	0	0	-2.2	-6.4
TH-MU	NG	NG	0	0	0	0	0	0	0	0	0	0	-0.7	-2.0
TH-EU	NG	NG	0	0	0	0	0	0	0	0	0	0	-1.9	-5.5
APT-MU-U	NG	NG	0	0	0	0	0	0	0	0	0	0	-3.8	-10.8
APT-MU-D	NG	NG	0	0	0	0	0	0	0	0	0	0	0	0
APT-EU-U	NG	NG	0	0	0	0	0	0	0	0	0	0	-3.8	-10.8
APT-EU-D	NG	NG	0	0	0	0	0	0	0	0	0	0	0	0
MH-MS	NG	NG	0	0	0	0	0	0	0	0	0	0.012	-4.5	0
SFR-1S	E-HP[d]	Elec.	-21	-36	-0.45	-1.21	-281	-400	-22	-56	-0.053	-0.709	-28.2	-231.5
SFR-2S	E-HP	Elec.	-22	-38	-0.47	-1.28	-297	-422	-24	-59	-0.028	-0.369	-35.0	-382.2
TH-MU	E-HP	Elec.	-3	-10	-0.33	-1.09	-118	-248	-24	-61	0	0	-5.2	-11.1
TH-EU	E-HP	Elec.	-27	-47	-0.58	-1.57	-320	-474	-29	-73	-0.029	-0.369	-36.8	-360.3
APT-MU-U	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-10.6	-24.5
APT-MU-D	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-6.8	-13.7
APT-EU-U	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-10.6	-24.5
APT-EU-D	E-HP	Elec.	-4	-15	-0.50	-1.64	-177	-373	-37	-92	0	0	-6.8	-13.7
MH-MS	E-HP	Elec.	-4	-14	-0.48	-1.57	-169	-357	-35	-88	0	0.012	-11.0	0

(a) Concentration values are printed with extended precision to illustrate the direction of changes. The listing of extended precision should not be taken to imply absolute accuracy for these typical and worst-case values.
(b) SFR-1S = Single-family residence, one story; SFR-2S = Single-family residence, 2 story; TH-MU = townhouse middle unit; TH-EU = townhouse, end unit; APT-MU-U = Apartment, middle unit (upstairs); APT-EU-D = apartment, middle unit (downstairs); APT-EU-U = apartment, end unit (upstairs); APT-EU-D = apartment, end unit (downstairs); MH-MS = mobile home, multisection.
(c) NG = natural gas.
(d) E-HP = electrical heat pump.

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 a combination 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.

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. These compounds tend to come 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 Standard. Design of residential buildings to meet the proposed 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 infiltration rate of the structure.

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 a major source of indoor air pollution (Molhave 1982). Residences designed to meet baseline conditions and residences designed to meet the proposed standard use the same inventory of building materials, except for the amount of insulation materials. Table 3.14 shows the emissions 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, or 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 having emanation rates that

TABLE 3.14. 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	--
Fiberglass	Batt, 3.0"	--	0.02 to 0.17
Mineral Wool	Insulation Batt	0.012	--
Organic	Woodfiber Board	0.120	--
Foam	Polystyrene	1.4	--
Foam	Polyurethane	0.12	--

(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).

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 concentrations. As with other indoor air pollutants discussed above, individuals will have a wide range of sensitivities to these indoor chemical pollutants. The proposed 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. Immunity conditions vary from individual to individual. 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. A primary condition in which microorganisms grow is a source of moisture. Thus, any area that has been flooded, that has received moisture during a rain storm, or that is where moisture condenses is a candidate host area for a microorganism colony. When the host site is attached to or adjacent to a residential central air-handling system, the microorganisms have a potential path for distribution beyond their immediate area. Because outdoor air enters a residence through the building's envelope (ceiling, floor and exterior walls), microorganisms around the foundation of a residence and in the intra-wall space can also be sources of indoor pollution.

Moisture is generated in residences by people, by occupant activities such as showering and cooking, and by plants. As much as five gallons of moisture can be generated by a family of four in a day. Residential structures need to dissipate this moisture in a way that does not create host areas for microorganisms. The principal design change affecting moisture shedding between the baseline residential units and those designed under the proposed standard is the use of air-to-air heat exchangers. Air-to-air heat exchangers are used in some units to maintain an indoor/outdoor air exchange rate of 0.7 ACH. (See Appendix C, Table C.4 for the case-study units using air-to-air heat exchangers.) Moisture condensation is expected as warm moisture laden air is exhausted through air-to-air heat exchangers. If the condensed moisture is not effectively collected and disposed of over the entire life of the operating unit, reservoirs of water or damp areas will be created, providing potential host areas for microorganisms. If even very small air leakages occur between incoming and exhaust air, microorganisms grown in or near the air-to-air heat exchange ventilation system may be distributed indoors. Air-to-air heat exchangers when properly installed and maintained should not create environments which support microorganism growth. However, the use of air-to-air heat exchangers in large numbers of residential units is a relatively new phenomenon in the U.S. Currently, equipment research and use information are not available to assure that air-to-air heat exchange ventilation systems over the long term will always be operated and maintained as intended.

3.3.3 Other Health and Safety Concerns

All design modifications to buildings must conform to building safety codes. The same holds true for heating and cooling equipment and cooking appliances. 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 standard generally adopted eliminates (or reduces to an acceptable degree) all of the likeliest hazards (or suspected hazards).

3.4 OUTDOOR ENVIRONMENTAL IMPACTS

The reduction in the amount of energy (natural gas and electricity) consumed by the 18,500 residential units to be built under the proposed standard between 1986 and 1990 would reduce only negligibly the amount of outdoor pollutant emissions. The reduction in the amount of insulation materials used in the 18,500 residential units also would reduce slightly the amount of insulation material manufactured and thus manufacturing-related emissions. Net improvement at the national level of outdoor environmental quality from reduced fuel usage and reduced insulation production would not be discernible. Although changes in outdoor environmental quality were not measured, they would likely be positive.

3.5 ECONOMIC IMPACTS

The economic analysis conducted to determine the impact of requiring federal agencies to design their new residential buildings according to the proposed standard concluded that no major impacts are expected to occur.[a] The analysis addresses only economic impacts that could result from federal agency compliance. The impacts that could occur as a result of voluntary compliance by the private sector were not calculated.

The economic analysis compared the proposed standard with a no-action alternative or baseline (based on current practice as determined by a survey of recent military construction projects). The building categories used in the economic analysis were those for which redesign and computer simulation of energy use and life-cycle cost analysis had been conducted. The buildings were first analyzed as if constructed under current practice at four geographical

(a) Roop, J. M., and R. G. Pratt. To be published in 1986. Economic Analysis - Proposed Interim Energy Conservation Standard for Design of New Federal Residential Buildings. Pacific Northwest Laboratory, Richland, Washington.

locations, then analyzed a second time after being reconfigured to comply with the proposed standard. The life-cycle costs were aggregated to the national level using federal-sector construction forecasts. The aggregate net benefits (i.e., the reduction in total life-cycle costs at the national level) were then analyzed to determine the direct impact of adopting the proposed standard.

The primary national effects of adopting the proposed standard by federal agencies, cumulated over five years, would be to reduce federal government expenditures over the life cycle of these residential buildings by about $27 million (1985 dollars). This $27 million savings is comprised of fuel savings of approximately $53 million, offset by increased capital costs of about $26 million. Sensitivity analysis suggests that fuel savings could be as high as $121 million, while increased nonfuel costs could be as large as $87 million. The net expenditure savings could range from $10 to $67 million. These results are based on assumptions about energy prices that are specified for this analysis by the Federal Energy Management Program (FEMP). Even the maximum impact of $67 million over 5 years of federal residential construction is too small to be considered a major effect.

Regional impacts are also expected to be small. Although specific building types vary widely across regions, the average of all building-type impacts within each region shows little regional variation. The maximum regional variation is only about $500 per residential unit, or less than 1% of the life-cycle cost of the unit. Buildings constructed in all regions under the proposed standard would experience reduced costs over the life cycle of the building compared to the no-action alternative.

There are no discernible sectoral or industry impacts as a result of adopting the proposed standard, nor will there be any discernible adverse impacts on small businesses. The standard, as proposed, would provide adequate flexibility to the contractor to both meet the standard and minimize construction costs under a wide range of local costs of labor, material and equipment. The local information on costs used for this analysis suggests that life-cycle costs would be minimized by substituting more efficient equipment for a more energy-efficient shell. Given these cost data, residences built to the proposed standard would use less insulation, etc., more energy-efficient

equipment, and substantially less energy over the life of the building. This would shift construction expenditures from materials to equipment with minimal effects on industries supplying these building components. Similarly, there would be less use of energy over the life of the buildings, thus reducing revenues to utilities supplying residential energy. These substitution effects are of almost no consequence in comparison to the benefits from the new residential construction.

Some slight nonquantifiable effects could be associated with a change in the procedures that result from adopting the proposed standard, but these also are determined to be small. This finding is based on the large amount of paperwork already required to meet current practice and the flexibility of the proposed standard. A contractor bidding on new federal residential construction would not have to have any greater expertise under the proposed standard than under current practice.

3.6 INSTITUTIONAL IMPACTS

The NEPA legislation requires consideration of the possible institutional impacts that might result from implementing a significant federal action. Although it is unlikely that this issuance will be classified as a significant federal action, this assessment has addressed the potential institutional effects.

Although nearly 15 federal agencies procure housing, the Department of Defense (DOD) procures nearly 95% of the total. For this reason, the institutional assessment has focused on DOD effects. Furthermore, because of DOD's major role, the standard was developed in consultation with DOD and the military services.

The military services purchase housing through Requests For Proposals (RFPs) using a turnkey approach. Each service uses an approach very similar to those used by the other services, but each adds specific materials or requirements tailored to the individual service's needs. Each service has energy requirements built into their RFPs, and housing bidders must respond to these requirements.

This new proposed standard has been designed to be compatible with the federal housing acquisition process. The COSTSAFR computer program produces a point system designed specifically for attachment to procurement RFPs. A federal agency applying the standard could use the COSTSAFR program and point system to specify the energy design requirements in RFPs. The agency would only need to generate one point system for each housing type and attach the resulting output to its RFP.

Because it provides a substitute for current energy requirements in federal housing RFPs, the proposed standard should impose no additional administrative requirements on federal agencies. Because it relies on computer analysis, however, the standard could require the agencies to employ a new analysis approach. This would require gaining familiarity with the COSTSAFR program. Ease of use, however, was a major consideration in developing the program, and numerous demonstrations with users unfamiliar with COSTSAFR, or even computer software in general, have shown it to be a very simple program to operate. Use of the standard would require availability of computer hardware. Most agencies develop RFPs at a limited number of locations, however, so each agency would require only a few computers. Furthermore, the software was developed for use with IBM-compatible personal computers. Recently, these computers have become very common and inexpensive.

In summary, this proposed standard should have negligible institutional effects on the agencies that procure federal housing. The standard basically would substitute for existing procedures and requirements implemented by the affected agencies.

4.0 AGENCIES AND PERSONS CONSULTED

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APPENDIX A

DESCRIPTION OF CASE-STUDY RESIDENCES

APPENDIX A

DESCRIPTION OF CASE-STUDY RESIDENCES

The majority of federal residential housing is purchased for military use. Therefore, this environmental assessment focuses on the proposed standard's effects on military housing design. To form a design base case for evaluating the incremental effect of the proposed design standard, current military design practices for residential housing were examined. To obtain the design information, military housing procurement officials were contacted, and request-for-proposals for military housing, blueprints, and specifications for specific housing developments were analyzed. From this information, construction documents were selected for 6 major housing developments containing over 800 residential units. The 800 units represented 19 different designs and were selected from locations that represent the various climatic zones of the continental U.S. Sensitivity analyses were conducted on these units to identify the relationship between insulation and location.

A base case description for five buildings was developed from blueprints and specifications that represent typical current military residential housing design practices with respect to floor area, foundation, building materials, furnishings, and occupancy (see Table A.1). The five buildings contain nine types of residential units, listed in Table A.2. Split-level single-family residences and single-section mobile home residences were not characterized because they were determined to be atypical of military housing. These nine base case residences became the baseline from which the incremental impact of the proposed standard is evaluated.

