LBL-25211

#3480

MACROMODEL FOR ASSESSING RESIDENTIAL CONCENTRATIONS OF COMBUSTION-GENERATED POLLUTANTS: MODEL DEVELOPMENT AND PRELIMINARY PREDICTIONS FOR CO, NO_2, AND RESPIRABLE SUSPENDED PARTICLES

by

Gregory W. Traynor,[1] Janet C. Aceti,[1], Michael G. Apte,[1]
Brian V. Smith,[1] Linda L. Green,[2] Ann Smith-Reiser,[3]
Kenneth M. Novak,[4] and David O. Moses[5]

1 Indoor Environment Program, Lawrence Berkeley Laboratory, Berkeley, CA 94720
2 Formerly with EA-Mueller, Inc., Baltimore, MD 21227
3 Energetics, Inc., Columbia, MD 21045
4 Formerly with Brookhaven National Laboratory, Upton, NY 11973
5 Office of Environmental Analysis, U.S. Department of Energy, Washington, DC 20585

January 1989

The work conducted at the Lawrence Berkeley Laboratory was supported by the Assistant Secretary for Environment, Safety and Health, Office of Environmental Analysis, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy under contract No. DE-AC03-76SF00098, and by the U.S. Consumer Product Safety Commission under Contract No. CPSC-IAG-86-1280 through the U.S. Department of Energy.

The work conducted at EA-Mueller, Inc., Energetics, Inc., and Brookhaven National Laboratory was supported by the Assistant Secretary for Environment, Safety and Health, Office of Environmental Analysis of the U.S. Department of Energy.

CONTENTS

PREFACE

This report is the first in a series intended to assess residential air-pollution concentrations in the U.S. housing stock. A "macromodel" has been developed to simulate/predict selected residential air-pollution concentration distributions across specified house populations. Combustion pollutants are initially addressed because (1) they are a major class of indoor pollutants with documented adverse health effects at elevated concentrations, (2) the underlying mathematical relationships are somewhat understood, and (3) sufficient input data exist to allow the macromodel to obtain results (i.e., predictions). This report addresses the macromodel development and preliminary predictions for carbon monoxide, nitrogen dioxide, and respirable suspended particles. Subsequent reports address (1) sensitivity analysis of the macromodel, (2) micro/macro comparisons, and (3) preliminary predictions for organic compounds and sulphur dioxide.

ABSTRACT

A simulation model (also call a "macromodel") has been developed to predict residential air pollutant concentration distributions for specified populations. The model inputs include the market penetration of pollution sources, pollution source characteristics (e.g., emission rates, source usage rates), building characteristics (e.g., house volume, air exchange rates), and meteorological parameters (e.g., outside temperature). Four geographically distinct regions of the U.S. have been modeled using Monte Carlo and deterministic simulation techniques. Single-source simulations were also conducted. The highest predicted CO and NO_2 residential concentrations were associated with the winter-time use of unvented gas and kerosene space heaters. The highest predicted respirable suspended particulate concentrations were associated with indoor cigarette smoking and the winter-time use of non-airtight wood stoves, radiant kerosene heaters, convective unvented gas space heaters, and oil forced-air furnaces. Future field studies in this area should (1) fill information gaps identified in this report, and (2) collect information on the macromodel input parameters to properly interpret the results. It is almost more important to measure the parameters that affect indoor concentration than it is to measure the concentrations themselves.

I. INTRODUCTION

Efforts to characterize the nature and levels of indoor air pollutants, especially in residences, have increased markedly over the last decade because of the recognition that indoor exposures to the public can be substantial. Numerous studies have found that indoor air-pollutant levels can often exceed, and occasionally greatly exceed, those outdoors (e.g., Nero *et al.*, 1986; Nitschke *et al.*, 1985; Spengler *et al.*, 1979; Wallace *et al.*, 1986; USDOE, 1985). In addition, human activity-pattern studies show that people spend approximately 90% of their time indoors and 65 to 70% of their time in their residences (Chapin, 1974; Quackenboss *et al.*, 1982; Spengler *et al.*, 1979; Szalai, 1972). Thus, although total human exposures include those occurring in occupational settings, outdoors, and in vehicles, indoor exposures to air pollutants are an important, possibly dominant, factor in total exposures to air pollutants, and residential exposures are an important, possibly dominant, factor in indoor exposures.

There are five major categories of indoor-pollution sources in the residential environment that have been identified as potential health threats to the occupants. These categories are (1) combustion pollutants (including some organic compounds) from a variety of sources including smoking, attached garages, and unvented or partially vented combustion appliances; (2) radon, primarily from the soil surrounding a residence; (3) organic compounds from building materials and consumer products (e.g., formaldehyde, solvents); (4) biological contaminants (e.g., microorganisms, molds, pet dander); and (5) remnants from past building practice (e.g., asbestos, lead).

Exposures to combustion pollutants are extremely important from a health perspective since there are 700 to 1000 deaths per year in the U.S. due to accidental carbon monoxide (CO) poisoning (USDHHS, 1986a; NSC, 1986), numerous non-fatal CO poisonings, various lung ailments caused or exacerbated by exposure to nitrogen dioxide (NO_2) (NAS, 1977; Ferris, 1978; Jakab, 1980), and a wide variety of organic compounds, many of which are mutagenic, emitted from some combustion sources (Peters, 1982; Skopek *et al.*, 1979; Tokiwa *et al.*, 1985; Traynor *et al.*, 1986; USDHHS, 1986b).

There have been extensive laboratory studies to characterize the pollutant emission rates of many sources and extensive field studies to characterize indoor concentrations because of the health importance of indoor combustion pollutants (USDOE, 1985). In addition, there have been recent studies to develop source usage-models for space-heating sources (Traynor *et al.*, 1987, Hemphill *et al.*, 1987). There is also information on the market penetration of many sources from surveys by utilities and other organizations. The development of a residential concentration simulation model (also called a "macromodel") addressing key combustion pollutants across specified populations is (1) possible because of the availability of appropriate models and data, and (2) desirable because of adverse health effects associated with exposures to combustion pollutants. The goal of this work is to develop the model to characterize the distribution of indoor combustion-pollutant concentrations in residences on a regional, temporal, and source basis.

There are other efforts to characterize indoor concentrations of radon (e.g., Nero *et al.*, 1986) and the potential health risk due to indoor organic compounds (e.g., McCann *et al.*, 1986). However, it would be necessary to collect additional information on source strength, source usage, emission rate, and/or market penetration to develop and obtain results from parallel simulation models for radon and organic compounds.

Although the simulation model presented here addresses residential pollutant concentrations, such concentrations are good estimates of both the indoor component of personal exposures and, in at least some cases, of total personal exposures. One study, using 23 participants in 23 houses, determined that 88% of the variation in total personal exposure to NO_2 was accounted for by the variation in indoor NO_2 concentrations averaged over the kitchen, bedroom, and living-room monitoring sites (Leaderer, *et al.*, 1986). Therefore, by characterizing the indoor concentrations of combustion pollutants, reasonably good estimates of the indoor component of total personal exposures and, in some cases, total personal exposures themselves can be obtained.

Approaches to assess total exposures to air pollutants fall into three categories: (1) personal monitoring (i.e., dosimetry); (2) monitoring of concentrations in the various human environments; and (3) modeling of exposures based on a wide array of information, including pollutant sources, building characteristics, pollutant behavior, and human activities. These approaches can be complementary. Moreover, the optimal approach depends on the specific pollutant being studied and the specific goals of the study. Exposure assessment, and the associated estimation of potential health risks, can have several objectives including (1) determining the magnitude of potential risks to public health; (2) examining dependence of exposures on various influencing factors, including pollutants sources, building-related factors, and life-style factors; and (3) analyzing the potential impact of changes in these factors, such as introduction of indoor air quality control strategies or reduction in ventilation rates to save energy.

The most direct way to quantify personal exposures, typically employed to determine occupational or total exposures, involves the use of personal monitors that are worn by, or placed near, each study subject. This approach yields a direct measurement of each subject's exposure to the pollutant being monitored. One drawback to this approach is that the relative contribution of various environment settings is not addressed. However, for many pollutants (e.g., radon) the evidence indicates that indoor exposures are dominant, so this drawback is not always important. In some situations, it may be sufficient to adopt the approach of area monitoring in selected indoor environments. Area monitoring requires pollutant monitoring in the various locations where people conduct their daily activities. A drawback to this approach, particularly if personal exposures are sought, is that unless it is known *a priori* where the subjects will be throughout the period of study, important environments can be missed. A more serious drawback is that expensive real-time pollution monitors are needed in each environmental setting (or microenvironment) the subject(s) can visit during the study period. Both of the above "micro" approaches to exposure assessment are very labor intensive and expensive, especially if used alone. And, although these studies are occasionally needed (e.g., for model calibration, verification, and/or quality-control/quality-assurance studies), they are economically impractical for use in large-scale multipollutant exposure-assessment or concentration-assessment studies.