The design characteristics common to all nine types of units are summarized in Table A.3. The eight-case study site-built housing units have many features in common. All are constructed with slab-on-grade foundations, wood-frame walls and trussed roof systems. The walls and ceilings are insulated with fiberglass batts, and the slabs are insulated with extruded polystyrene insulation board around the perimeter. Roof sheathing consists of

TABLE A.1 Characteristics of Current Practice Residential Buildings and Composite Baseline Residential Buildings[a]

ACTUAL BUILDINGS

Project Location (service)	Unknown		Yorktown, VA	Ft. Irwin, CA (Army) Barstow, CA			New Orleans			
Building Plan	A	B		A	B	C	A	B	C	D
1. Heating Degree Days (65° Base)	?		3488	2203			1465			
2. Cooling Degree Days (65° Base)	?		1600	2200			2600			
3. Year of Project	1983		1981	1982			1975			
4. Building Type	Apt	TH	Apt	4-Plex (prefab)			TH	TH	SFD	Apt 4-plex & Multi
5. Subtype	Apt EU	TH EU	Apt EU	Apt	EU	?	TH EU	TH MU,EU	1S SFD	Apt MU,EU
6. # of Units In Project	96	62	232	58	84	581	26	90	4	80
7. Occupant Grade	JEM	JEM	?	SNCO	NCO	CGO	FGO	JEM	SGO	JEM
8. Gross Sq. Ft. ~~Net Sq. Ft.~~	1073 ~~949~~	1436 ~~1200~~	1064 ~~949~~	1156 ~~1040~~	1116 ~~996~~	1387 ~~1270~~	1994 ~~1714~~	1567 ~~1326~~	2046 ~~1898~~	1060 ~~995~~
9. # of BRs	2	3	2	2			4	3	4	2
10. # of Bath Rs	1	2 1/2	1	1			2 1+1/2+1/2		2	1
11. Heating Type	Gas Ignition		Heat Pump	LP Gas			Gas			
12. Cooling Type	None		Heat pump	Split/Electric			Split/Electric			
13. DHW Type	Gas		Electric	LP Gas			Gas			
14. Appliances Type	Gas		Electric	LP Gas			Gas			
15. Exterior Wall Finish	50% Stucco 40% Slump 10% Siding		75% Brick Siding	90% Stucco 10% Brick			100%	40% 60%	90% 10%	40% Brick 60% Siding
16. Exterior Wall Sheathing	none		1/2" Fiberbol	3/8" Ply			1/2" Plywood			
17. Wall Framing	2x14 16"		2x4 16" OC	2x4 16" OC			2 x 4 16" OC			
18. Wall Insulation	R-13 F		R-13 F	R-11 F or MF			R-11 Flb.			
19. Ceiling/Wall Interior Finish	5/8" gyp		1/2" Gyp	1/2"/5/8" Gyp			1/2" Gyp			
20. Window Layers	2		1?	1			2(?)			
21. Window Sash Type	Al		?	Al			Al			
22. Passive Solar	none		none	none			None			

TABLE A.1. (contd)

ACTUAL BUILDINGS

Project Location (service)	Unknown		Yorktown, VA	Ft. Irwin, CA (Army) Barstow, CA			New Orleans			
Building Plan	A	B		A	B	C	A	B	C	D
23. Window Treatments	?		?	75% Solar Screen Blinds & Drape tracks			?			
24. Door Type	Metal 1 3/4" Insulated		?	Metal Insulated			Solid Wood			
25. Storm Doors	none		Yes	None			None			
26. Ceiling Insulation	R-35 Cellulose		R-33 Flb'g	R-25 F or MF			R-19 Flb.			
27. Floor Underlayment (2nd Floor)	1 1/2" GypCrete 5/8" CDX Ply		1 1/2" Gyp 5/8" Ply	3/4" Ply (both) (floors)			5/8" Ply plus 3/8" Ply			
28. Floor Insulation	NA		2" x 24" foam	R-19 Flb.			NA			
29. Perimeter Insulation	None		3/4" foam	NA			None			
30. Flooring	Carpet-U Vinyl-L		Carpet-U Vinyl-L	Carpet-Upper Vinyl-Lower			Vinyl all except "D": C-U, V-L			
31. Infiltration Reduction	WS, S, VB		VB, ?	None			WS			
32. Roof Sheathing	Ply 1/2"		1/2" CDX Ply	Plywood			1/2" Plywood			
33. Foundation Type	Slab		Slab	Crawlspace			Slab			
Sources	Plans		Plans	Plans & Specs			Plans			

TABLE A.1. (contd)

ACTUAL BUILDINGS

	Project Location (Service)	Ft. Powell, WY (Air Force) Powell, WY							Chase Field Beeville, TX (Navy)	
	Building Plan	A	B	C	D	E	F	G	A	B
1.	Heating Degree Days (65° Base)	7708							876	
2.	Cooling Degree Days (65° Base)	400							3200	
3.	Year of Project	1984							1981	
4.	Building Type	1S SFD	1S SFD	1S SFD	1S SFD	2S Duplex	TH	4-plex	TH	4-plex
5.	Subtype	1S SFD	1S SFD	1S SFD	1S SFD	2S SFD	TH EU	Apt EU	TH MU,EU	Apt EU
6.	# of Units in Project	1	1	4	6	4	12	22	12	68
7.	Occupant Grade	FGO	CGO	SEM	SEM	JEM	JEM	JEM	?	
8.	Gross Sq. Ft. / ~~Net Sq. Ft.~~	1746 / ~~1615~~	1548 / ~~1417~~	1650 / ~~1523~~	1530 / ~~1414~~	1655 / ~~1418~~	1506 / ~~1260~~	1069 / ~~948~~	1782 / ~~1568~~	1877 / ~~1035~~
9.	# of BRs	4	3	4	3	4	3	2	4	2
10.	# of Bath Rs	2	2	2	2	2 1/2	2 1/2	1 1/2	2 1/2	1
11.	Heating Type	Gas							Gas Al	
12.	Cooling Type	None							Split/ Electric	
13.	DHW Type	Gas							Gas	
14.	Appliances Type	Gas							Gas	
15.	Exterior Wall Finish	Cedar w' Stain,							40% Brick 50% 50% Stucco 50% 10% Siding	
16.	Exterior Wall Sheathing	1/2" Gyp							1/2" Fiberboard	
17.	Wall Framing	2 x 6 16" OC							2 x 4 16" OC	
18.	Wall Insulation	R-19 Fib.							R-13 Mineral Fib.	
19.	Ceiling/Wall Interior Finish	2% Brick 5/8" Gyp							1/2" Gyp	
20.	Window Layers	3							2 (1/4")	
21.	Window Sash Type	Wood							Al	
22.	Passive Solar	Yes							None	
23.	Window Treatments	Blinds and drape tracks							?	
24.	Door Type	Metal Insulated							Metal Insulated	

TABLE A.1. (contd)

ACTUAL BUILDINGS

	Project Location (Service)	Ft. Powell, WY (Air Force) Powell, WY							Chase Field Beeville, TX (Navy)	
	Building Plan	A	B	C	D	E	F	G	A	B
25.	Storm Doors	Yes							None	
26.	Ceiling	R-50 Fiberglass							R-22 Mineral F.	
27.	Floor Underlayment (2nd Floor)	1 1/2" Gyp. Crete 1/2" Plywood Ply 3/4" Ply							3/4" 3" lt.wt. conc.	
28.	Floor Insulation	NA							None	
29.	Perimeter Insulation	R-24 Foam							None	
30.	Flooring	Carpet 2nd fl. apt. only Vinyl otherwise							Vinyl-Asbestos Tile	
31.	Infiltration Reduction	VB, WS, S							S	WS
32.	Roof Sheathing	1/2" Plywood							5/8" Ply	
33.	Foundation Type	Slab							Slab	
	Sources	Plans & Specs							Plans & Specs	

TABLE A.1. (contd)

Project Location (Service)						
	Building Plan	Composite Case-Study Buildings (based on Actual Buildings)[b]				
1.	Heating Degree Days (65° Base)	NA	NA	NA	NA	NA
2.	Cooling Degree Days (65° Base)	NA	NA	NA	NA	NA
3.	Year of Projec	1984	1984	1984	1984	1984
4.	Building Type	MS	Apt	TH	SFD	SFD
5.	Subtype	MS	Apt,EU,MU	TH,EU,MU	1S,SFD	2S,SFD
6.	# of Units in Project	NA	NA	NA	NA	NA
7.	Occupant Grade	JEM/NCO	JEM/NCO	JEM/NCO	FGO	JEM/NCO
8.	Gross Sq. Ft. / Net Sq. Ft.	1344 / 1270	1073 / 949	1436 / 1200	1746 / 1615	1655 / 1418
9.	# of BRs	3	2	3	4	4
10.	# of Bath Rs	2	1	2 1/2	2	2 1/2
11.	Heating Type	Gas	Gas	Gas	Gas	Gas
12.	Cooling Type	Split/ Electric	Split/ Electric	Split/ Electric	Split/ Electric	Split/ Electric
13.	DHW Type	Gas	Gas	Gas	Gas	Gas
14.	Appliances Type	Gas	Gas	Gas	Gas	Gas
15.	Exterior Wall Finish	100% wood Siding	50% Brick/50% Wood Siding			
16.	Exterior Wall Sheathing	None	1/2" Ply	1/2" Ply	1/2" Ply	1/2" Ply
17.	Wall Framing	Variable				
18.	Wall Insulation	Variable				
19.	Ceiling/Wall Interior Finish	5/8" Gypsum Bd.				
20.	Window Layers	Variable				
21.	Window Sash Type	Al	Al	Al	Al	Al
22.	Passive Solar	None	None	None	None	None
23.	Window Treatments	40% Drapes 60% Blinds				
24.	Door Type	Metal Insulated				

TABLE A.1. (contd)

	Project Location (Service) / Building Plan		Composite Case-Study Buildings (based on Actual Buildings)[b]				
25.	Storm Doors		Yes	Yes	Yes	Yes	Yes
26.	Ceiling		Variable				
27.	Floor Underlayment (2nd Floor)		NA	5/8" Plywood plus 1 1/2" Gypcrete			
28.	Floor Insulation		R-19	NA	NA	NA	NA
29.	Perimeter Insulation		NA	Variable			
30.	Flooring		Vinyl	Carpet-Upper Vinyl-Lower	Vinyl	Vinyl	Vinyl
31.	Infiltration Reduction		VB, WS, S	VB, WS, S	VB, WS, S	VB, WS, S	VB, WS, S
32.	Roof Sheathing		3/8" Ply	1/2" Ply	1/2" Ply	1/2" Ply	1/2" Ply
33.	Foundation Type		Crawl	Slab	Slab	Slab	Slab

(a) Key (by line number):
1. ? = information not obtained or not certain; NA = not applicable.
4. Apt = apartment; TH = townhouse; 1S SFD = one-story single-family residence; 2S = two story; MS = multisection.
5. EU = end unit; MU = middle unit.
7. JEM = Jr. Enlisted Man; SNCO = Staff Noncommissioned Officer; CGO = Commanding Grade Officer; FGO = Field Grade Officer; SEM = Senior Enlisted Man.
11. Ignition = automatic ignition; LP = liquid petroleum.
13. DHW = domestic hot water.
17. OC = on center
18. F = fiberglass; MF = mineral fiber
30. U = upper floor; L = lower floor
31. WS = weather stripping; S = sealing; VB = vapor barrier.

(b) These case-study configurations are used as the baseline buildings in this assessment.

TABLE A.2. Case Study Residences

Site-Built Residences

Detached

1) Single-family residence, 1 story (SFR-1S)
2) Single-family residence, 2 story (SFR-2S)

Attached

3) Townhouse, middle unit (TH-MU)
4) Townhouse, end unit (TH-EU)
5) Apartment, middle unit (upstairs) (APT-MU-U)
6) Apartment, middle unit (downstairs) (APT-MU-D)
7) Apartment, end unit (upstairs) (APT-EU-U)
8) Apartment, end unit (downstairs) (APT-EU-D)

Manufactured Residences

9) Mobile home, multi-section (MH-MS)

1/2" plywood. Exterior wall finishes consist of approximately 50% brick veneer and 50% factory-finished wood siding over 1/2" plywood sheathing. Interior wall and ceiling finishes consist of 5/8" gypsum board (wall board). Windows have aluminum sashes, and 40% have drapes and the remainder have blinds. Doors are insulated metal units with exterior storm doors. Second floors (not applicable to single-story residences) are constructed of 5/8" plywood underlayment covered with 1 1/2" of gypcrete (lightweight gypsum concrete). All floors are finished with vinyl floor tiles or sheet vinyl, except for the second floors of townhouses and apartments and stairways in two-story residences, which are carpeted.

Other characteristics also apply to all case-study residential units, including the manufactured types. Cabinets are constructed from hardwood plywood for exposed surfaces and particleboard for dividers, shelves, and countertop bases. Moisture and air infiltration control measures include vapor barriers under slabs (under the floor in manufactured units) and on the interior side of walls and ceilings. Windows and doors are weatherstripped and caulked. Gas-fired appliances are typically used in the residences. Each unit is equipped with a kitchen range exhaust hood capable of exhausting 150 cfm,

TABLE A.3. Design Characteristics Applicable to All Nine Types of Residences

Item	Base Case Characteristics
Air Exchange	Bathroom fan 50 cfm Kitchen fan 150 cfm No whole house mechanical fresh air system No air-to-air heat exchanger
Infiltration Reduction	Vapor barrier 6 mil polyethylene walls 6 mil polyethylene ceiling Weatherstripping Sealing of cracks
Heating/Cooling	Natural gas forced-air furnace Electric central air conditioning No woodstoves, fireplaces or kerosene heaters Standard home HVAC air filters
Hot Water Heater	Natural gas heated
Cooking	One gas stove per unit One gas oven per unit
Water	Provided by basewide system
Window Sash	Aluminum
Window Coverings	Drapes at 40% of windows Blinds at 60% of windows
Door	Metal insulated door Storm door
Furnishings	Supplied by occupant
Foundation	Slab-on-grade (except mobile home)
Passive Solar	Not typically used
Occupancy	2 bedroom residence - 2 adults, 1 child 3 bedroom residence - 2 adults, 2 children 4 bedroom residence - 2 adults, 3 children

and all bathrooms include 50 cfm exhaust fans. Heating systems are forced-air type with standard residential furnace filters. Outside air is not introduced into the furnace return air. Fireplaces and wood stoves are not typical in military housing. Air-to-air heat exchangers are not used in the base-case

residential units. The water supply is from a base-wide system rather than individual wells. Specific design characteristics are summarized in Table A.4.

A.1 SITE-BUILT RESIDENCES - DETACHED

Two detached site-built residences were analyzed and are briefly described below.

A.1.1 Single-Family Residence Single-Story

The case-study single-story single-family residence (SFR) has four bedrooms and 2 full baths, and is occupied by a family of 5 persons. It has a gross floor area of 1746 square feet (Figure A.1).

A.1.2. Single-Family Residence Two-Story

The case study two-story SFR has four bedrooms and 2 1/2 baths, and is also occupied by a family of 5. The 4 bedrooms and 2 baths are located on the second floor. The unit has a gross floor area of 1655 square feet (Figure A.2).

A.2 SITE-BUILT RESIDENCES - ATTACHED

Two types of attached site-built residences were analyzed and are described below.

A.2.1 Townhouses

The case study townhouse unit has 3 bedrooms and 2 1/2 baths, and is occupied by a family of 4. The unit has a gross floor area of 1343 square feet on 2 floors, and all the bedrooms and 2 of the baths are located on the second floor. End-unit and middle-unit townhouses have identical floorplans; the only difference is that the end-unit has only one wall in common with an adjacent unit, while the middle-unit shares two common walls. The end-unit has all its windows on two walls, as does the middle-unit, so the window and door areas and locations are the same for both types. The case-study townhouse building has 4 units (Figure A.3.)

TABLE A.4. Unit-Dependent Characteristics

Item	SFR-1S	SFR-2S	TH-MU	TH-EU	APT-MU-U	APT-MU-D	APT-EU-U	APT-EU-D	MH-MS
Gross Square Feet	1746	1655	1436	1436	1073	1073	1073	1073	1344
Net Square Feet	1615	1418	1200	1200	949	949	949	949	1270
Bedrooms	4	4	3	3	2	2	2	2	3
Bathrooms	2	2 1/2	2 1/2	2 1/2	1	1	1	1	2
Foundation	SOG[a]	SOG	SOG	SOG	SOG	SOG	SOG	SOG	CS[b]
Exterior Wall: Finish	B/W[c]	B/W	B/W	B/W	B/W	B/W	B/W	B/W	wood
Sheathing	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	none
Roof Sheathing	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	1/2" ply.	3/8" ply.
Interior Finish: Wall	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	1/2" gyp.
Ceiling	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	5/8" gyp.	1/2" gyp.
Flooring: 1st Floor	vinyl	vinyl	vinyl	vinyl	--	vinyl	--	vinyl	vinyl
2nd Floor	--	vinyl	carpet	carpet	carpet	--	carpet	--	--

(a) SOG = Slab on grade.
(b) CS = Crawl space.
(c) B/W = 50% brick/50% wood.

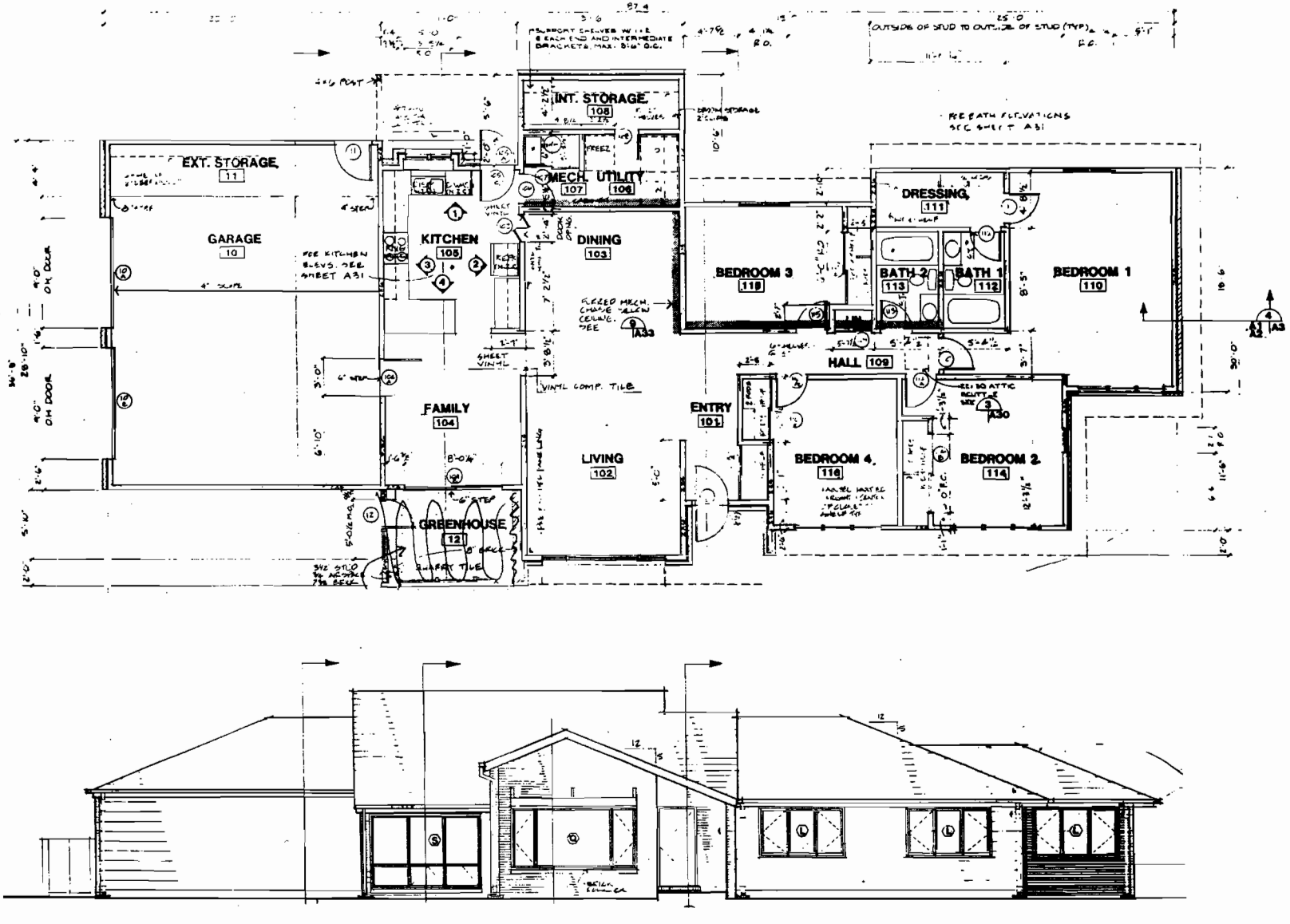
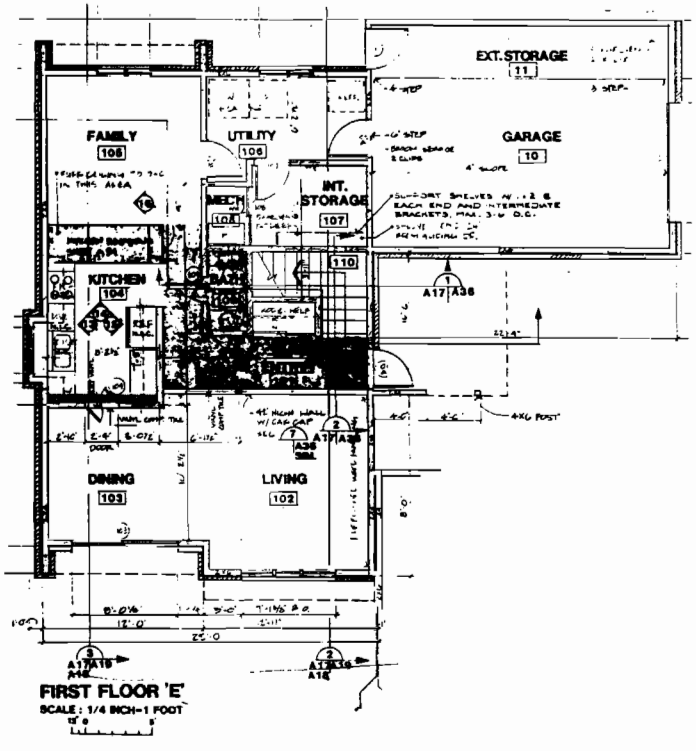
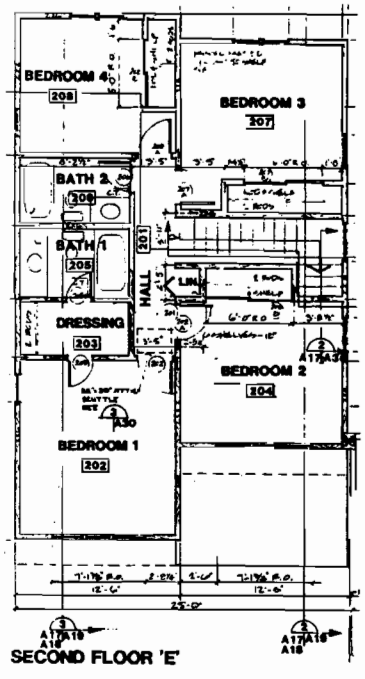


FIGURE A.1. Case-Study One-Story Single-Family Residence





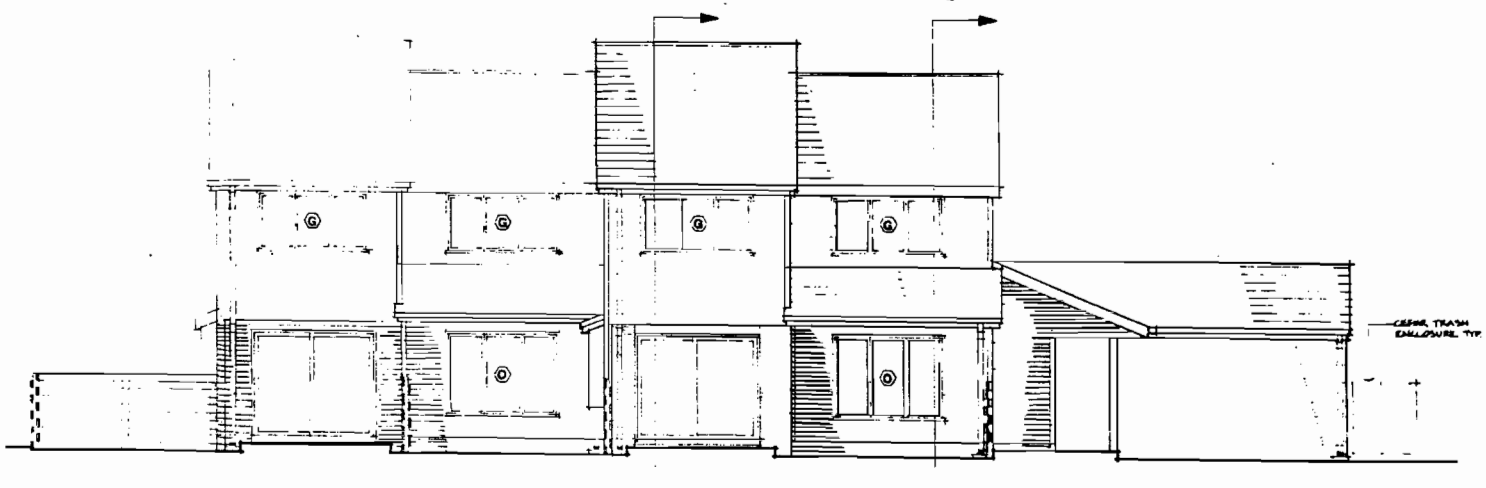
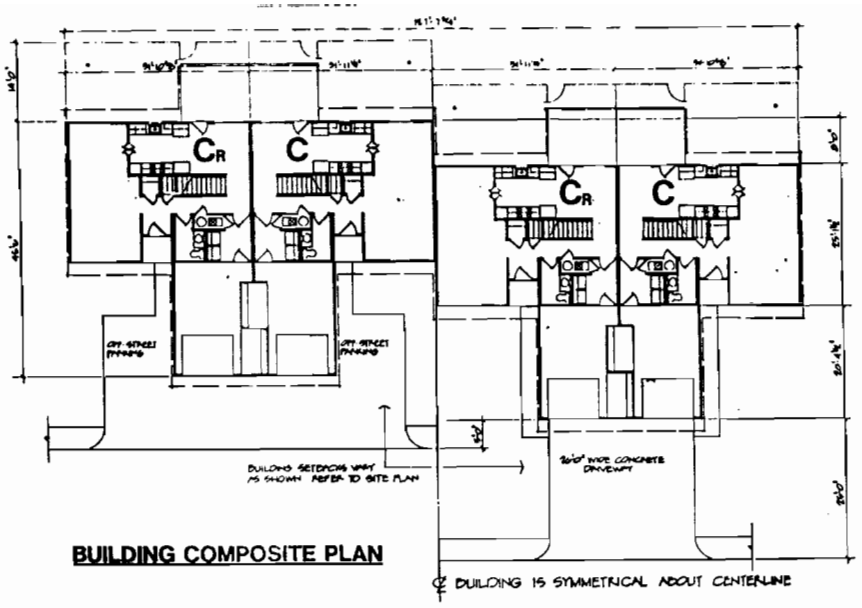
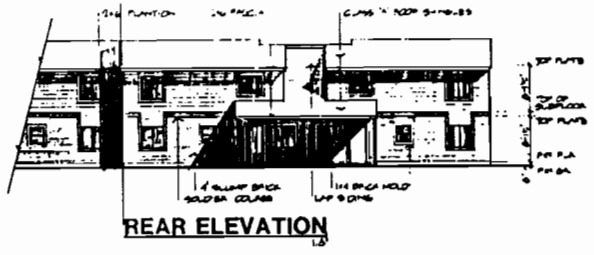