Many indoor-pollution studies have provided information suited to estimate indoor concentrations/exposures based on a combination of indoor-pollution monitoring and the assessment of the factors that influence indoor concentrations, thus providing another approach to exposure assessment. These studies of indoor source emission rates, source usage rates, ventilation rates, pollutant reaction rates, etc., provide a basis for estimating indoor concentrations from mass-balance principles. This approach to exposure assessment can be used to extrapolate data acquired from a relatively small sample to a larger housing (or other building) population. In addition, the model can be the central element in concentration-/exposure assessments, in which data from a limited monitoring study become a reference against which the output of the simulation model may be compared. This approach has been described as a basis for simulating total air-pollution exposure by monitoring and/or modeling the air-pollution concentration distributions in a set of major microenvironments where the population spends time (Ott, 1980 and 1984). The pollutant concentration distributions are combined with actual or simulated human-activity patterns to determine the total exposure distributions for the study population. One advantage to this approach is its cost effectiveness. Another advantage is that high-exposure environmental settings can be targeted for mitigation measures to reduce total and/or indoor air-pollutant exposures. The work described in this report takes the third approach to simulate indoor concentrations, and hence first-order indoor exposures.

This macromodeling effort to assess indoor concentrations of combustion pollutants addresses carbon monoxide (CO), nitrogen dioxide (NO_2), and respirable suspended particles (RSP)--particles that are less than 2.5 μm in diameter--in single-family detached homes. Table I-1 lists the potential indoor combustion sources considered in this effort. Other potential sources such as cars in attached garages, cigars, pipes, coal stoves, wood and coal forced-air furnaces, kerosene lamps, fireplaces, indoor charcoal cooking, and candles have been excluded from this report either because of a serious lack of emission-rate or usage data or because of negligible (or unknown) market-penetration levels. The macromodel was developed to characterize the distribution of indoor concentrations across houses, including the high-exposure "tail" of the distribution, since these houses pose the greatest risk to their occupants. The macromodel developed here cannot address "catastrophic" events such as accidental CO poisoning but does address predicted concentration distributions for the bulk of homes in a specific population. This effort is an expansion of previously published ideas directed at efficiently utilizing monitoring and modeling efforts to understand the indoor combustion-related air-pollution picture (e.g., Ott, 1980; Ott, 1984; Sexton, *et al.* 1983; Nitschke *et al.*, 1985; Leaderer *et al.*, 1986; Ryan *et al.*, 1986; Quakenboss and Lebowitz, 1987; Traynor, 1987).

The macromodel is based on, and is an expansion of, mass-balance principles commonly used in indoor-air-quality (IAQ) studies. Keys to the model include building stock parameters relevant to IAQ (e.g., house volume, air exchange rate), market penetration of indoor combustion sources, and source-usage models. The macromodel takes advantage of laboratory and field research on appliance pollutant emission rates and pollutant-specific building-penetration factors and reactivity rates. The model also utilizes existing regional data from utilities, state agencies, Federal agencies, and trade organizations, when available, for model inputs. The model employs Monte Carlo and deterministic simulation techniques to combine model inputs yielding indoor-pollutant concentration distributions.

Four regions of the country were chosen for developing and operating the model. The regions are (1) the eastern part of the State of Washington and the western part of Idaho serviced by the Washington Water and Power (WWP) Company, including Spokane, WA; (2) the region of upstate New York serviced by the Rochester Gas and Electric (RGE) Corporation, including the city of Rochester, NY; (3) part of the region in northwestern California serviced by the Pacific Gas and Electric (PGE) Company; and (4) that portion of Louisiana served by the Louisiana Power and Light (LPL) Company. These regions were chosen because of the availability of housing-stock and appliance market-penetration data, because market penetration of space-heating appliances was significantly different among regions and because of homogeneous outdoor temperature profiles within each region. In the RGE region, primary space heating appliances are dominated by gas and oil forced-air furnaces; in the WWP region, a relatively high fraction of houses use wood stoves for primary heat; in the PGE region, gas wall/floor furnaces have a relatively high market penetration; and in the LPL region there is a high market penetration of unvented gas space heaters.

Chapter II of this report describes the model development. Chapter III summarizes the key input data used in the model (Appendix A contains a detailed description of the input data). Chapters IV and V present selected model results. Chapter VI presents conclusions and recommendations for future work. Appendices B and C present the results of a nine-house pilot study and selected graphic output of the macromodel, respectively.

The ultimate goals of this macromodeling approach to characterizing indoor concentrations/exposures are to (1) provide a method for ranking the importance of indoor sources that emit the same pollutant; (2) quantify indoor concentration distributions based on regional, temporal, source, or other key parameters that may influence indoor concentrations; (3) help to identify high-risk populations exposed to high indoor-pollutant concentrations; (4) provide field-study design assistance by determining key parameters to measure and information gaps to fill; (5) provide a tool for policy makers involved with energy conservation, new-housing codes, source emission rates, etc.; (6) identify key parameters to target for control/mitigation efforts; and (7) help estimate indoor-pollutant exposures for epidemiology studies. The macromodel can help achieve the latter goal by identifying high and low exposure subpopulations and by modeling the indoor concentrations in their residences.

References for Chapter I

Chapin, F.S. (1974) *Human Activity Patterns in the City.* Wiley-Interscience, New York, NY.

Ferris, B.G. (1978) Health effects of exposure to low levels of regulated air pollutants: a critical review. *J. Air Pollut. Control Assoc. 28:* 488-497.

Hemphill, C.P., Ryan, P.B., Billick, I.H., Nagda, N.L., Koontz, M.D., and Forthmann, R.C. (1987) Estimation of nitrogen dioxide concentrations in homes equipped with unvented gas space heaters. In *Indoor Air '87: Proceedings of The 4th International Conference on Indoor Air Quality and Climate, Vol. 1,* pp. 420-424, Institute of Water, Soil and Air Hygiene, Berlin (West).

Jakab, G.J. (1980) Nitrogen dioxide-induced susceptibility to acute respiratory illness: a perspective. *Bull. N.Y. Acad. Med.* **56**:847-855.

Leaderer, B.P., Zagraniski, R.T., Berwick, M., and Stolwijk, J.A.J. (1986). Assessment of exposure to indoor air contaminants from combustion sources: methodology and application. *Amer. J. of Epidemiol.* **124**:275-289.

McCann, J., Horn, L., Girman, J., and Nero, A.V. (1986) *Potential risks from exposure to organic carcinogens in indoor air.* Presented at EPA Symposium on the Application of Short-Term Bioassays in the Analysis of Complex Environmental Mixtures, Durham, NC, Oct. 20-23, 1986; also LBL-22474, Lawrence Berkeley Laboratory, Berkeley, CA.

NAS (1977) Nitrogen Oxides: *Medical and Biological Effects of Environmental Pollutants.* National Academy of Sciences, Washington, DC.

NSC (1986) *Accident Facts: 1986 Edition,* National Safety Council, Chicago, IL.

Nero, A.V., Schwehr, M.B., Nazaroff, W.W., and Revzan, K.L. (1986) Distribution of airborne radon-222 concentrations in U.S. homes. *Science* **234**:992-997.

Nitschke, I.A., Clarke, W.A., Clarkin, me, Traynor, G.W., and Wadach, J.B. (1985) *Indoor Air Quality, Infiltration and Ventilation in Residential Buildings.* W.S. Fleming & Associates, 5802 Court Street Rd., Syracuse, NY 13206; NYSERDA Report #85-10, New York State Energy Research and Development Authority, Albany, NY 12223.

Ott, W.R. (1980) Models of human exposure to air pollution. Technical Report No. 32, Study on statistics and environmental factors in health, Department of Statistics, Stanford University, Stanford, CA.

Ott, W.R. (1984) Exposure estimates based on computer generated activity patterns. *J. Toxicol. - Clin. Toxicol.* **21**:97-128.

Peters, J.A. (1982) POM emissions from residential woodburning: an environmental assessment. In *Residential Solid Fuels: Environmental Impacts and Solutions,* J.A. Cooper and D. Malek, eds., Oregon Graduate Center, Beaverton, OR, pp. 267-288.

Quackenboss, J.J., Kanarek, M.S., Spengler, J.D. and Letz, R. (1982) Personal monitoring for nitrogen dioxide exposure: methodology considerations for a community study. *Environ. Intern.* **8**:249-258.

Quackenboss, J.J. and Lebowitz, M.D. (1987) Requirements for exposure assessment, modeling and validation for human health effects studies. *Proceedings of the 80th Annual Meeting of APCA.* Paper #87-101.4. APCA, Pittsburgh, PA.

Ryan, P.B., Spengler, J.D., and Letz, R. (1986) Estimating personal exposures to NO_2. *Environ. Intern.* **12**:395-400.

Sexton, K., Letz, R., and Spengler, J.D. (1983) Estimating human exposure to nitrogen dioxide: an indoor/outdoor modeling approach. *Environ. Res.* **32**:151-166.

Skopek, T.R., Liber, H.L., Kaden, D.A., Hites, R.A. and Thilly, W.G. (1979) Mutation of human cells by kerosene soot. *JNCI* **63**:309-312.

Spengler, J.D., Ferris, B.G., Jr., Dockery, D.W., and Speizer, F.E. (1979) Sulfur dioxide and nitrogen dioxide levels inside and outside houses and the implications on health effects research. *Environ. Sci. & Technol.* **13**:1276-1280.

Szalai, A., ed. (1972) *The Use of Time: Daily Activities of Urban and Suburban Populations in Twelve Countries.* Morton Publishers, The Hauge, Netherlands.