FIGURE A.2. Case-Study Two Story Single-Family Residence





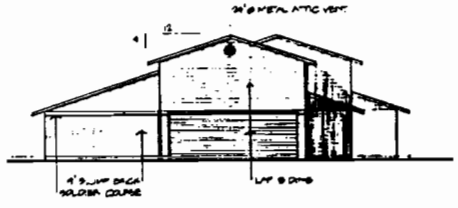


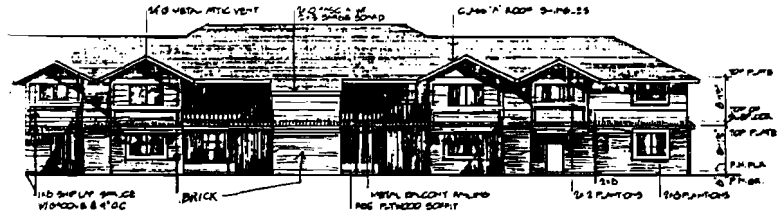
FIGURE A.3. Case-Study Townhouse Building

A.2.2 Apartments

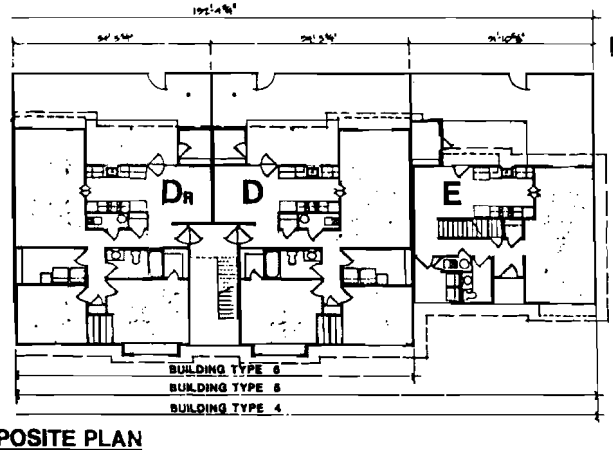
The case-study apartment unit pair consists of an upstairs unit and a downstairs unit, identical in plan and located one above the other. An apartment unit has 2 bedrooms and 1 bath, and is occupied by a family of 3. Each unit has a gross floor area of 1057 square feet. Upstairs units are carpeted except for the kitchen and bathroom. Like townhouses, the windows and doors in end-unit and middle-unit apartments are identical. The typical apartment building has 6 units (Figure A.4).

A.3 MANUFACTURED HOUSES

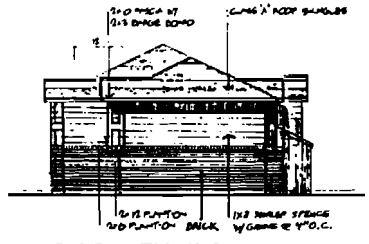
The case-study multisection manufactured home has 3 bedrooms and 2 baths, and is occupied by a family of 4. The unit has a gross floor area of 1263 square feet (Figure A.5). Case-study manufactured homes have some different characteristics from the case-study site-built homes. Rather than having brick veneer exterior finish, 100% wood siding is used. Exterior wall sheating is not used, and interior finishes are typically 1/2" gypsum board. Roof sheathing is 3/8" plywood. Foundations are not typically used, but a crawlspace is created by constructing a concrete perimeter skirting to give the appearance of a foundation. The floor space is insulated with fiberglass; its thickness varies with climate.



REAR ELEVATION



BUILDING COMPOSITE PLAN



SIDE ELEVATION

FRONT ELEVATION

EXTERIOR ELEVATIONS
BUILDING TYPES 4, 5 & 6

18

FIGURE A.4. Case-Study Apartment Building

24' x 56' MULTI-SECTION PROTOTYPE
PLAN

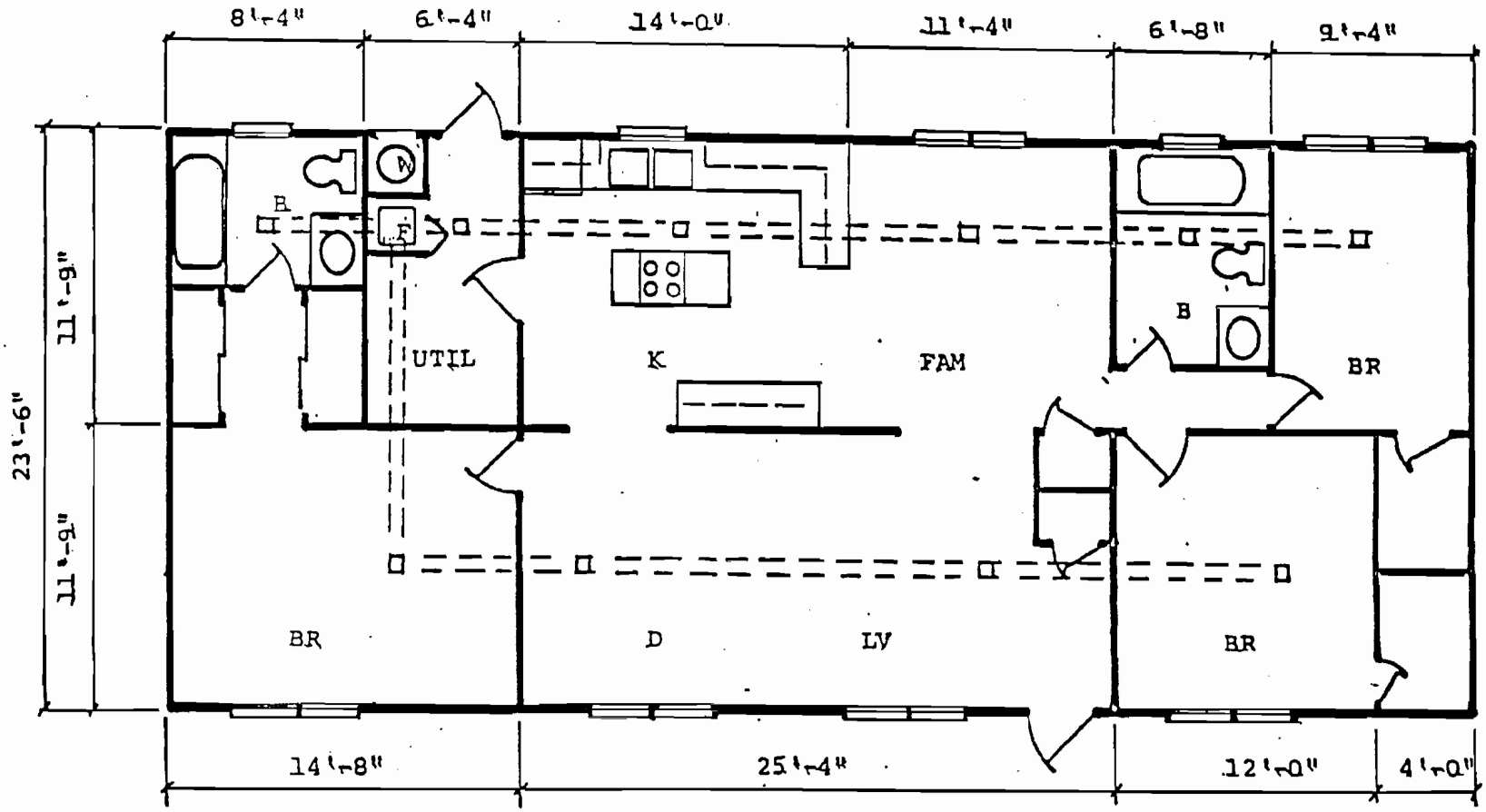


FIGURE A.5. Case-Study Multisection Manufactured Home

APPENDIX B

INDOOR AIR QUALITY MONITORING

APPENDIX B

INDOOR AIR QUALITY MONITORING

This appendix describes measurements of indoor air quality and air exchange rates taken in three occupied units of a multifamily housing complex at the Naval submarine base in Bangor, Washington, over five consecutive days during the heating season. Although three buildings do not constitute a representative sample, the measurements were taken to directly obtain some indication of indoor air quality in occupied federal residences for the indoor air quality modeling effort.

The Housing Division of the Bangor Naval Submarine Base assisted in finding volunteer residents to participate in this study. Three units were selected to participate based on their location within the housing complexes on the base and ease of access to the unit during the monitoring period. The 3 units were constructed in 1978 and are identical in size. Each unit was in a separate 2-story 4-unit complex. One unit was a downstairs unit and the other two units were upstairs units.

Indoor levels of daily air exchange rates, particulate matter, carbon monoxide (CO), nitrogen dioxide (NO_2), and formaldehyde were measured for about one week, and radon was measured for one month in each unit. Indoor and outdoor temperatures and windspeed were also recorded. Daily activity records (cooking, cleaning, tobacco use, window and door openings) were kept by each occupant. The instrumentation, measurement protocol, description of the units and a summary of the monitoring results for each units are discussed in the following sections.

B.1 INSTRUMENTATION

Air exchange rates were measured using perfluorocarbon tracer sampled by a programmable atmospheric tracer sampler. A portable weather station was set up to measure outdoor temperature, windspeed, and wind direction. Indoor temperature was measured using a thermistor and a bimetallic thermometer. Real-time

measurements of indoor concentrations of particulate matter and CO were taken daily in each residence. Week-long integrated measurements of indoor and outdoor formaldehyde and NO_2 and a month-long integrated measurement of radon were also taken. The instruments used to measure these parameters are listed below.

B.1.1 Air Exchange Rate

The air exchange rate was measured using perfluorocarbon tracer (PFT) gas. The principle of this technique is based on the steady-state assumption that the average concentration of a tracer gas or vapor in a structure is equal to the emission rate of the tracer source divided by the air exchange or infiltration rate of air. The tracer source is a fluoroelastomer plug impregnated with a known mass of PFT and crimped within a metal shell. The PFT diffuses from the end of the plug at a known rate, which somewhat depends on room temperature.

The tracer is captured by diffusion of the airborne gas onto a solid sorbent. The PFT was captured using a Gillian[(a)] Programmable Atmospheric Tracer Sampler (PATS) placed in each residence. The PATS units were programmed to capture the tracer gas onto stainless tubes containing the solid adsorbent at approximately 6- to 8-hour intervals for each tube during the monitoring period. The concentration of the tracer gas is determined on each sampling tube by gas chromatographic analysis. The air exchange rate is then calculated from the tracer gas concentration on each tube, the tracer gas emission rate from each source deployed (approximately 1 per every 500 ft^2), the sampling time, and the structure volume.

B.1.2 Indoor/Outdoor Temperature

Temperature was measured using thermistors and recorded on a data logger. Temperature was also recorded using a bimetallic thermometer. The outdoor thermistor was shielded.

(a) Gillian Instrument Corporation, Wayne, New Jersey.

B.1.3 Windspeed and Direction

Windspeed and direction were measured with a portable cup anemometer and wind vane set on the ground. The unit extended 10 ft above the ground and was set on a tripod. A battery-operated data logger recorded the data.

B.1.4 Particulate Matter

Particulate matter was measured with a GCA Corporation, Real-Time Aerosol Monitor, Model RAM-1. The RAM-1 measures aerosols from approximately 0.1 to 20 mm in diameter. The continuous readout of particulate matter concentration was recorded on a chart recorder.

B.1.5 Carbon Monoxide

Carbon monoxide (CO) was measured using a direct indicating SPE continuous digital readout electrochemical analyzer manufactured by General Electric Company, Aircraft Engine Group. The instrument is capable of detecting CO as low as 1 ppm with an accuracy of 10% of the reading. The continuous readout of CO level was recorded on a chart recorder.

B.1.6 Nitrogen Dioxide

Nitrogen dioxide (NO_2) was measured using an MDA Scientific Inc., Model 530, passive sampler. The sampler collects NO_2 according to the principles of molecular diffusion of NO_2 onto a coated disc built into the sampler. The amount of NO_2 is analyzed colormetrically. Exposure can be measured reliably within 10% accuracy.

B.1.7 Radon

Radon was measured by deploying a single Terradex Type F Track Etch®(a) radon detector inside the house. The Track Etch® detector is designed to be left in the measurement area for 30 days or more and can measure concentrations as low as 0.2 pCi/ℓ for an exposure time of 1 to 3 months.

(a) A registered trademark of the Terradex Corp., Walnut Creek, California.

B.1.8 Formaldehyde

Formaldehyde was measured indoors and outdoors using an Air Quality Research Inc., PF-1 passive integrated monitor. The monitor is capable of detecting formaldehyde concentrations as low as 0.001 ppm for a 7-day exposure period.