Tokiwa, H., Nakagawa, R., and Horikawa, K. (1985) Mutagenic/carcinogenic agents in indoor pollutants: the dinitropyrenes generated by kerosene heaters and full gas and liquified petroleum gas burners. *Mutation Research* **157**:39-47.

Traynor, G.W., Apte, M.G., Sokol, H.A., Chuang, J.C., and Mumford, J.L. (1986) Selected organic pollutant emissions from unvented kerosene heaters. *Proceedings of the 79th Annual Meeting of the Air Pollution Control Association.* Paper #86-52.5. Air Pollution Control Association, Pittsburgh, PA.

Traynor, G.W. (1987) Field monitoring design considerations for assessing indoor exposure to combustion pollutants. *Atmos. Environ.* **21**:377-383.

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.F., Prill, R.J., Grimsrud, D.T. and Turk, B.H. (1987) The effects of infiltration and insulation on the source strengths and indoor air pollution from combustion space heating appliances. *J. Air Pollut. Control Assoc.* **38**:1011-1015.

USDOE (1985) *Indoor Air Quality Environmental Information Handbook: Combustion Sources.* Report #DOE/EV/10450-1, Office of Environmental Analysis, U.S. Department of Energy, Washington, DC 20585.

USDHHS (1986a) *Vital Statistics of the United States 1982: Volume II - Mortality,* Part A, U.S. Department of Health and Human Services, Public Health Service, National Center for Health Statistics, Hyattsville, MD.

USDHHS (1986b) *The Health Consequences of Involuntary Smoking: a Report of the Surgeon General.* U.S. Department of Health and Human Services, Public Health Service, Center for Disease Control, Rockville, MD.

Wallace, L.A. (1986) Personal exposure, indoor and outdoor air concentrations, and exhaled breath concentrations of selected volatile organic contaminants measured for 600 residents of New Jersey, North Dakota, North Carolina and California. *Toxicol. Environ. Chem.* **12**:215-236.

Table I-1. Combustion Sources Included in the Macromodel.

Source	Type of Ventilation
Space-Heating Sources:	
Unvented gas space heaters (Convective and Infrared)	Unvented
Unvented kerosene space heaters (Convective and Radiant)	Unvented
Airtight wood stoves	Gravity flue
Non-airtight wood stoves	Gravity flue
Forced-air furnaces (gas and oil)	Gravity flue
Gas water boilers	Gravity flue
Gas wall heaters	Gravity flue
Gas floor heaters	Gravity flue
Gas ranges	Unvented
Other Sources:	
Cigarette smoke	Unvented
Gas cooking ranges without hoods	Unvented
Gas cooking ranges with hoods	Mechanical ventilation
Gas water heaters	Gravity flue
Gas dryers	Gravity flue

II. MODEL DEVELOPMENT

The macromodel developed here takes advantage of (1) the mass-balance model commonly used in IAQ studies, (2) a source-usage model for space-heating appliances, and (3) an air-exchange-rate model. These individual models are combined into a larger "macromodel" that can describe indoor combustion-pollutant concentration distributions given the proper input data. The macromodel uses a combination of Monte Carlo and deterministic techniques to simulate or predict indoor air-pollution concentration distributions.

There were numerous practical decisions made during the model development resulting in explicit and implicit model assumptions. A major practical decision made as part of the model development was the use of the steady-state version of the mass-balance equation over a one-week time interval. A major explicit assumption of the model is that the house air is sufficiently mixed to treat the house as a single well-mixed zone. This assumption greatly decreases the complexity of the modeling effort and of the presentation of results.

The one-week time interval was chosen to reflect the five-weekday, two-weekend-day life-style of the majority of U.S. residents. One alternative of using a one-year time period was rejected because seasonal effects would be lost. Another alternative of using a one-hour time period was rejected because of the lack of hourly source-usage profiles, the lack of hourly field data to compare with modeled results, and the great difficulty associated with usefully presenting massive amounts of hourly data. Short-term (or hourly) concentrations can be considered as modifications to the one-week average and houses with high (or low) one-week average concentrations have the potential for high (or low) short-term peaks.

The steady-state version of the mass-balance model was chosen to describe one-week average indoor concentrations because of its simplicity, because of the lack of short-term data for many model inputs, and because the one-week time interval was greater than the daily variations associated with many of the input parameters (e.g., air exchange rates, source-usage rates, and outdoor air-pollution concentrations). The use of the steady-state version may introduce some error (bias) into the results if a severe, and unaccounted for, correlation exists between certain input parameters. However, some attention was given to address and eliminate the effects of known correlations, such as the correlation between space-heating requirements and house volumes and between space-heating requirements and air exchange rates. Future work will address errors introduced by using a one-week time period and the steady-state version of the mass-balance model.

The assumption of well-mixed air in the modeled houses was chosen, not only because of its simplicity, but because there was no alternative. The variations in the floor plans of houses, source locations, internal convective flows, and, most importantly, the location of people inside the houses make it virtually impossible to subdivide houses into more than one zone. Even if it were theoretically possible to intelligently subdivide a house into more than one zone, research has shown that personal exposures, specifically to NO_2, correlated better with the average of the kitchen, bedroom, and living-room sampling locations than with any individual sampling location (Leaderer *et al,* 1986). There are pollutant gradients within a house, especially in two-story houses and while a source is on; therefore, the location of the person in the house could cause that person to be exposed to a higher or lower concentration than the house average. However the systematic error associated with this assumption is expected to be low. Currently, a method for quantitatively correcting for such deviations from the average does not exist, thus adding further support for using the well-mixed air assumption. Future work will address the validity of the well-mixed air assumption. Table II-1 lists conversion factors between common units.

1. Nomenclature

a = air exchange rate (h^{-1});

A = total house surface area including ceiling and floor (m^2);

AM = arithmetic mean;

ASD = arithmetic standard deviation;

$A_w, A_f, A_c, A_d, A_{wn}$ = wall, floor, ceiling, outside door, and window surface areas (m^2);

A_{wa}, A_{wb} = area of above-grade wall and below-grade wall for a crawlspace or basement (m^2);

b = life-style factor (unitless);

C = indoor pollutant concentration ($\mu g/m^3$ or ppm);

C_o = outdoor pollutant concentration ($\mu g/m^3$ or ppm);

ϵ = appliance efficiency (unitless; 1 = 100% efficient);

E = source emission rate (μg/kJ or μg/cigarette);

ELA = effective leakage area (m^2);

F_v = appliance venting factor (unitless; 1 = 100% unvented);

f_s = reference stack parameter for infiltration model (430 m/h $℃^{0.5}$);

f_w	=	reference wind parameter for infiltration model (120,000 m^2/km^2);
GM	=	geometric mean;
GSD	=	geometric standard deviation;
H	=	total depth below grade (m);
k	=	reactivity rate, net rate of removal processes other than air flow (h^{-1});
N_1, N_2	=	normal random number [0,1];
P	=	penetration factor, fraction of outdoor contaminants that penetrate the building shell (unitless, 1 = 100% penetration);
Q	=	source-usage rate, same as house heating requirements for space heaters (kJ/h or cigarettes/h);
Q_f	=	house "free" heat (kJ/h);
q	=	heat content of dry air (1.2 $kJ/m^3℃$);
Q_{appl}	=	interior heat generated by appliances (kJ/h);
Q_{people}	=	interior heat generated by people (kJ/h);
Q_s	=	solar gain (kJ/h);
R_1, R_2	=	uniform random numbers [0,1];
S	=	pollutant source strength (μg/h or cm^3/h);
SLA	=	specific leakage area (unitless);
t	=	time (h);
ΔT	=	indoor/outdoor temperature difference (℃);
U	=	building shell thermal conductance ($kJ/hm^2℃$);
U_g	=	equivalent ground U-value of ($kJ/hm^2℃$);
U_{sf}	=	Equivalent floor U-value accounting for sub-floor influences ($kJ/hm^2℃$);

$U_w, U_f, U_c, U_d, U_{wn}$ = wall, floor, ceiling, outside door, window, U-values (kJ/hm²°C);

U_{wa}, U_{wb} = equivalent U-values for crawlspace/basement wall above grade and below grade (kJ/hm²°C);

U'_{slab} = slab heat-loss coefficient (kJ/hm°C)

V = house volume (m³);

v = wind speed (km/h);

Z_{appl} = wood-stove-flue flow rate (m³/h).

Table II-1 lists conversion factors between common units.

2. Mass-Balance Model

Four basic physical/chemical processes that describe the behavior of pollutants in an enclosed space were described by Turk (1963) and Alzona *et al.* (1979) and later used by Dockery and Spengler (1981) to analyze field samples of respirable suspended particles (RSP) and by Traynor *et al.* (1982) to determine pollutant emission rates from a gas range. The two processes that increase indoor contaminant levels are the flow of outdoor contaminants into the interior environment (less the fraction that is removed by the building shell) and the indoor generation of contaminants (i.e., the pollutant source strength). The two processes that decrease indoor contaminant levels are the flow of indoor air to the outside and the removal rate of indoor contaminants via various chemical and physical removal processes that occur completely indoors (e.g., wall adsorption). Turk (1963), Alzona *et al.* (1979), and Dockery and Spengler (1981) combined these processes into a single mass-balance model. The model assumes that the pollutant concentration of the air that flows out of the chamber is the same as the average indoor concentration. This assumption is always valid if the house air is well-mixed, but it can also be approximated without well-mixed air. The mathematical expression for the change in mass concentration of indoor contaminants, using notation similar to Dockery and Spengler (1981), is

$$dC = PaC_o dt + \frac{S}{V} dt - (a+k) C\, dt. \qquad (1)$$

If we assume C_o, P, a, S and k are constant, Eq. (1) can be solved for $C(t)$ to give

$$C(t) = \frac{PaC_o + S/V}{a+k}[1 - e^{-(a+k)t}] + C(0)e^{-(a+k)t}. \qquad (2)$$

Equation (2) describes the average (spatial) concentration of a pollutant in an enclosed space. This approach, which was used by Alzona *et al.* (1979) to describe the indoor particulate behavior, has been used for gases by Shair and Heitner (1974). When gases are used, the model is sometimes referred to as the "well-mixed chemical-reactor" model, and pollutant concentrations are typically reported as volumetric concentrations. Mass and volumetric concentrations for gases are linked by the ideal gas law.

At steady-state, Eq. (2) becomes

$$C = \frac{PaC_o + S/V}{a + k}. \tag{3}$$

3. Source-Strength Model

The pollutant source strength of a given indoor source is a combination of the source-usage rate, the source pollutant emission rate (also called the emission factor), and the degree of venting:

$$S = Q\,E\,F_v. \tag{4}$$

The source-usage rate *(Q)* for space-heating appliances is based on the heating requirements of the stove and is equal to the heat loss through conduction and infiltration minus the "free" heat (Traynor, *et al.* 1988), all modified by the appliance efficiency and a life-style factor. (The life-style factor can account for behavior such as underheating or overheating the house or heating only certain rooms of the house.)

$$Q = \frac{b}{\epsilon}(UA\Delta T + aVq\Delta T - Q_f). \tag{5}$$

Equation (5) is similar to that used by Hemphill *et al.* (1987) to interpret winter indoor NO_2 data in Texas houses with unvented gas space heaters. The life-style factor was assumed to be equal to one since one goal of the model is to assess the source-usage rate while the house is occupied. Free heat is a combination of solar heat gain, internal-appliance heat, and human-generated heat:

$$Q_f = Q_s + Q_{appl} + Q_{people}. \tag{6}$$

Using approximate values from ASHRAE (1985), Q_{appl} was estimated to be 2000 kJ/h, and Q_{people} was estimated to be 1000 kJ/h for a house with two adults and two children. Eq. (6) can be rewritten:

$$Q_f = Q_s + 3000\,kJ/h. \tag{7}$$

The solar heat gain is dominated by the solar radiation entering windows and is calculated for each region and each week of the year using a solar-gain factor, expressed as kJ/h per m^2 of window area, generated by the Computerized Instrumented Residential Audit (CIRA) computer program (Sonderegger *et al.*, 1982; Sonderegger and Dixon, 1983; BHKRA, 1984).

The $UA\Delta T$ term in Eq. (5) accounts for conduction losses through the building envelope. The whole-house U-value is a surface-area weighted average of individual component U-values of the ceiling, walls, exterior doors, windows, and floor including subfloor:

$$U = \frac{A_c U_c}{A} + \frac{A_w U_w}{A} + \frac{A_d U_d}{A} + \frac{A_{wn} U_{wn}}{A} + \frac{A_f U_{sf}}{A}. \tag{8}$$

Most surface-area and volume calculations were based on total floor area as reported by utility surveys (a length-to-width ratio of 1.5 and a ceiling height of 2.4 m were assumed). The fraction of two-story houses was determined from utility and housing-industry surveys, and the same fraction of houses with the largest floor areas were assumed to be two-story houses.

The window U-value is a weighted average of storm windows and nonstorm windows. Similarly, the door U-value is a weighted average of storm doors and nonstorm doors. The equivalent U-value for floors was calculated differently for houses with basements and crawlspaces than for houses with slab floors. U-value calculations and assumptions for crawlspaces and basements were based on algorithms from CIRA, whereas the U-value calculations and assumptions for slabs were based on algorithms from ASHRAE (1985). For basements and crawlspaces:

$$U_{sf} = \left(\frac{1}{U_f} + \frac{A_f}{A_{wa} U_{wa} + A_{wb} U_{wb} + A_f U_g} \right)^{-1}. \tag{9}$$

For basements, the above-grade basement height was assumed to be 0.9 m (3 ft) and the below-grade depth was assumed to be 1.2 m (4 ft) to calculate A_{wa} and A_{wa}, respectively. U_{wa} was assumed to be 9.2 kJ/hm^2°C and U_{wb} was assumed to be 3.1 kJ/hm^2°C.

For crawlspaces, the above-grade crawlspace height was assumed to be 0.3 m (1 ft), and the below-grade height was 0.9 m (3 ft) to calculate A_{wa} and A_{wb}, respectively. U_{wa} was assumed to be 9.2 kJ/hm^2°C, U_{wb} was assumed to be 4.8 kJ/hm^2°C, and U_g was assumed to be 1.6 kJ/hm^2°C.

For slabs, the heat loss is primarily through the perimeter of the slab. The equivalent UA term for slabs is the slab heat-loss coefficient (U'_{slab}) times the perimeter of the slab. By rearranging terms and assuming the length of the slab is 1.5 times the width, we can calculate an equivalent U-value for slabs:

$$U_{sf} = 4.1\, U'_{slab}\, A_f^{\,0.5}. \tag{10}$$

Further discussions on U-values used in the macromodel are contained in Chapter III and Appendix A.

4. Air Exchange Rate Model

A calculation of the air exchange rate is needed for Eqs. (3) and (5). The air exchange rate model consists of the infiltration model developed by Sherman and Grimsrud (1980) with an additional term to account for increased air exchange rates due to the use of a wood stove (Modera and Peterson, 1985). The air exchange rate model follows:

$$a = \frac{(ELA^2 f_s{}^2 \Delta T + ELA^2 f_w{}^2 v^2 + Z^2_{appl})^{0.5}}{V}, \tag{11}$$

and

$$ELA = SLA \ x \ A_f. \tag{12}$$

The stack parameter, f_s, and wind parameter, f_w, were calculated from standard reference conditions (Grimsrud *et al.*, 1981). Converting to the units used in this report, f_s equals 430 $m/h℃^{0.5}$ and f_w = 120,000 m^2/km^2. The air flow rates of wood stoves, Z_{appl}, were calculated from data reported by Traynor *et al.* (1987). The results showed that Z_{appl} was 76 m^3/h for airtight wood stoves, and 130 m^3/h for non-airtight wood stoves. (Although not used in this report, the flow rate for a wood stove used as a fireplace, i.e., wood stove with doors open, was calculated to be 190 m^3/h.)

There is no provision in the macromodel for the effects of open house doors and windows because of the lack of relevant models or data. This probably will cause the macromodel to underestimate the air exchange rates during the summer; however, predicted winter air exchange rates should be close to the actual rates.

5. Monte Carlo Simulation

The Monte Carlo simulation technique (Dahlquist and Bjork, 1984) was used to reconstruct or simulate the building stock from input parameter distributions.

For empirical distributions, the uniform random number generated by the computer was fractionated to reflect the empirical distribution itself. For log-normal distributions, the distribution was converted to log space, and the generation of a normal distribution was accomplished using the Box-Mueller transformation of uniform random numbers (Box and Mueller, 1958). The transformation is

$$N_1 = (-2 \ ln \ R_1)^{0.5} \ \cos(2\pi R_2) \tag{13}$$

$$N_2 = (-2 \ ln \ R_1)^{0.5} \ \sin(2\pi R_2), \tag{14}$$

where N_1 and N_2 are normally distributed (mean = 0; standard deviation = 1) and R_1 and R_2 are computer-generated random numbers uniformly distributed between zero and one.

The Monte Carlo technique was used to "create" a housing stock of 3500 houses. This number was chosen so that 35 houses would be beyond the extremes of the distribution precentiles (1% and 99%) reported in this paper. The physical characteristics of the houses (floor area, volume, insulation, specific leakage area, etc.), the number and type of sources, the emission rates of the sources, and the venting factors of the sources of each house were simulated in this manner. These parameters were then kept constant throughout the modeling process. The impact of changes in, for example, outdoor temperatures were then deterministically calculated using the previously described equations. No simulations of space-heating-appliance parameters, except usage rates, occurred after the housing stock was initially "created." Only the usage of non-space-heating sources was re-simulated each week. This may tend to reduce or dampen the high- and low-concentration tails of houses with indoor-pollutant levels dominated by non-space-heating sources.

6. Log-normal Distribution

The distributions of model input parameters are either empirical or log-normal. The use of normal distributions was rejected, even if used by the relevant report, because (1) negative numbers could be generated by the Monte Carlo simulation technique and (2) the actual data often fit a log-normal distribution better then a normal distribution. The latter is true if the reported ASD is close in magnitude to the AM.

Log-normal distributions are often appropriate if the following conditions exist: (1) the values vary widely (i.e., orders of magnitude); (2) the values are positive but can be close to zero; (3) the ASD is close in magnitude to the AM; and (4) a finite probability exists of having very large values (Leidel *et al.*, 1977). In general, a log-normal distribution can adequately describe a normal distribution and will typically have a GSD of 1.4 or less (Leidel *et al.*, 1977). However, normal distributions, in general, cannot approximate log-normal distributions.