B.2 RESIDENCE DESCRIPTION

All three residences were located in recently constructed (about 1978) complexes. One of the residences is a downstairs unit of a four-plex and two residences are the upstairs units of a four-plex. The complexes are sheltered by a small hill on the west side bordering about half of the residential area.

The three residences each have 940 ft^2 with 8-ft ceilings and identical floor plans of two bedrooms, a living room/dining room, family room, kitchen, and one bathroom. The first-floor unit shares a common wall with a garage. Construction is wood framed with slab-on-grade for the first floor unit and a 2-in. concrete slab floor for the second-floor units. All units are about 75% carpeted, and none of the units have any combustion appliances or wood-burning facilities.

B.3 MEASUREMENT PROTOCOL

Each residence was surveyed to determine the locations for the instruments and the sources of the perfluorocarbon tracer gas. In each residence, the active instruments were placed in the main living area near an inside wall and away from windows and outside doors. Inside passive pollutant monitors for NO_2, radon and formaldehyde were hung from the ceiling in each residence. The inside temperature monitor was placed in the hallway, and an additional temperature probe was placed near the active instruments in the main living area. The outdoor monitors for NO_2 and formaldehyde were placed on the weather station.

The weather station to measure outdoor temperature, windspeed, and wind direction was placed behind the complexes. The data logger for the weather station was placed next to the building complex, and all sensor leads were run

to the residential unit. After the experiments were concluded, it was noted that the logger had not recorded the outdoor temperature and, therefore, these data were lost. However, temperature was recorded from thermometer readings, and these values were used.

B.3.1 Residence #1

Residence #1 is an upstairs unit occupied by three people, one of whom smoked. The residence was monitored from Monday, November 7, until Saturday, November 12, for air exchange and all pollutants including radon. Monitoring for radon continued until December 7.

Two sources of perfluorocarbon were placed in this residence 24 hours before air infiltration was measured. One source was placed in the family room, and the other was placed in the hallway attached to the thermistor.

Particulate matter was monitored every other day because only one instrument was available to monitor residences #1 and #2. The second particulate matter instrument scheduled to be used was too noisy. The remaining instrument was therefore shuttled between residences #1 and #2. In addition, the CO monitor malfunctioned Thursday night and Friday morning, so those data were lost.

The tracer gas was sampled for air exchange rate every 8 hours, starting at 8 pm on November 7. Beginning on November 8, the occupants kept daily activity records.

B.3.2 Residence #2

Residence #2 is a downstairs unit occupied by four people, two of whom smoked. The residence was monitored from Tuesday, November 8, through Saturday, November 12, for air exchange rate and for all pollutants including radon. Monitoring for radon continued until December 9.

Two perfluorocarbon sources were placed in this residence 24 hours before monitoring. One was placed in the hallway near the bedrooms, and the other on the temperature probe between the family and dining rooms. Particulate matter was sampled every other day for residence #1. Sampling of CO was not performed on Saturday and the instrument malfunctioned on Friday and the data were

lost. Tracer gas concentration was sampled every 6.3 hours from November 8 at 8 pm until 12 am on November 12. Daily activity records were kept by the occupants beginning November 9.

B.3.3 Residence #3

Residence #3 is an upstairs unit occupied by three people, none of whom smoked. This residence was monitored from Monday, November 14, until Saturday, November 19.

Only one source of perfluorocarbon tracer was placed in this residence, 24 hours before monitoring. The tracer was sampled using the PATS unit every 8 hours, beginning at 10 pm on November 14 and ending at 9 am on November 19. Carbon monoxide and particulate matter were continuously monitored during that period. A daily activity record was kept by the occupants beginning on November 14.

Indoor temperature was measured by a thermistor hung in the hallway and the perfluorocarbon source was attached to this thermistor. Temperature was also recorded using a bimetallic thermometer near the PATS unit.

B.4 RESULTS OF AIR QUALITY AND AIR EXCHANGE MEASUREMENTS

The monitoring results for residence #1 (upstairs unit) are summarized in Table B.1. Mean concentrations and standard deviations and monitoring times are given for each pollutant for each day of the monitoring. Mean values of air exchange rate are listed. The values for formaldehyde, nitrogen dioxide, and radon are average values for the given time period. Table B.1 also gives mean daily temperature difference (outside-inside) and daily average windspeed. Also noted are any significant activities recorded on the daily activity forms. The PATS unit sampled the tracer gas every 8 hours during the monitoring period.

The monitoring results for residence #2 (downstairs unit) are summarized in Table B.2. Mean concentrations and standard deviations are given for each pollutant monitored for each monitoring period indicated. Daily average air

TABLE B.1. Summary of Measurements in Residence #1

Day/Date	Time	Parameter	Average Values	Notes/Significant Activities
Monday 11/07	1400-2400	Temperature Difference	Not Noted	
	0000-2400	Windspeed	0.5 m/s	
	1400-1830	Particulate Matter	<10 $\mu g/m^3$	
	1500-1800	Carbon Monoxide	<1 ppm	None
	2000-0400 (11/08)	Air Exchange Rate	0.26 ACH	
Tuesday 11/08	0000-2400	Temperature Difference	13.9°C	
	0000-2400	Windspeed	0.7 m/s	
	0000-1600	Particulate Matter	Missing	Child played with equipment
	0700-1600	Carbon Monoxide	Missing	Child played with equipment
	1600-2400	Carbon Monoxide	<1 ppm	7 cigarettes smoked during evening
	0400-0400 (11/09)	Air Exchange Rate	0.30 ACH	
Wednesday 11/09	0000-2400	Temperature Difference	14.4°C	
	0000-2400	Windspeed	0.9 m/s	
	1600-2400	Particulate Matter	35 ± 8 $\mu g/m^3$	5 cigarettes smoked during evening
	0100-2400	Carbon Monoxide	1.8 ± 0.5 ppm	
	0400-0400 (11/10)	Air Exchange Rate	0.28 ACH	
Thursday 11/10	0000-2400	Temperature Difference	12.8°C	
	0000-2400	Windspeed	1.6 m/s	
	0000-1500	Particulate Matter	<10 $\mu g/m^3$	No cigarettes smoked during day
	0000-1600	Carbon Monoxide	<1 ppm	
	1600-2400	Carbon Monoxide	Missing	Instrument Malfunctioned
	0400-0400 (11/11)	Air Exchange Rate	0.52 ACH	
Friday 11/11	0000-2400	Temperature Difference	13.9°C	
	0000-2400	Windspeed	1.2 m/s	
	1100-2400	Particulate Matter	32 ± 30 $\mu g/m^3$	4 cigarettes smoked during evening
	0000-1100	Carbon Monoxide	Missing	
	1100-1500	Carbon Monoxide	<1 ppm	Instrument Malfunctioned
	0400-2000	Air Exchange Rate	0.52 ACH	
Saturday 11/12	0000-1200	Particulate Matter	41.5 ± 27 $\mu g/m^3$	8 cigarettes smoked
	0000-2400	Windspeed	2.5 m/s	
11/07-11/11		Air Exchange Rate	0.38 ± 0.1 ACH	
11/07-11/12	(120 h)	Nitrogen Dioxide (inside)	<0.003 ppm[a]	
11/07-11/12	(120 h)	Nitrogen Dioxide (outside)	<0.003 ppm[a]	
11/07-12/07		Radon	1.8 pCi/l[b]	
11/07-11/12	(169 h)	Formaldehyde (inside)	0.089 ppm[c]	
11/07-11/12	(169 h)	Formaldehyde (outside)	0.01 ppm[c]	

(a) ±20%.
(b) ±12.5%.
(c) ±15%.

TABLE B.2. Summary of Measurements in Residence #2

Day/Date	Time	Parameter	Average Values	Notes/Significant Activities
Tuesday 11/08	1600-2400	Temperature Difference	14.4°C	Activity record not completed
	0000-2400	Windspeed	0.7 m/s	
	1600-2400	Particulate Matter	31 ± 13 $\mu g/m^3$	
	1200-2400	Carbon Monoxide	1.4 ± 0.8 ppm	
	2000-0200 (11/09)	Air Exchange Rate	0.31 ACH	
Wednesday 11/09	0000-2400	Temperature Difference	13.3°C	
	0000-2400	Windspeed	0.9 m/s	
	0000-1600	Particulate Matter	21 ± 12 $\mu g/m^3$	6 cigarettes smoked
	0000-1500	Carbon Monoxide	1.2 ± 1.6 ppm	Cloths dryer used 2 h
	0200-0330 (11/10)	Air Exchange Rate	0.37 ACH	
Thursday 11/10	0000-2400	Temperature Difference	14.4°C	
	0000-2400	Windspeed	1.6 m/s	
	1500-2400	Particulate Matter	46 ± 14 $\mu g/m^3$	10 cigarettes smoked during day
	1500-2200	Carbon Monoxide	2.6 ± 0.7 ppm	
	2200-0000	Carbon Monoxide	Missing	
	0330-0400 (11/11)	Air Exchange Rate	0.24 ACH	
Friday 11/11	0000-2400	Temperature Difference	12.2°C	Dryer used 1 h
	0000-2400	Windspeed	1.2 m/s	
	0000-1000	Particulate Matter	24 ± 19 $\mu g/m^3$	9 cigarettes smoked during day
	0000-2400	Carbon Monoxide	Missing	Instrument malfunctioned
	0400-2400	Air Exchange Rate	0.29 ACH	Kitchen exhaust fan used
Saturday 11/12	0000-2400	Windspeed	2.5 m/s	
	0000-1200	Air Exchange Rate	0.22 ACH	
11/08-11/12		Air Exchange Rate	0.29 ± 0.06 ACH	
11/08-11/12	(96 h)	Nitrogen Dioxide (inside)	<0.004 ppm[a]	
11/08-11/12	(120 h)	Nitrogen Dioxide (outside)	<0.003 ppm[a]	
11/08-12/09		Radon	2.9 pCi/l[b]	
11/07-11/12	(169h)	Formaldehyde (outside)	0.01 ppm[c]	

(a) ±20%.
(b) ±9.7%.
(c) ±15%.

exchange rates are also given, along with daily average windspeed and temperature difference (inside-outside). Also shown in Table B.2 are the significant activities recorded on the daily activity forms. The tracer gas was sampled every 6.3 hours and, therefore, air exchange rate was calculated for 6.3 hour intervals.

Table B.3 summarizes the monitoring results for residence #3 (upstairs unit). Mean concentrations and standard deviations are given for the pollutants monitored. All pollutants were monitored every day in this residence for the hours indicated. The daily average air exchange rates, windspeed, and temperature difference are also given. Significant daily activities are also identified.

TABLE B.3. Summary of Measurements in Residence #3

Day/Date	Time	Parameter	Average Values	Notes/Significant Activities
Monday 11/14	1100-2400	Temperature Difference	12.8°C	Vacuum used 1 h
	0000-2400	Windspeed	6.6 m/s	
	1100-2400	Particulate Matter	13 ± 6 $\mu g/m^3$	
	1100-2400	Carbon Monoxide	<1 ppm	Kitchen fan used 1 h
	2200-0600 (11/15)	Air Exchange Rate	0.69 ACH	Clothes dryer used 1 h
Tuesday 11/15	0000-2400	Temperature Difference	12.2°C	
	0000-2400	Windspeed	6.7 m/s	
	0000-2400	Particulate Matter	<10 $\mu g/m^3$	
	0000-2400	Carbon Monoxide	<1 ppm	Bath vent used 30 min
	0600-0600 (11/16)	Air Exchange Rate	0.69 ACH	
Wednesday 11/16	0000-2400	Temperature Difference	13.3°C	Windows open 3 h
	0000-2400	Windspeed	6.0 m/s	
	0000-2400	Particulate Matter	<10 $\mu g/m^3$	
	0000-2400	Carbon Monoxide	<1 ppm	Bath vent used 1 h
	0600-0600 (11/17)	Air Exchange Rate	1.14 ACH	Clothes dryer used 3 h
Thursday 11/17	0000-2400	Temperature Difference	15.6°C	
	0000-2400	Windspeed	3.5 m/s	
	0000-2400	Particulate Matter	<10 $\mu g/m^3$	Bath vent used 2 h
	0000-2400	Carbon Monoxide	<1 ppm	
	0600-0600 (11/18)	Air Exchange Rate	0.28 ACH	
Friday 11/18	0000-2400	Temperature Difference	14.4°C	Activity record not completed
	0000-2400	Windspeed	2.8 m/s	
	0000-2400	Particulate Matter	<10 $\mu g/m^3$	
	0000-2400	Carbon Monoxide	<1 ppm	
	0600-0600 (11/19)	Air Exchange Rate	0.31 ACH	
Saturday 11/19	0000-0900	Carbon Monoxide	<1 ppm	
	0000-0900	Particulate Matter	<10 $\mu g/m^3$	
11/12-11/19		Air Exchange Rate	0.62 ± 0.35 ACH	
11/12-11/19	(120 hrs)	Nitrogen Dioxide (inside #1)	<0.003 ppm[a]	
11/12-11/19	(120 hrs)	Nitrogen Dioxide (inside #2)	<0.003 ppm[a]	
11/10-11/19	(164 hrs)	Nitrogen Dioxide (outside)	<0.002 ppm[a]	
11/14-12/19		Radon	1.42 pCi/ℓ[b]	
11/12-11/19	(119 hrs)	Formaldehyde (inside)	0.124 ppm[c]	
11/12-11/19	(119 hrs)	Formaldehyde (outside)	0.005 ppm[c]	

(a) ±20%.
(b) 13.1%.
(c) ±15%.