Using a normal distribution, 66% of the data in the distribution are between the AM minus the ASD and the AM plus the ASD. Analogously, for a log-normal distribution, 66% of the data are between the GM divided by the GSD and the GM times the GSD.

Occasionally, we had to convert a normal distribution to a log-normal one using the following conversion equations obtained from Leidel *et al.*, 1977.

$$GM = AM^2/(AM^2 + ASD^2)^{0.5} \tag{15}$$

$$GSD = e^{[ln(1+ASD^2/AM^2)]^{0.5}}. \tag{16}$$

For more information on log-normal distributions, see Aitchison and Brown (1976).

References for Chapter II

Aitchison, J. and Brown, J.A.C. (1976) *The Lognormal Distribution with Special Reference to its Uses in Economics.* Cambridge University Press: Cambridge, U.K.

Alzona J. Cohen, B.L., Rudolph, H., Jow, H.N. and Frohliger, J.O. (1979) Indoor-outdoor relationships for airborne particulate matter of outdoor origin. *Atmos. Environ.* **13**:55-60.

ASHRAE (1985) *ASHRAE Handbook: 1985 Fundamentals, SI Edition,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

BHKRA (1984) *EEDO: Energy Economics of Design Options,* Burt Hill Kosar Rittelman Associates, Butler, PA.

Box, G.E.P. and Mueller, M.A. (1958) A note on the generation of random normal deviates. *Ann. Math. Statist.* **29**:610-613.

Dahlquist, G. and Bjork, A. (1984) *Numerical Methods*, translated by Ned Anderson, Prentice Hall, Inc., Englewood Cliffs, NJ.

Dockery, D.W. and Spengler, J.D. (1981) Indoor-outdoor relationships of respirable sulfates and particles. *Atmos. Environ.* **15**:335-343.

Grimsrud, D.T., Sonderegger, R.C., and Sherman, M.H. (1981) *Infiltration Measurements in Audit and Retrofit Programs.* LBL-12221, Lawrence Berkeley Laboratory, Berkeley, CA.

Hemphill, C.P., Ryan, P.B., Billick, I.H., Nagda, N.L., Koontz, M.D., and Fortmann, R.C. (1987) Estimation of nitrogen dioxide concentrations in homes equipped with unvented gas space heaters. In *Indoor Air '87: Proceedings of The 4th International Conference on Indoor Air Quality and Climate, Vol. 1,* pp. 420-424, Institute for Water, Soil, and Air Hygiene, Berlin (West).

Leaderer, B.P., Zagraniski, R.T., Berwick, M., and Stolwijk, J.A.J. (1986). Assessment of exposure to indoor air contaminants from combustion sources: methodology and application. *Amer. J. of Epidemiol.* **124**:276-289.

Leidel, N.A., Busch, K.A., and Lynch, J.R. (1977) *Occupational Exposure Sampling Strategy Manual,* National Institute of Occupational Safety and Health, Cincinnati, OH.

Modera, M. and Peterson, F. (1985) *Simplified Methods for Combining Mechanical Ventilation and Natural Infiltration.* LBL-18955, Lawrence Berkeley Laboratory, Berkeley, CA.

Shair, F.H. and Heitner, K.L. (1974) Theoretical model for relating indoor pollutant concentrations to those outside. *Environ. Sci. Technol.* **8**:444-451.

Sherman, M.H. and Grimsrud, D.T. (1980) Infiltration-pressurization correlation: simplified physical modeling. *ASHRAE Trans.* **86,II**:778-807.

Sonderegger, R.C., Garnier, J.Y., and Dixon, J.D. (1982) *Computerized Instrumented Residential Audit: CIRA.* Pub-425, Lawrence Berkeley Laboratory, Berkeley, CA.

Sonderegger, R.C., and Dixon, J.D. (1983) *CIRA -- A Microcomputer-based Energy Analysis and Auditing Tool for Residential Applications.* LBL-15720, Lawrence Berkeley Laboratory, Berkeley, CA.

Traynor, G.W., Anthon, D.W., and Hollowell, C.D. (1982) Technique for determining pollutant emissions from a gas-fired range. *Atmos. Environ.* **16**:2979-2987.

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.F., Grimsrud, D.T. and Gundel, L.A. (1987) Indoor air pollution due to emissions from wood-burning stoves. *Environ. Sci. & Technol.* **21**:691-697.

Traynor, G.W. Apte, M.G., Carruthers, A.R., Dillworth, J.F., Prill, R.J., Grimsrud, D.T., and Turk, B.H. (1988) The effects of infiltration and insulation on the source strengths and indoor air pollution from combustion space heating appliances. *J. Air Pollut. Control Assoc.* **38**:1011-1015.

Turk, A. (1963) Measurements of odorous vapors in test chambers: theoretical. *ASHRAE J.* **5**:55-58.

Table II-1. Conversion Factors Between Common Units

To convert from	To	Multiply by
kJ/h	W	0.278
W	kJ/h	3.6
kWh	kJ	3600
kJ	kWh	0.000278
kJ	Btu	0.95
Btu	kJ	1.05
lb/10^6 Btu	μg/kJ	430
μg/kJ	lb/10^6 Btu	0.0023
ft	m	0.305
m	ft	3.28

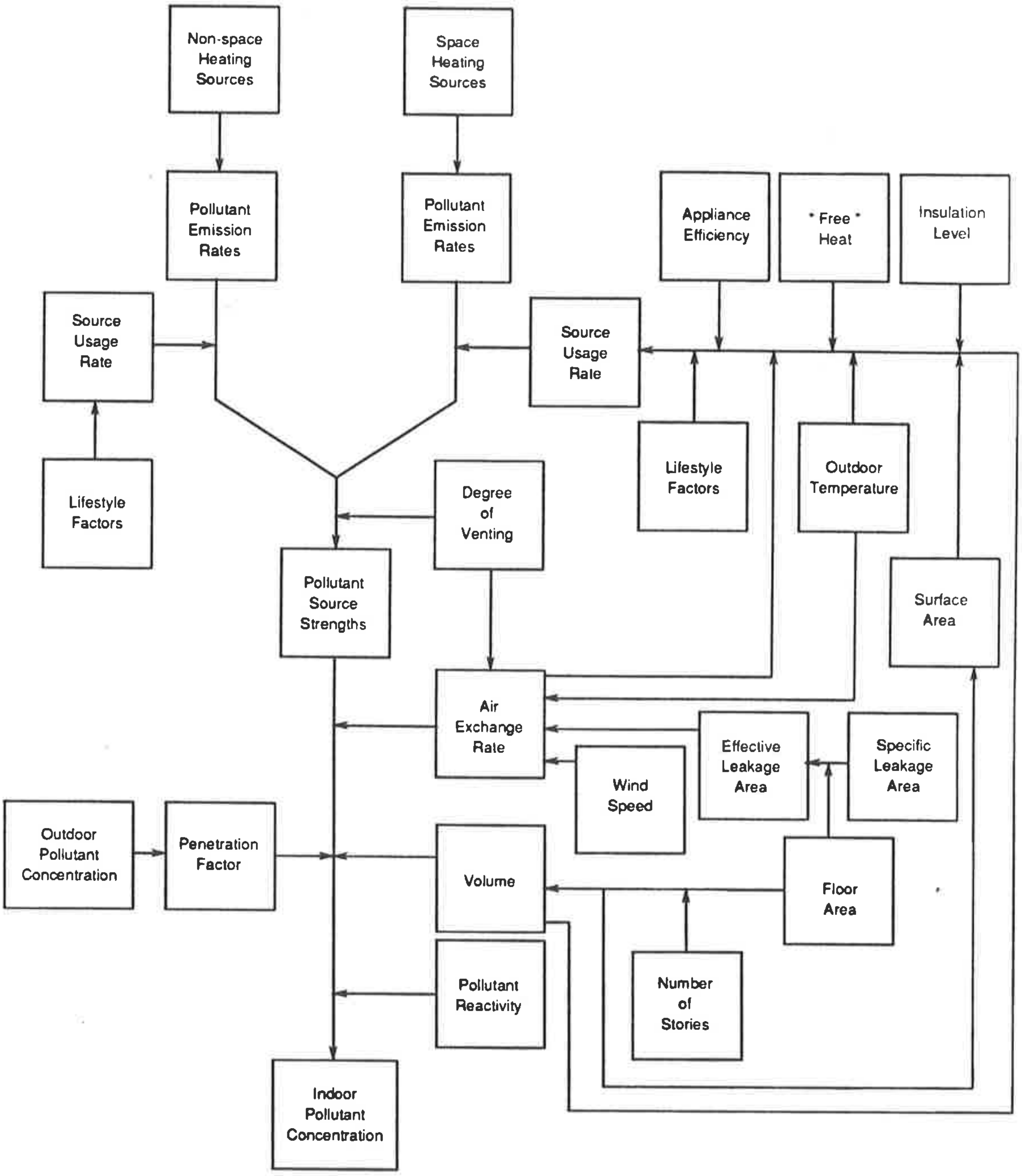


Figure II-1. Schematic diagram of data flow for key inputs to the combustion macromodel.

III. SUMMARY OF MACROMODEL INPUT PARAMETERS

This chapter contains a summary of the input parameters used to run the macromodel. A detailed discussion of these parameters is provided in Appendix A. The input parameters are divided into two categories: (1) parameters common to the entire U.S. housing stock (i.e., global parameters) and (2) region-specific parameters.

The four regions under study are areas within the boundaries of the following utility-company service areas: Rochester Gas and Electric (RGE) Corporation (New York); Washington Water Power (WWP) Company (Washington, Idaho); Pacific Gas and Electric (PGE) Company (California); and Louisiana Power and Light (LPL) Company (Louisiana). These particular regions were selected because (1) they represented four distinct geographic, climactic, and demographic areas of the country with different mixtures of space-heating appliances, and (2) the data required to run the macromodel were available. However, the macromodel could be used to model any area, provided sufficient input data were available.

Since the results generated by the macromodel are only as good as the input data, it is important that the data be carefully chosen and well documented. Unfortunately, the quality and applicability of the input data collected for this project varies widely. Many input parameters are well understood and a wealth of good data exists for them, but many input parameters have very little data available in the literature. In many cases, a "best-guess" approach has been taken using small data sets to form tentative input distributions.

The global parameters are summarized in Table III-1. Input distributions in this category include heating-appliance efficiencies; smoking frequency; carbon monoxide, nitrogen dioxide, and RSP emission rates from indoor-pollutant sources; venting factors for indoor-pollutant sources; pollutant penetration factors; and pollutant reactivities.

The regional input parameters are summarized in Table III-2. Parameter distributions in this category include market penetration of primary heating appliances, non-space-heating gas appliances, and the usage of non-space-heating gas appliances; house volumes; outdoor pollutant concentrations; building-component U-values for ceilings, walls, floors, windows, and doors; number of stories; outdoor temperatures; and specific leakage areas.

References for Chapter III

AGA (1980) *Space Heating Efficiency Program: 1978-79 Heating Season Status Report.* AGA Catalog No. 560080, American Gas Association, Washington D.C.

AGA (1985) *Gas Facts 1985 Data.* American Gas Association, Arlington, Virginia.

AIP (1985) *Energy Sources: Conservation and Renewables.* Chapter 16, Conference Proceedings #135. American Institute of Physics, New York, NY.

Apte M.G. (1988) Personal communication, Indoor Environment Program, Lawrence Berkeley Laboratory, Berkeley, CA. 94720

ASHRAE (1985) *Handbook of Fundamentals.* American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA.

Barrett, R., Miller, F. and Locklin, D. (1973) *Field Investigation of Emissions from Combustion Equipment for Space Heating.* EPA-R2-73-084A, Battelle-Columbus Laboratories. Prepared for the US Environmental Protection Agency, Washington, DC.

BPA (1983) *Pacific Northwest Residential Energy Survey.* Bonneville Power Administration, Portland, OR.

Bureau of the Census (1985) *Current Population Survey.* U.S. Department of Commerce, Washington, DC.

CARB (1985) *California Air Quality Data; Summary of 1985 Air Quality Data Gaseous and Particulate Pollutants.* Aerometric Data Division, California Air Resources Board, Sacramento, CA.

Cote, W.A., Wade, W.A. III, and Yocum, J.E. (1974) *A Study of Indoor Air Quality.* Prepared for the Environmental Protection Agency. The Research Corporation of New England, EPA-650/4-74-042 NTIS No. PB 238 556.

CPUC (1986) *Statewide Saturation Survey on Weatherized Dwelling Units.* Energy Branch, Evaluation and Compliance Division, California Public Utilities Commission, Sacramento, CA.

DAR (1986) *New York State Air Quality Report.* DAR-86-1, Division of Air Resources, New York State Department of Environmental Conservation, Albany, NY.

Dockery, D.W. and Spengler, JD, (1981) Indoor-outdoor relationships of respirable sulfates and particles. *Atmos. Environ.* 15:335-343.

EIA (1984) *Residential Energy Consumption Survey: Housing Characteristics.* Energy Information Administration, Washington, DC.

Fogg, T.T. (1987) Personal communication. Rate and Economic Research Department, Rochester Gas and Electric Corporation, Rochester, NY.

Fortmann, R.C., Borrazzo, J.E., and Davidson, C.I. (1984) Characterization of parameters influencing indoor pollutant concentrations. *Proceedings of the 3rd. International Conference on Indoor Air Quality and Climate, August 20-24, Stockholm, Sweden* **4**:259-264. Published by the Swedish Council for Building Research.

GAMA (1987) *Consumers Directory of Certified Furnace And Boiler Efficiency Ratings,* Gas Appliance Manufacturers Association, Arlington, VA.

Geller, H. (1985) *Progress in the Energy Efficiency of Residential Appliances and Space Conditioning Equipment.* American Council for an Energy Efficient Economy. Washington, DC.

Girman, J.R., Apte, M.G., Traynor, G.W., Allen, J.R. and Hollowell, C.D. (1982) Pollutant emission rates from indoor combustion appliances and sidestream cigarette smoke. *Environ. Intern.* **8**:213-221.

Goto, Y. and Tamura, G.T. (1984) Measurement of combustion products from a gas cooking stove in a two story house. Presented at 77th Annual Meeting of APCA, San Francisco, CA. June 24-29.

GRI (1985a) *Emissions from Residential Gas-fired Appliances.* GRI-84/0164, Gas Research Institute, Chicago, IL.

GRI (1985b) *Characterization of Emission Rates from Indoor Combustion Sources.* GRI-85/0075, Gas Research Institute, Chicago, IL.

Grimsrud, D.T., Sherman, M.H., and Sonderegger, R.C. (1982) Calculating infiltration: implications for a construction quality standard. *Thermal Performance of the Exterior Envelopes of Buildings II*, ASHRAE sp38, ASHRAE Publications, Atlanta, GA, pp. 422-452.

Himmel, R.L. and Dewerth, D.W. (1974) *Evaluation of the Pollutant Emissions from Gas-Fired Ranges.* American Gas Association Laboratories Research Report No. 1492, Cleveland, Ohio.

Leaderer, B.P. (1987) Personal communication, John B. Pierce Foundation Laboratory, and Yale University School of Medicine, New Haven, CT.

Leaderer, B.P., Renes, S., Bluyssen, P., and Van D.E. Loo, H. (1986) Chamber Studies of NO_2, SO_2, and RSP deposition rates indoors. Presented at the 79th Annual Meeting of APCA, Minneapolis, MN, June 22-27.

Leaderer, B.P. (1982) Air pollution emissions from kerosene-fired space heaters. *Science* 218:1113-1115.

Levy, A., Miller, SE, Barrett, RE, Schulz, E.J., Melvin, R.H., Axtman, W.H., and Locklin, D.W. (1971). *Field Investigation of Emissions from Fuel Oil Combustion for Space Heating.* Battelle-Columbus Laboratories. Prepared for the American Petroleum Institute. API Publication 4099, Washington, DC.

Louisiana Department of Environmental Quality (1985) *Ambient Air Quality Data Annual Report.* Baton Rouge, LA.

LPL (1984) *Residential Customer Questionnaire for 1984 Load Profile Samples.* Louisiana Power and Light Co., New Orleans, LA.

MIT (1976) *Experimental Evaluation of Range-Top Burner Modification to Reduce NO_x Formation,* Massachusetts Institute of Technology, Prepared for American Gas Association, No. M40677.

Moschandreas, D.J., Relwani, S., Cole, J.T., Elkins, R.H., and Macriss, R.A. (1983) *Characterization of Emission Sources into the Indoor Environment.* Annual report prepared for Gas Research Institute by Illinois Institute of Technology Research Institute.

Moschandreas, D., Relwani, S., Johnson, D., and Billick, I. (1986) Emission rates from unvented gas appliances. *Environ. Intern.* 12:247-253.

Moschandreas, D.J., and Stark, W.C. (1978) *The Geomet Indoor-outdoor Air Pollution Model.* EPA 600/7-78-106, Geomet, Inc., Washington, DC.

Nitschke, I.A., Clarke, W.A., Clarkin, M.E., Traynor, G.W., and Wadach, J.B. (1985) *Indoor Air Quality, Infiltration and Ventilation in Residential Buildings.* W.S. Fleming & Associates, 5802 Court Street Rd., Syracuse, NY 13206; NYSERDA Report #85-10, New York State Energy Research and Development Authority, Albany, NY 12223.

NRC (1981) *Indoor Pollutants.* National Research Council, Washington D.C., National Academy Press.

Ozkaynak, H., Ryan, P.B., and Turner, W.A. (1982) Indoor air quality monitoring: compartmental approach with reactive chemistry. *Environ. Intern.* 8:461-471.

PGE (1984) *Residential Appliance Saturation Survey, Volume II.* Pacific Gas and Electric Company, San Francisco, CA.

Proctor, J. (1984) Low Cost Furnace Improvements. In *ACEEE Proceedings,* American Council for an Energy Efficient Economy, Washington D.C., 20036.

Quackenboss, J.J. (1984) Personal communication, University of Arizona Medical Center, Tuscon, AZ.

Repace, J.L. and Lowrey, A.H. (1985) A quantitative estimate of non-smoker's lung cancer risk from passive smoking. *Environ. Intern.* **11**: 3-22.

RGE (1985) *Home Appliance Survey,* Rochester Gas and Electric Co., Rochester, NY.

Rickert, W.S., Robinson, J.C. and Collishaw, N. (1984) Yields of tar, nicotine, and carbon monoxide in the sidestream smoke from 15 brands of Canadian cigarettes. *Amer. J. Pub. Hlth.* 74 228.