APPENDIX C

INDOOR AIR QUALITY ANALYSIS

APPENDIX C

INDOOR AIR QUALITY ANALYSIS

This appendix identifies the methods used to compute pollutant levels for five pollutants and presents information on the source and character of a number of pollutants that cannot be quantified. For these five pollutants, information is available to allow computation of the incremental effects that residence design changes may have on the annual average concentration in residential air.

C.1 APPROACH

Indoor air pollutants can be transported to or can be released directly into the indoor environment from 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 dioxide (NO_2), radon and formaldehyde. For these six pollutants, quantitative evaluations were made using a computer model to compute pollutant steady-state concentration levels. For many other pollutants, quantitative information is not as complete, so the incremental change in pollution concentrations levels attributable to building design changes were not computed. For these pollutants, qualitative information is provided in an effort to determine if design changes could influence the level of these pollutants.

C.1.1 Computed Pollutant Levels

Long-term average concentrations of indoor pollutants were computed for nine case-study residences. The computations were made for each residential building before and after the proposed standard is applied. To develop these computations both residence ventilation rates and indoor pollutant source terms had to be identified. Source-term emanation rates were both intermittent (e.g., particulates and CO from smoking) and continuous (e.g., radon from soil and formaldehyde from building materials). A range of indoor pollutant concentrations was computed for each case-study residence: low, typical, and

maximum. The computed values represent the range of emission rates that are expected for each evaluated pollutant, based on computational and available information from the literature.

C.1.2 Nonquantified Pollutants

Hundreds of pollutants have been identified in residential indoor air. The literature was reviewed for qualitative information on these pollutants. Of particular interest is the range of chemical compound pollutants found in residential air and the source for these pollutants. Building materials, for example, can be a source of chemical pollutants. However, except for formaldehyde, little quantitative information is available on these chemicals. Even less quantitative information is available about the presence of microorganisms in residences. The focus of the latter part of the appendix is, thus, focused on factors that influence the presence of chemicals and the growth of microorganisms in the residential environment.

C.2 QUANTIFYING POLLUTANT LEVELS

The proposed design standard allows a great many residential design possibilities. To incorporate this range and to establish a reasonable scope for the analysis, nine residential buildings were chosen for analysis. Each building represents a major category of residential housing for both the public and private sectors. Indoor air pollutant levels in these nine residences were quantified using a computer simulation of the generation, buildup and dissipation of six pollutants in these residences.

C.2.1 Computation Methods

For computing indoor pollutant concentrations, methods that met the requirements for this assessment were selected (e.g., methods that provide reasonable and comparable estimates of indoor air quality across generically different building categories and between the baseline and proposed standard designs) without introducing unnecessary complicating factors. The computation methods described below are relatively simple; they are based primarily on the use of empirical emission factors that were derived from observations of indoor air quality as described in the literature. The use of these factors and the

representative residence characteristics and ventilation rates provides a consistent method for assessing incremental indoor air quality differences.

Although the computation methods selected are appropriate 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 those cases, more detailed methods may be needed if information on building characteristics, air-handling equipment, emissions, and ambient outdoor concentrations is available. Examples of such models are described in documents by the U.S. Environmental Protection Agency (EPA) (1978) and the Electric Power Research Institute (1981, 1985).

C.2.1.1 Method Used to Evaluate Continuous Sources

Continuous sources of contaminants were computed by a simple steady-state approach. Emanation rates from soils and building materials for contaminants such as radon and formaldehyde are available in the literature. Table C.1 lists pollutant source terms for indoor air concentration calculations taken from the literature. These rates are usually given as mass emission per time from either a surface area or a mass of material.

Equations for computing pollutant concentrations at steady state take the following general form (typical units shown below in parentheses):

$$\begin{array}{l}\text{Pollutant} \\ \text{Concentration} \\ \text{For Each Source}\end{array} = \text{Emanation Rate} \times \begin{array}{l}\text{Mass of} \\ \text{Emanating} \\ \text{Material}\end{array} \div \begin{array}{l}\text{Fresh Air} \\ \text{Exchange} \\ \text{Rate}\end{array} \div \begin{array}{l}\text{Building} \\ \text{Volume}\end{array}$$

$$(g/m^3) = \frac{g}{kg\ hr} \times (kg) \div \left(\frac{1}{hr}\right) \div (m^3) \qquad (C.1)$$

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

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 $\mu g/g$-day		Gupta 1982
	Plywood	0.03-9.2 $\mu g/g$-day		Gupta 1982
	Paneling	0.84-2.1 $\mu g/g$-day		Gupta 1982
	Fiberglass insulations	0.3-2.3 $\mu g/g$-day		Gupta 1982
	Clothing	0.2-4.9 $\mu g/g$-day		Gupta 1982
	Drapery	ND[a] -3.0 $\mu g/g$-day		Gupta 1982
	Paper products	0.03-0.36 $\mu g/g$-day		Gupta 1982
	Carpet	ND[a] -0.06 $\mu g/g$-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.

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

$$C = C_o + \sum_{i = 1,S} \frac{(Ei * Mi)}{V * I} \qquad (C.2)$$

where

C = long-term average pollutant concentration

C_o = average annual pollutant concentration in outdoor fresh air supply

i = pollutant source material

E = emanation rate for pollutant source material, i

M = mass of emanating materials

S = number of sources of the pollutant in the building

V = volume of building

I = the fresh air exchange rate for the pollutant.

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

$$I = (T + (R * f))/V \qquad (C.3)$$

where

T = the volume of outdoor air supplied per unit time within the building

R = recirculation flow

f = average removal efficiency for filtration on recirculating air

V = volume of building.

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.2.1.2 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 combustion pollutants from combustion sources, the following equation is used:

$$\text{Average Daily Concentration} = \frac{(E * t_1)}{24\ \text{hr} * I * V} + C_o \qquad (C.4)$$

where

E = the constant source term emission rate (e.g., mg/hr)

t = the duration of that source term (hr)

I = the air-infiltration rate (total air changes/hr)

V = the building volume in m^3

C_o = ambient concentration in supply air.

The ambient (background) concentration in the supply air was assumed as footnoted in Tables 3.7 through 3.12. The fraction of air pollutants introduced into the residence may vary. The computed pollutant level should be adjusted upward for residences located in areas where significant concentrations of a pollutant above those assumed for ambient conditions will be infiltrating the residence.

C.2.1.3 Method Used to Compute Radon Concentrations

Indoor radon concentrations are computed using

$$C = \frac{S + B + W}{V * I} + C_o \qquad (C.5)$$

where

C = radon concentration, pCi/ℓ

S = soil emission rate, pCi/hr

B = building emission rate, pCi/hr

W = water emission rate, pCi/hr

V = building volume (ℓ)

I = infiltration rate of outside air, total changes per hour

C_o = 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:

$$S = F * R * G * 3600 \qquad (C.6)$$

where

S = radon emission rate, pCi/hr

F = fractional air exchange between foundation and residence[a]

R = radon emanation rate, 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:

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

where

the subscripts f, w, and c refer to the total floor, walls and ceiling areas, respectively

p = densities of building material

a = emission surface area

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

(a) F is unity (one) for residences built slab-on-grade and with unvented crawl spaces. For residences with basement or vented crawl spaces, F is less than 1. All residences except mobile homes were assumed to be built as slab-on-grade; mobile homes were assumed to have a ventilated crawl space.

e = emanation rate

n = number of floors.

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. 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. The formula used for steady-state radon emission rate is:

$$W = R * U * E \qquad (C.8)$$

where

R = a constant (=0.6)

U = the water use per hour in the building

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

Table C.2 contains typical water-use values for certain activities. The use values may then be combined with the occupancy rate to obtain estimates of U. For specific buildings, the usage per fixture may be used as an alternative computation approach.

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

Building volume is computed using the physical dimensions of the building's usable area. Ambient radon concentrations of 0.25 pCi/ℓ were used. To estimate indoor radon concentration values, the concentrations from each source are computed and added to an assumed background value.

C.2.1.4 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:

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

where

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

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

M_i = mass of building material for ith source, kg

W = wall and ceiling insulation emission rate, $\mu g/m^2\text{-}hr$

A = total wall and ceiling area, m^2

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

V = the volume of the residence, m^3

I = the infiltration rate of outside air, total changes per hour

C_o = ambient outdoor formaldehyde concentrations, $\mu g/m^3$.

Formaldehyde emissions from the area of carpet specified for the representative buildings were used to estimate one portion of the indoor formaldehyde concentration.

The amount of formaldehyde released from insulation is highly variable. Although ureaformaldehyde 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). New building materials have a

higher total organics emission rate because of the aging effect on these pollutants' release rates (Miksch, Hollowell and Schmidt 1982).

The following relationship provides a typical emission rate from the insulation:

$$W = S_w * A \qquad (C.10)$$

where W = typical emission rate from insulation
S_w = the emission rate per area of wall
A = the total insulation wall area computed from the dimensions of the buildings.

Unlike the first two steady-state categories above (building materials and UFFI), the following steady-state relationship was derived from intermittent releases of formaldehyde from combustion:

$$E_i = (C_s * I_o) + (C_g * I_o) \qquad (C.11)$$

where E_i = steady-state relationship for formaldehyde
C_s = the computed air concentrations from smoking
C_g = the computed air concentrations from an unvented gas stove for a specific building at the baseline air exchange rate of I_o
I_o = the baseline air exchange rate.

As discussed above, ambient formaldehyde concentrations are very small, and C_o was set equal to zero. After each emission rate has been determined, formaldehyde concentrations for different air exchange rates may be computed.

C.2.2 Building Characteristics and Assumptions

Information on recently constructed military housing was examined to determine the current construction practices for military housing. From this assessment, nine types of residences were selected for case-study analysis. These typical residences are described in Appendix A. Blueprints and construction specifications were used to characterize the energy efficiency of the as-built residences (baseline). The plans and construction specifications were

then modified to meet building practices as proposed under the new proposed energy standard for each structure located at four different sites: New Orleans, LA; Barstow, CA; Washington, D.C.; and Sheridan, WY. These sites represent distinguishable types of climates for military housing. The construction specifications for each location were then tailored to meet the proposed standard. These revised construction specifications became the basis for characterizing energy-efficient military housing.

The floor plans for the residences designed according to the baseline and proposed standard are essentially the same. The layout of rooms and the space contained in each residence do not change. The principal difference between the residences designed according to the baseline and proposed standard is the tightness of the envelope and the location and amount of insulation placed in the buildings' envelopes.

Using the data derived from the literature (shown in Table C.1), minimum (min), typical, and maximum (max) emission rates for the various pollutant sources were assumed. Table C.3 summarizes the emission rates used in the simulation analysis of indoor pollutant concentrations. The radon computation assumed the following building material densities: concrete density, 143 lb/ft^3 (2304 kg/m^3) (Eschbach 1956); wood density, 27 lb/ft^3 (435 kg/m^3); and brick density 94 lb/ft^3 (1520 kg/m^3) (Lang 1956). A gas stove with an oven was included in the gas heated residential units. The stoves were assumed to operate several hours per day and no credit was given for possible external venting. The source terms for pollutants resulting from cigarette smoking are based on the number of smokers.

C.2.2.1 Fresh Air Ventilation

The exchange of outside air and indoor air is measured in air changes per hour (ACH). The principal means of exchanging indoor and outdoor air is through air infiltrating the envelope of the residence. The principal determinants of a building's ACH is the amount of cracks and other openings in a building's envelope, the temperature differential between indoor and outdoor air, and wind speed. Under special conditions of very low natural infiltration rates, air-to-air heat exchangers can be incorporated in the design of residential structures to increase the building's ACH.

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

Pollutant	Source	Min.	Typical	Max.	Units
Radon	Concrete	0.4	0.7	1.2	pCi/kg-hr
Radon	Red brick	0.1	0.1	0.1	pCi/kg-hr
Radon	Adobe brick	0.35	0.35	0.35	pCi/kg-hr
Radon	Drinking water	10	100	1,000	pCi/ℓ
Radon	Wood	0.02	0.02	0.02	pCi/kg-hr
Radon	Mix soil	0.1	0.32	10	pCi/m^2-sec
Particulate	Tobacco sm	10.8	10.8	10.8	mg/cigarette
Particulate	Gas stove	10	17	30	mg/burner-hr
Formaldehyde	Tobacco sm	1	1	1	mg/cigarette
Formaldehyde	Gas oven	25	25	25	mg/oven-hr
Formaldehyde	Gas stove	15	15	15	mg/burner-hr
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-hr
CO	Gas stove	200	1,000	1,800	mg/burner-hr
CO_2	Tobacco sm	80	80	80	mg/cigarette
CO_2	Gas oven	383,000	391,000	400,000	mg/oven-hr
CO_2	Gas stove	483,000	515,000	550,000	mg/burner-hr
CO_2	Respiration	8.91	8.91	8.91	mg/person-sec
NO_2	Gas oven	80	105	130	mg/oven-hr
NO_2	Gas stove	70	95	120	mg/burner-hr
NO_2	Tobacco sm	0.065	0.065	0.065	mg/cigarette

Baseline. Analysis of current design practice for all nine types of baseline residences indicates that a 0.7 ACH is a normal annual average for occupied residences. Under current design practices for the baseline residences, air-to-air heat exchangers are not required.