Ryan, P.B., Spengler, JD and Letz, R. (1983) The effects of kerosene heaters on indoor pollutant concentrations: A monitoring and modeling study. *Atmos. Environ.* **17**:1339-1345.

Shelton, J. (1987) Personal communication, Shelton Research, Santa Fe, NM.

Shelton, J. (1985) *Wood Stoves - A Progress Report.* Shelton Research, Santa Fe, NM.

SoCal (1987) *Residential Indoor Air Quality Characterization Study of Nitrogen Dioxide - Phase II - Wall and Floor Furnace Inspection Study,* Southern California Gas Company, Los Angeles, CA, 90051.

Sonderegger, R.C., Garnier, J.Y., and Dixon, JD (1982) *Computerized Instrumental Residential Audit: CIRA.* Pub. #425, Lawrence Berkeley Laboratory, Berkeley, CA.

Surprenant, N.F., Hall, R.R., McGregor, K.T., and Werner, AS (1979) *Emissions Assessment of Conventional Stationary Combustion Systems: Volume I, Gas and Oil-fired Residential Heating Sources.* EPA-600/7-79-029b, Environmental Protection Agency, Washington, DC.

Szydlowski, R. (1987) Personal communication, Energy Performance of Buildings Group Lawrence Berkeley Laboratory, Berkeley, CA.

Thrasher, W.H., and Dewerth, D.W. (1977) *Evaluation of the Pollutant Emissions from Gas-fired Water Heaters.* GRI research report No. 1507. American Gas Association Laboratories, Cleveland, OH.

Traynor, G.W., Anthon, D.W., Hollowell, C.D. (1982a) Technique for determining pollutant emissions from a gas-fired range. *Atmos. Environ.* **16**:2979-1987.

Traynor, G.W., Apte, M.G., Dillworth, J.F., Hollowell, C.D., and Sterling, E.M. (1982b) The effects of ventilation on residential air pollution due to emissions from a gas-fired range. *Environ. Intern.* **8**:447-452.

Traynor, G.W., Allen, J.R., Apte, M.G., Girman, J.R., and Hollowell, C.D. (1983) Pollutant emissions from portable kerosene-fired space heaters. *Environ. Sci. Technol.* **17**:369-371.

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, JD and Grimsrud, D.T. (1984) *Pollutant Emission Rates from Unvented Infrared and Convective Gas-Fired Space Heaters.* LBL-18258, Lawrence Berkeley Laboratory, Berkeley, CA.

Traynor, G.W., Girman, J.R., Allen, M.G. and Apte, M.G. (1985) Indoor air pollution due to emissions from unvented gas-fired space heaters. *J. Air Pollut. Control Assoc.* **35**:231-237.

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.F., Grimsrud, D.T., and Gundel, L.A. (1987) Indoor air pollution due to emissions from wood-burning stoves. *Environ. Sci. Technol.* **21**:691-697.

TVA (1983) *TVA/BPA: Indoor Air Quality Study - Phase I.* Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, TN.

TVA (1985a) *TVA/CPSC: Indoor Air Quality Study.* Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, TN.

TVA (1985b) *TVA/BPA: Indoor Air Quality Study - Phase II.* Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, TN.

USDHHS (1986) *The Health Consequences of Involuntary Smoking: A Report of the Surgeon General.* US Department of Health and Human Services, Public Health Service, Center for Disease Control, Rockville, MD.

Wade, W.A., Cote, W.A. and Yocum, J.E. (1975) A study of indoor air quality, *J. Air Pollut. Control Assoc.* **25**:933-939.

WWP (1981). *Washington Water Power Residential Survey.* Consumer Services Research and Forecasting Section, Washington Water Power Company, Spokane, WA.

Woodring, J.L., Duffy, T.L., Davis, J.T., and Bechtold, R.R. (1985) Measurements of combustion product emission factors of unvented kerosene heaters. *Amer. Ind. Hyg. Assoc. J.* **46**:350-356.

Woods, J.E. and Crawford, R.R. *et al.* (1983) Calculation methods to assess indoor air quality. *ASHRAE Transactions, Vol. 89, Part 2B,* Paper No. DC-83-12, No. 1.

Zawacki, T.S., Cole, J.T., Huang, V.M., Banasiuk, H., and Macriss, R.A. (1984) *Efficiency and Emissions Improvement of Gas-Fired Space Heaters, Task 2. Unvented Space Heater Emission Reduction.* Institute of Gas Technology, Chicago, IL.

Table III-1. Global input parameters.

Input Parameter	Data Points	Geometric Mean	Geometric Standard Deviation	Empirical Distribution Range	References
HEATING APPLIANCE EFFICIENCY (%)					
a) Gas FAF				55-95	2,10
b) Gas boiler				60-95	9
c) Gas wall/floor furnace				75-85	10
d) Oil FAF				70-90	2,9,10
e) Airtight Wood Stove				45-65	31,32
f) Non-airtight Wood Stove				35-45	31,32
SMOKING FREQUENCY (Cig/h)	-	0.8	1.5		5,28,46
POLLUTANT EMISSION RATES (μg/kJ or μg/Cig)					
Gas FAF (CO)	11	11.4	6.4		19,34,35
Gas FAF (NO_2)	17	8.4	2.3		19,34
Gas FAF (RSP)	6	1.1	3.0		19,34
Gas boiler (CO)	32	24.5	7.4		13
Gas boiler (NO_2)	32	4.4	1.8		13
Gas boiler (RSP)	-	0.3	2.1		see UVGSH IR
Gas W/F (CO)	-	11.4	6.4		see Gas FAF
Gas W/F (NO_2)	-	8.4	2.3		see Gas FAF
Gas W/F (RSP)	-	1.1	3.0		see Gas FAF
UVGSH Infrared (CO)	6	49.5	1.5		22,23,43
UVGSH Infrared (NO_2)	4	4.6	1.1		22,23,43
UVGSH Infrared (RSP)	4	0.3	2.1		43
UVGSH Convective (CO)	12	27.9	2.4		22,23,43,44,50
UVGSH Convective (NO_2)	12	13.0	1.3		22,23,43,44,50
UVGSH Convective (RSP)	9	0.4	3.3		43,44
Gas stove top (CO)	53	81.3	3.1		8,12,13,15,23,40,41
Gas stove top (NO_2)	53	11.8	1.4		8,12,13,15,23,40,41
Gas stove top (RSP)	4	0.27	1.5		13,40
Gas stove oven (CO)	56	38.6	4.1		8,13,15,23,40,41
Gas stove oven (NO_2)	56	7.4	1.8		8,13,15,23,40,41
Gas stove oven (RSP)	1	0.015	1.5		40
Gas dryer (CO)	2	52.0	1.5		13
Gas dryer (NO_2)	4	8.5	1.3		13
Gas dryer (RSP)	-	0.27	1.5		see Gas Stove Top
Gas water heater (CO)	55	5.8	1.9		35
Gas water heater (NO2)	32	3.1	1.9		39
Gas water heater (RSP)	-	1.1	3.0		see Gas FAF
Oil FAF (CO)	30	6.3	11.7		4,19,34
Oil FAF (NO2)	28	10.6	2.9		4,19
Oil FAF (RSP)	31	17.9	2.4		4,19,34
Wood airtight (CO)	12	3.9	2.1		36,37,38,45
Wood airtight (NO_2)	9	0.07	2.9		36,37,38,45
Wood airtight (RSP)	8	0.09	1.4		36,37,38,45
Wood non-airtight (CO)	4	3.2	2.0		37,45
Wood non-airtight (NO_2)	3	0.09	3.0		37,45
Wood non-airtight (RSP)	47	0.15	3.0		37,45
Kerosene Radiant (CO)	7	67.9	1.4		16,42,48
Kerosene Radiant (NO_2)	7	4.7	1.2		16,42,48
Kerosene Radiant (RSP)	5	0.59	3.1		42
Kerosene Convective (CO)	4	42.1	3.4		16,42,48
Kerosene Convective (NO_2)	4	18.4	1.5		16,42,48
Kerosene Convective (RSP)	1	0.02	1.0		45

Table III-1 Global input parameters (continued).