Proposed Standard. The proposed standard would increase the natural infiltration rate for some residential units in some locations and would require the use of air-to-air heat exchangers to meet the 0.7 ACH in other units and locations. Table C.4 shows the incremental change in the residential structures air exchange rate and whether an air-to-air heat exchanger is used.

Expected Air Exchange Rate. The correlation of residential infiltration air exchange rates with construction techniques and climate parameters is not well established. Typical models of air infiltration recognize three mechanisms as driving air infiltration: 1) temperature differences between indoors and outdoors cause a pressure differential because of buoyancy effects; 2) wind also creates a pressure differential across the building envelope; and 3) occupant behavior such as opening of doors for ingress and egress also contributes to infiltration. The two driving forces related to induced-pressure differentials 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.

Results from three large surveys of residential infiltration rates have been published. A paper by Grot and Clark (1979) presents blower door and tracer gas tests for 266 low-income housing units with ages ranging from new to 100 years old. The mean infiltration rate for the homes was 1.12 ACH. 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.

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 medium rate of 0.50 ACH were found for the sample. Again, average infiltration rates do not exhibit a clear relation to the climatic driving factors.

TABLE C.4. Incremental Change in Residential Air Exchange Rate (ACH difference between baseline and proposed standard)

Configuration[a]	New Orleans, LA	Barstow, CA	Washington, D.C.	Sheridan, WY
SFR-1S				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	0.3	-0-	-0-	-0-
SFR-2S				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	0.3	-0-	-0-	0.3
Townhouse-MU				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	-0-	-0-	-0-	-0-
Townhouse-EU				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	0.3	-0-	-0-	-0-
Apartment-MU-U				
Natural Gas	-0-	-0-	-0-[b]	-0-[b]
Electric Furnace	-0-	-0-	-0-[b]	-0-[b]
Electric Heat Pump	-0-	-0-	-0-[b]	-0-[b]
Apartment-MU-D				
Natural Gas	-0-	-0-	-0-[b]	-0-[b]
Electric Furnace	-0-	-0-	-0-[b]	-0-[b]
Electric Heat Pump	-0-	-0-	-0-[b]	-0-[b]
Apartment-EU-U				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	-0-	-0-	-0-	-0-
Apartment-EU-D				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	-0-	-0-	-0-	-0-
Mobile Home-MS				
Natural Gas	-0-	-0-	-0-	-0-
Electric Furnace	-0-	-0-	-0-	-0-
Electric Heat Pump	-0-	-0-	-0-	-0-

(a) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; MU = middle unit; EU = end unit; MU-U = middle unit, upstairs; MU-D = middle unit, downstairs; EU-U = end unit, upstairs; EU-D = end unit, downstairs; MS = multisection.
(b) An air-to-air heat exchanger is used to assure a 0.7 ACH.

Recently, Doyle et al. (1983) surveyed 58 houses in 4 cities and found infiltration rates varying from 0.5 to 1.0 ACH. The mean rate for the locations was 0.71 ACH. Average infiltration rates for each city again did not show a relationship to climate.

ASHRAE (1985) recommends adding an infiltration rate of 0.10 to 0.15 ACH to the rates published in Grot and Clark (1979) and Grimsrud, Sherman and Sondregger (1982) to account for occupant behavior when estimating infiltration over a large number of homes. The lack of a clear relationship between climatic driving forces and average infiltration rates may be partially explained by builders paying closer attention to caulking, sealing, and vapor barrier detailing in more severe climates. Adding to the uncertainty is the major variable of occupant behavior.

Because military residential construction tends to be relatively energy-efficient and well constructed, it is reasonable to assume that the infiltration rates found by Grimsrud, Sherman and Sondregger (1982) would apply. Adding the range of occupancy-influenced air exchange rate (0.10 to 0.15 ACH) to the median and mean rates results in a range of total infiltration rates of 0.60 to 0.78 ACH. An intermediate value of 0.7 ACH was assumed to represent current practice for this study. Insufficient data exist to determine whether significant differences in infiltration rates exist for manufactured and multi-family housing types compared to single-family residences, so this rate was assumed to apply to all case-study residences.

The proposed standard considers two alternate air infiltration rates. The higher rate of 1.0 ACH results from applying only a limited set of infiltration reducing measures. This relative change in infiltration rate is estimated from the relative increase in estimated leakage area. Similarly, a lower rate of 0.3 ACH resulting from very tight construction practices is estimated from the decrease in leakage area due to the measures. In very tight construction, the standard requires the use of an air-to-air heat exchanger to provide another 0.4 ACH of ventilation air, while recovering 75% of the heat from the exhaust air stream. Thus, the overall air exchange rate is maintained at 0.7 ACH, while heat losses are reduced to a level corresponding to 0.4 ACH.

C.2.2.2 Building Materials

The general characteristics of each of the nine residences are discussed in Appendix A. The eight site-built residences are all constructed slab-on-grade with wood frame walls and trussed system roofs. Building materials used in the representative residences for the eight site-built residences are shown in Table C.5.

Baseline. For the building materials listed in Table C.5, the amount of material used for a specific category of residence (e.g., single-family residence, one story) will be the same regardless of the location of the residence. The principal building material changes occurring in the baseline residences result from modifications in residence envelope to meet different climate conditions. The primary envelope change is the addition of envelope insulation. For example, wall insulation is increased from 3 1/2" fiberglass batt in New Orleans and Barstow to 5 1/2" fiberglass batt in Washington, D.C. and Sheridan; Table C.6 shows building insulation for the nine configurations for the baseline. (Modifications to envelope insulation thicknesses are also the principal change that occurs as the baseline residences are redesigned to meet the proposed standard.) Table C.6 also shows the area insulated for each type of residence, the type of insulation used and its thickness. Note that

TABLE C.5 Building Materials

Location	Materials
First Floor	Slab-on-grade
Second Floor	5/8" CDX plywood covered with 1 1/2" light-weight concrete
Floor Finish	First floor - vinyl floor tiles or sheet vinyl Second floor - carpet
Exterior Walls	50% Brick veneer 50% Wood siding over 1/2" plywood
Roof	Wood-trussed system Sheathing, 1/2" plywood
Interior Walls	5/8" Gypsum board
Windows	40% Drapes 60% Blinds
Cabinets	Hardwood for exposed surfaces Particle board for dividers, shelves and countertop bases

TABLE C.6 Building Insulation (Baseline)

Configuration[a]	Area Insulated (ft^2)				
	Outside Wall	Partition	Ceiling	Floor	Perimeter
SFR-1S	1233	-0-	1583	-0-	43
SFR-2S	1516	-0-	882	-0-	129
TH-MU 935	714	612	-0-	72	
TH-EU 1181	476	612	-0-	97	
APT-MU-U	622	277	951	-0-	-0-
APT-MU-D	622	277	-0-	-0-	124
APT-EU-U	788	111	951	-0-	-0-
APT-EU-D	788	111	-0-	-0-	149
MH-MS 952	-0-	1185	1333	-0-	

Location/ Insulation	Insulation Data			
	New Orleans, LA	Barstow, CA	Washington, D.C.	Sheridan, WY
Wall				
Type	Fiberglass[b]	Fiberglass	Fiberglass	Fiberglass
Thickness	3 1/2"	3 1/2"	5 1/2"	5 1/2"
Partition				
Type	Fiberglass	Fiberglass	Fiberglass	Fiberglass
Thickness[c]	3 1/2"	3 1/2"	3 1/2"	3 1/2"
Ceiling				
Type	Fiberglass	Fiberglass	Fiberglass	Fiberglass
Thickness	7"	7"	8 1/2"	10 1/2"
Floor				
Type	Fiberglass	Fiberglass	Fiberglass	Fiberglass
Thickness	5 1/2"	5 1/2"	5 1/2"	5 1/2"
Perimeter				
Type	N/A[d]	N/A	Styrofoam	Styrofoam
Thickness			1"	2"
Depth		1 1/2'	3'	

(a) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = mobile home, multisection.
(b) Fiberglass batt.
(c) Partition insulation is two 3 1/2" layers; one layer is associated with each unit.
(d) N/A = Not Applicable.

for the baseline residences, the insulation thickness for each type of residence depends on location, whereas the amount of area insulated does not.

Incremental Change. Table C.7 shows the incremental change in insulation thickness from the baseline residences to the proposed standard. For each location, the table shows the inches of insulation added or subtracted as a result of the design change. Whereas no differentiation was made for fuel costs in the baseline unit, for the proposed standard fuel costs have been used in determining the optimum amount of insulation designated for each residence and each location. As a result, insulation thickness may increase or decrease depending on the type of fuel used and location. Options available for heating a residence were assumed to be natural gas, electric resistance, or electric heat pump. Because of the relative costs of natural gas and electricity, electric heat pumps were normally the least-expensive option for residential heating. Perimeter insulation information in both Tables C.6 and C.7 is provided for thickness (inches) and depth (feet).

C.2.3 Pollutant Source-Term Information

Pollutants addressed in the computation of indoor air quality are discussed in more detail in the following sections. Table C.3 lists the source terms for the calculations of indoor air concentrations of those pollutants.

C.2.3.1 Suspended Particulate Matter

Tobacco smoke is a major contributor to the indoor concentration of respirable particulate matter (RSP) (particles less than 3.5 μm in diameter). An average of 18 μg of particulates per mg of tobacco has been reported for sidestream cigarette smoke (Girman et al. 1982). Based on 600 mg of fuel per cigarette, smoking a cigarette will generate 11 mg of particulates. Gas stoves contribute RSP emissions ranging from 10 to 30 mg/burner-hour. Normally, RSP produced by furnaces and hot water heaters are vented directly outdoors in residential buildings. Therefore, in this analysis, direct outside venting was assumed to remove suspended particulates from all sources but gas-cooking appliances and cigarette smoke.

TABLE C.7 Changes in Insulation Thickness from the Baseline Residences to the Proposed Standard

Geographic Location	Insulation Location	Heating Fuel Type[a]	Change in Insulation Thickness (baseline to proposed standard)								
			1 SFR-1S[b]	2 SFR-2S	3 TH-MU	4 TH-EU	5 APT-MU-U	6 APT-MU-D	7 APT-EU-U	8 APT-EU-D	9 MH-MS
New Orleans, LA	Wall	Gas	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
		Elec.-R	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
		-HP	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-	-0-
	Partition	Gas	N/A[c]	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		Elec.-R	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		-HP	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
	Ceiling	Gas	-3 1/2"	-3 1/2"	-1 1/2"	-3 1/2"	-3 1/2"	-0-	-3 1/2"	-0-	-3 1/2"
		Elec.-R	-1 1/2"	-1 1/2"	-1 1/2"	-1 1/2"	-1 1/2"	-0-	-1 1/2"	-0-	-3 1/2"
		-HP	-3 1/2"	-3 1/2"	-1 1/2"	-3 1/2"	-3 1/2"	-0-	-3 1/2"	-0-	-3 1/2"
	Floor	Gas	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2"
		Elec.-R	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2"
		-HP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-2"
	Foundation	Gas	1"/2'[d]	1"/2'	1"/2'	1"/2'	N/A	1"/2'	N/A	1"/2'	N/A
		Elec.-R	1"/2'	1"/2'	1"/2'	1"/2'	N/A	1"/2'	N/A	1"/2'	N/A
		-HP	1"/2'	1"/2'	1"/2'	1"/2'	N/A	1"/2'	N/A	1"/2'	N/A

(a) Elec.-R = Electric Resistance Heating; Elec.-HP = Electric Heat Pump Heating.
(b) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = mobile home, multisection.
(c) N/A = Not applicable.
(d) Foundation perimeter insulation thickness/depth.

TABLE C.7 (contd)

Geographic Location	Insulation Location	Heating Fuel Type[a]	Change in Insulation Thickness (baseline to proposed standard)								
			1 SFR-1S[b]	2 SFR-2S	3 TH-MU	4 TH-EU	5 APT-MU-U	6 APT-MU-D	7 APT-EU-U	8 APT-EU-D	9 MH-MS
Barstow, CA	Wall	Gas	2"	2"	2"	2"	2"	2"	2"	2"	2"
		Elec.-R	3"(c)	3"(c)	3"(c)	3"(c)	2"	2"	3"(c)	3"(c)	2"
		-HP	2"	2"	2"	2"	-0-	-0-	2"	2"	2"
	Partition	Gas	N/A[d]	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		Elec.-R	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		-HP	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
	Ceiling	Gas	1 1/2"	1 1/2"	1 1/2"	1 1/2"	-1 1/2"	-0-	1 1/2"	-0-	-1 1/2"
		Elec.-R	1 1/2"	1 1/2"	1 1/2"	1 1/2"	1 1/2"	-0-	1 1/2"	-0-	-1 1/2"
		-HP	1 1/2"	1 1/2"	1 1/2"	1 1/2"	-1 1/2"	-0-	1 1/2"	-0-	-1 1/2"
	Floor	Gas	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
		Elec.-R	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
			N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
	Foundation	Gas	1"/4'(e)	1"/4'	1"/4'	1"/4'	N/A	1"/2'	N/A	1"/2'	N/A
		Elec.-R	1"/4'	1"/4'	1"/4'	1"/4'	N/A	1"/2'	N/A	1"/2'	N/A
		-HP	1"/4'	1"/4'	1"/4'	1"/4'	N/A	1"/2'	N/A	1"/2'	N/A

(a) Elec.-R = Electric Resistance Heating; Elec.-HP = Electric Heat Pump Heating.
(b) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = mobile home, multisection.
(c) Two inches fiberglass plus 1 inch polyisocyanurate.
(d) N/A = Not applicable.
(e) Foundation perimeter insulation thickness/depth.

TABLE C.7 (contd)

Geographic Location	Insulation Location	Heating Fuel Type[a]	Change in Insulation Thickness (baseline to proposed standard)								
			1 SFR-1S[b]	2 SFR-2S	3 TH-MU	4 TH-EU	5 APT-MU-U	6 APT-MU-D	7 APT-EU-U	8 APT-EU-D	9 MH-MS
Washington, DC	Wall	Gas	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	-0-
		Elec.-R	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	-0-
		-HP	-0-	-0-	1"(c)	1"(c)	-2"	-2"	-2"	-2"	-2"
	Partition	Gas	N/A[d]	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		Elec.-R	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		-HP	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
	Ceiling	Gas	-0-	-0-	-0-	-0-	-0-	N/A	-0-	N/A	-3"
		Elec.-R	-0-	-0-	-0-	-0-	-0-	N/A	-0-	N/A	-3"
		-HP	-3"	-3"	-0-	-0-	-3"	N/A	-3"	N/A	-3"
	Floor	Gas	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
		Elec.-R	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
		-HP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
1/2'	Foundation N/A	Gas	0"/2 1/2'(e)	0"/2 1/2'	0"/2 1/2'	0"/1 1/2'	N/A	0"/2 1/2'		N/A	0"/2
		Elec.-R	0"/2 1/2'	0"/2 1/2'	0"/2 1/2'	0"/2 1/2'	N/A	0"/2 1/2'		N/A	0"/2
1/2'	N/A	-HP	0"/2 1/2'	0"/2 1/2'	0"/2 1/2'	0"/2 1/2'	N/A	0"/1/2'	N/A	0"/1/2'	N/A

(a) Elec.-R = Electric Resistance Heating; Elec.-HP = Electric Heat Pump Heating.
(b) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = mobile home, multisection.
(c) One inch polyisocyanurate insulation.
(d) N/A = Not applicable.
(e) Foundation perimeter insulation thickness/depth.

TABLE C.7 (contd)

Geographic Location	Insulation Location	Heating Fuel Type[a]	Change in Insulation Thickness (baseline to proposed standard)								
			1 SFR-1S[b]	2 SFR-2S	3 TH-MU	4 TH-EU	5 APT-MU-U	6 APT-MU-D	7 APT-EU-U	8 APT-EU-D	9 MH-MS
Sheridan, WY	Wall	Gas	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	-0-
		Elec.-R	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	1"(c)	-0-
		-HP	-0-	-0-	1"(c)	1"(c)	1"(c)	1"(c)	-0-	-0-	-0-
	Partition	Gas	N/A[d]	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		Elec.-R	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
		-HP	N/A	N/A	-0-	-0-	-0-	-0-	-0-	-0-	N/A
	Ceiling	Gas	-2"	-2"	-2"	-2"	-2"	N/A	-2"	N/A	-5"
		Elec.-R	-2"	-2"	-2"	-2"	-2"	N/A	-2"	N/A	-5"
		-HP	-5"	-5"	-2"	-2"	-2"	N/A	-5"	N/A	-8"
	Floor	Gas	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
		Elec.-R	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
		-HP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0-
	Foundation	Gas	-1"/1'(e)	-1"/1'	-1"/-1'	-1/-1'	N/A	-1"/-1'	N/A	-1"/-1'	N/A
		Elec.-R	-1"/1'	-1"/1'	-1"/-1'	-1"/-1'	N/A	-1"/-1'	N/A	-1"/-1'	N/A
		HP	-1"/1'	-1"/-1'	-1"/-1'	-1"/-1'	N/A	-1"/-1'	N/A	-1"/-1'	N/A

(a) Elec.-R = Electric Resistance Heating; Elec.-HP = Electric Heat Pump Heating.
(b) SFR-1S = single-family residence, 1 story; SFR-2S = single-family residence, 2 story; TH-MU = townhouse, middle unit; TH-EU = townhouse, end unit; APT-MU-U = apartment, middle unit, upstairs; APT-MU-D = apartment, middle unit, downstairs; APT-EU-U = apartment, end unit, upstairs; APT-EU-D = apartment, end unit, downstairs; MH-MS = mobile home, multisection.
(c) One inch polyisocyanurate insulation.
(d) N/A = Not applicable.
(e) Foundation perimeter insulation thickness/depth.

C.2.3.2 Carbon Monoxide

The greatest indoor source of CO is combustion. CO emissions range from 1.3 to 3.0 g/hr for steady-state operation of a gas stove oven (Girman et al. 1981) and 0.2 to 1.8 g/hr for a gas stove burner (Cole et al. 1983).

Tobacco smoke is also a minor source of CO. An average of 105 mg is emitted per cigarette. This average includes sidestream CO as well as CO inhaled and exhaled during smoking. A major fraction of elevated CO levels is often from outdoor sources. Indoor sources tend to be small, except in residences where automobile exhaust may enter the building.

C.2.3.3 Carbon Dioxide

Most outdoor CO_2 is generated by metabolic activity. In addition to that source, combustion sources (stoves and cigarettes) contribute the greatest amount of CO_2 to indoor air. An average emission of 143 mg CO_2/cigarette has been measured for the combined mainstream and sidestream CO_2.

C.2.3.4 Oxides of Nitrogen

Combustion products from gas stoves are a primary potential source of oxides of nitrogen (NO, NO_2) (See Table C.1). As the table shows, estimated values for NO_2 range from 70 to 120 mg/hr for a burner, and from 80 to 130 mg/hr for the oven. A NO_2 source term for tobacco smoking has also been measured and averages 0.065 mg/cigarette.

C.2.3.5 Radon

The source terms for radon pertain to gaseous radon-222 and are all assumed to be steady state (see Table C.1). Radon will decay into alpha-emitting daughter products called radon progeny. In this decay series, uranium (^{238}U) decays to thorium (^{234}Th), which in turns decays to protactinium (^{230}Pa), etc., until the series stops at stable lead (^{206}Pb). Uranium is found in trace levels in earthen building materials and soil and at higher levels in mineralized areas. Consequently, radon gas also is found in these materials and readily diffuses into the atmosphere. Radium (^{226}Ra), the predecessor to ^{222}Rn in the series, is relatively soluble in water.

The greatest single source of radon is from the soil. Source terms from the soil range from 0.1 to 1 pCi/m^2-sec in the low-radon areas to 1 to 10 pCi/m^2-sec in high-radon 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 of the concrete. The magnitude of the source term depends on whether the slab is on soil in a mineralized or nonmineralized area because of the variation in radon emanation from the soil in these two areas. Brick (adobe and red) building material is also a source of gaseous radon.

Another major source of indoor radon is well water. Radon dissolves in water and will remain dissolved until the water is vented. The magnitude of radon released from water within the building will depend on the radon concentration in water (Table C.1), the number of occupants, and their water usage (washing, flushing, showering). Radon emission rates were selected to cover the expected range in residential buildings. 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). Soil and concrete emission rates covering a range from nonmineralized to mineralized areas were used. Because ambient outdoor radon concentrations show considerable variation due to soil and weather factors, a typical background value was chosen for this computation. In this analysis the water supplies for the residential buildings were assumed to be from base-wide supply systems.

C.2.3.6 Formaldehyde and Other Organics

The source strength of formaldehyde from building material and furnishings/carpet decreases with time, based on an emanation half-life for formaldehyde of 58 months (NRC 1981b; Gupta, Ulsamer and Preuss 1982). Recorded measurements of formaldehyde concentrations (for both mobile homes and other dwellings) in Table C.1 are not necessarily correlated with home age, temperature, humidity, or the amount of formaldehyde-emitting materials in the structure. They do, however, represent a typical range of values.

Formaldehyde is also a combustion product for such common substances as natural gas and tobacco. Typical emission rates range from 15 to 25 mg/hr for gas stoves and 1 mg/cigarette (NRC 1981a).

Formaldehyde concentrations that are normally found in the atmosphere are generally well below the detectable limits of measuring devices (5 $\mu g/m^3$). Atmospheric formaldehyde is not considered a major source for indoor air concentrations when compared to combustion and/or building material source terms.

C.3 PRESENCE OF NONQUANTIFIED POLLUTANTS

Residential air contains many pollutants other than those computed through applied simulation models discussed above. The following sections provide overview information on chemical compounds and microorganisms found in residential indoor air environments. 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.8. 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 residence, 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

TABLE C.8. 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.8. (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)
1-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.8. (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]
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.

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

C.3.1.1 Infiltration

Chemicals compounds can enter into the residential environment through infiltration of air coming from outside residential living space. For example, operating an automobile or storage of chemicals in an attached garage for a long period of time can be an important source of indoor pollutants. Another source is chemical concentrations in soil. 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

A major source for indoor air pollutants is episodic events. 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 the activity (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. Adequate ventilation can be provided in the same way in an energy-efficient home.

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.9). 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.9. 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.9. (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
Paradichlorobenzene	Deodorizers Cat Spray Dog Repellant
Pentachlorophenol	Wood Preservatives
Perchloroethylene	Spot Remover Prewash Spray

TABLE C.9. (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.10), 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,

TABLE C.10. 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 1.2[c]	44.1 34.5[c]	2.1 3.4
Nicotie	0.92 0.46[c]	1.69 1.27[c]	1.8 2.8
Benzo[a]pyrene	3.5×10^{-5} 4.4×10^{-5}	1.35×10^{-4} 1.99×10^{-4}	3.9 4.5
Pyrene	1.3×10^{-4} 2.70×10^{-4}	3.9×10^{-4} 1.011×10^{-3}	3.0 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.10. (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 ÷ mainstram 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.

but also dibenzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene, 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.11), but they also contribute to indoor air pollution. These compounds generally are eliminated by natural air exchange. Some

TABLE C.11. 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

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 ("Formaldehyde - Assessing the Risk" 1984).

C.3.1.4 Outgassing of Building Materials and Household Furnishings

Long-term emission of chemical compound 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 1) released slowly over time, or 2) contaminants can slowly be produced as a result of degradation by air oxidation, photoinitiation, or retropolymerization reactions. Contamination from these mechanisms will be magnified 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

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.12). Over 52 different compounds were identified (see Table C.13). About 68% of the compounds were aliphatic or aromatic hydrocarbons, and the remainder were ketones, alcohols, esters, aldehydes, and halogenatedalcanes.

Table C.14 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 categorized 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.15. 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.16). 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.16. The most frequently occurring compounds are footnoted. Compounds emitted by individual building construction and interior finish materials are listed by component in Table C.17, while compounds emitted by adhesives are listed in Table C.18. Many minor compounds were also identified but they were not listed by Hodgson et al. (1983) because

TABLE C.12. 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	Polystyrene	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.13. 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

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

No.	Type[a]	Organic Gases		No. of Contaminants		Suspected	Airway	Odorous
		Concentration (mg/m^3)	Emission Rate (mg/m^2-hr)	Detected	Identified	Carcinogens	Irritants	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.15. 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.

Because building materials and household goods are a necessary consequence of twentieth century living, the only alternative is source control to mitigate

TABLE C.16. Major Compounds Emitted by Building Construction and Inferior 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.16. (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.

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.17. 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.18. 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 quality pollutants with potential human health concerns 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 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.19. As shown in Table C.19, some systems or

TABLE C.19. 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.

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 designs in housing design often do not specifically address humidity control.

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 foundation are well suited to control transfer of molds into the living area (Pfeiffer 1980). The concrete slab should be on a sufficient gravel bed to create adequate drainage, and a sand layer should be on top of the gravel to protect the plastic vapor barrier. This arrangement is adequate to isolate the porous concrete slab from the cool moisture beneath to prevent the concrete from becoming a mold supporting incubator. (Molds grow in cooler-temperatured incuberators than do bacteria.) A plastic barrier sheeting that is chemically stable should be used to

prevent pollutant fumes and gases from being discharged. This foundation prevents the dust and unknown accumulation that can occur in crawlspace or pier and post construction.

Each house has a breathing process--movement of air into a house, out of the house, and through the house walls--that occurs by other means 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 have spores disseminated into the living area by 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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HEALTH IMPACTS OF SELECTED AIR POLLUTANTS

In this appendix the health impacts of the five residential indoor air pollutants that have been the most thoroughly studied for their impacts on human health are discussed: particulate matter, 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 (Elsen, 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 10 μm (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

CO (ppm)	1 hour exposure		8 hours exposure	
	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 ($p \sim 0.10$). 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 residences 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 x 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 lifespan 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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