Input Parameter	Data Points	Geometric Mean	Geometric Standard Deviation	Empirical Distribution Range	References
Cigarettes (CO)	6	71400	1.3		3,11,14,24,29,49
Cigarettes (NO_2)	3	0.0	1.0		see Appendix A
Cigarettes (RSP)	12	15900	1.2		18
NON-ZERO VENT FACTORS FOR VENTED GAS/OIL SPACE HEATERS	5			6.8%	1,26,27,33
RANGE HOOD VENT FACTOR (unitless)	1			0.3	41
POLLUTANT PENETRATION FACTORS (unitless)					
a) CO	-	1.0			40
b) NO_2	-	1.0			40
c) RSP	-	0.7			7
POLLUTANT REACTIVITY (1/h)					
a) CO	-	-	-		-
b) NO_2	7	0.77	1.69		12,21,25,30,41,47
c) RSP	4	0.08	1.26		45

REFERENCES

1) AGA (1980)
2) AIP (1985)
3) Apte (1988)
4) Barrett et al. (1973)
5) Bureau of Census, (1985)
6) Cote et al. (1974)
7) Dockery and Spengler (1981)
8) Fortmann et al. (1984)
9) GAMA (1987)
10) Geller (1985)
11) Girman et al. (1982)
12) Goto and Tamura (1984)
13) GRI (1985a)
14) GRI (1985b)
15) Himmel and DeWerth (1974)
16) Leaderer (1982)
17) Leaderer et al. (1986)
18) Leaderer (1987)
19) Levy et al. (1971)
20) M.I.T. (1976)
21) Moschandreas and Stark (1978)
22) Moschandreas et al. (1983)
23) Moschandreas et al. (1986)
24) NRC (1981)
25) Ozkaynak et al. (1982)
26) Proctor et al. (1984)
27) Quackenboss (1984)
28) Repace and Lowry (1985)
29) Rickert et al. (1984)
30) Ryan et al. (1983)
31) Shelton (1985)
32) Shelton (1987)
33) SoCal (1987)
34) Surprenant et al. (1979)
35) Szydlowski (1987)
36) Tennessee Valley Authority (1983)
37) Tennessee Valley Authority(1985a)
38) Tennessee Valley Authority(1985b)
39) Thrasher and Dewerth (1977)
40) Traynor et al. (1982a)
41) Traynor et al. (1982b)
42) Traynor et al. (1983)
43) Traynor et al. (1984)
44) Traynor et al. (1985)
45) Traynor et al. (1987)
46) USDHHS (1986)
47) Wade et al. (1975)
48) Woodring et al. (1985)
49) Woods et al. (1983)
50) Zawacki et al. (1984)

Table III-2. Region-specific input parameters.

Input Parameter	Data Points	Geometric Mean	Geometric Standard Deviation	Empirical Distribution Range	References
MARKET PENETRATION OF APPLIANCES (%)					
RGE	a			e	RGE (1985)
WWP	b			e	WWP (1981)
PGE	c			e	PGE (1984)
LPL	d			e	LPL (1984)
PRIMARY HEATING APPLIANCE DISTRIBUTION (%)					
RGE	a			e	RGE (1985)
WWP	b			e	WWP (1981)
PGE	c			e	PGE (1984)
LPL	d			e	LPL (1984)
NON-HEATING-APPLIANCE DISTRIBUTION (%)					
RGE	a			e	RGE (1985)
WWP	b			e	WWP (1981)
PGE	c			e	PGE (1984)
LPL	d			e	LPL (1984)
NON-SPACE-HEATING APPLIANCE FUEL USAGE (kJ/h)					
RGE	-			e	AGA (1985)
WWP	-			e	AGA (1985)
PGE	-			e	AGA (1985)
LPL	-			e	AGA (1985)
HOUSE VOLUME (m^3)					
RGE	48			325 to 775	Grimsrud _et al_. (1982)
WWP	b			45 to 580	WWP (1981)
PGE	c			215 to 680	PGE (1984)
LPL	d			225 to 1150	LPL (1984)
OUTDOOR POLLUTANT CONCENTRATION					
RGE (CO) (ppm)	2	0.7	1.2		DAR (1986)
(NO_2)(ppm)	41	0.006	1.95		Nitschke _et al_. (1985)
(RSP)($\mu g/m^3$)	5	19.0	1.5		DAR (1986)
WWP (CO) (ppm)	720	1.7	1.1		Washington State Dept. of Ecology (1988)
(NO_2)(ppm)	41	0.006	1.95		See RGE
(RSP)($\mu g/m^3$)	351	34.9	1.7		Washington State Dept. of Ecology (1988)
PGE (CO) (ppm)	22	1.1	2.0		CARB (1985)
(NO_2)(ppm)	22	0.017	1.6		CARB (1985)
(RSP)($\mu g/m^3$)	30	27.5	1.5		CARB (1985)
LPL (CO) (ppm)	2	0.7	2.1		Louisiana Dept. of Env. Quality (1985)
(NO_2)(ppm)	1	0.012	1.9		Louisiana Dept. of Env. Quality (1985)
(RSP)($\mu g/m^3$)	15	20.0	1.2		Louisiana Dept. of Env. Quality (1985)
BUILDING U-VALUES ($kJ/hm^2 ℃$)					
Walls and ceilings					
RGE	-			e	RGE (1985)
WWP	-			e	BPA (1983), WWP (1981)
PGE	-			e	CPUC (1986)
LPL	-			e	LPL (1984)

Table III-2 Region-specific input parameters (continued).

Input Parameter	Data Points	Geometric Mean	Geometric Standard Deviation	Empirical Distribution Range	References
Building U-Values (continued)					
floor					
RGE	-			e	Fogg (1987)
WWP	-			e	WWP (1981)
PGE	-			e	CPUC (1986)
LPL	-			e	LPL (1984)
windows and storm windows					
RGE	-			e	RGE (1985), EIA (1984)
WWP	-			e	WWP (1981), EIA (1984)
PGE	-			e	PGE (1984), EIA (1984)
LPL	-			e	LPL (1984), EIA (1984)
doors and storm doors					
RGE	-			e	RGE (1985), EIA (1984)
WWP	-			e	WWP (1981), EIA (1984)
PGE	-			e	PGE (1984), EIA (1984)
LPL	-			e	LPL (1984), EIA (1984)
OUTDOOR TEMPERATURE (°C)					
RGE	-			-9 to 25	TMY., NOAA[f], Asheville, NC
WWP	-			-6 to 23	TMY., NOAA[f], Asheville, NC
PGE	-			6 to 19	TMY., NOAA[f], Asheville, NC
LPL	-			7 to 27	TMY., NOAA[f], Asheville, NC
WIND SPEED (m/s)					
RGE	-			4.4 to 16.2	TMY., NOAA[f], Asheville, NC
WWP	-			4.1 to 10.7	TMY., NOAA[f], Asheville, NC
PGE	-			1.4 to 4.5	TMY., NOAA[f], Asheville, NC
LPL	-			3.6 to 7.1	TMY., NOAA[f], Asheville, NC
SOLAR GAIN[g] (kJ/hm^2)					
RGE	-			39 to 455	Sonderegger et al. (1982)
WWP	-			93 to 977	Sonderegger et al. (1982)
PGE	-			155 to 488	Sonderegger et al. (1982)
LPL	-			188 to 429	Sonderegger et al. (1982)
NUMBER OF STORIES					
RGE	-			1 to 2	
WWP	-			1 to 2	
PGE	-			1 to 2	
LPL	-			1 to 2	
SPECIFIC LEAKAGE AREA ($10^{-4}m^2/m^2$)					
RGE	50	2.84	1.44		Sherman (1988)
WWP	61	3.15	1.92		Sherman (1988)
PGE	80	6.10	1.59		Sherman (1988)
LPL	37	7.78	1.45		Sherman (1988)

[a]RGE RASS Sample size = 350 responses out of 2074 possible (17%)
[b]WWP RASS Sample size = 2,611 responses out of 3,200 possible (82%)
[c]PGE RASS Sample size = 13,223 responses out of 26,840 possible (49%)
[d]LPL RASS Sample size = 401 responses out of 859 possible (47%)
[e]See Appendix A for data details
[f]National Oceanic and Atmospheric Administration
[g]Range of solar gain in houses with and without storm windows

IV. SELECTED MODEL RESULTS

The primary goal of this chapter is to compare macromodel predictions with IAQ-field study results to gain qualitative insight into the rough accuracy of the macromodel. These comparisons can only be approximate since the houses in the field studies were not sufficiently characterized to run the full model. Therefore, surrogate parameters are used in many instances. In addition, the effects of changes in specific leakage area on space-heating and non-space-heating sources are investigated. The effects of changes/reductions in the houses leakage area and, thus, its infiltration rate are of particular interest to Federal and other agencies involved with energy conservation in buildings. (Note: a full sensitivity analysis will be conducted and presented in a future report.)

To put the macromodel results into perspective, they are compared with outdoor air quality standards. The outdoor air quality standards used for comparisons in this report are listed in Table IV-1. Direct comparison of data presented here to outdoor air quality standards is not possible since, at the very least, the time frames of the standards all differ from the one-week time frame used in this report. These standards should not be considered thresholds above which adverse health effects occur, but should be used as rough benchmarks to qualitatively determine if a potential IAQ problem exists.

1. Effect of vent-factor distribution on NO_2 from forced-air furnaces and wall/floor furnaces.

One of the macromodel input parameters most lacking in good data is the distribution of vent factors for vented space-heating appliances. An extensive field study of the indoor NO_2 concentrations in houses with combustion appliances including vented space-heating appliances was recently conducted in Southern California (SoCal) with one of the sampling periods in January, 1985 (Wilson *et al.*, 1986) .

Using the PGE region housing stock as a surrogate for the SoCal housing stock, we ran an analysis of indoor NO_2 concentrations versus vent-factor distribution. An outdoor temperature of 11℃ and an outdoor NO_2 concentration GM of 0.055 ppm (GSD = 1.5) were used. Both are similar to the conditions of the January sampling period of the SoCal study (Wilson *et al.*, 1986). The vent-factor distributions used for the analyses are shown in Fig. IV-1. The macromodel uses the vent-factor distribution associated with 6.8% leaky furnaces. The linear nature of the vent-factor distributions was arbitrarily chosen. All other input parameters, such as NO_2 emission rates and house volumes, are the same as described for the PGE region in Chapter III and Appendix A.

Figures IV-2 and IV-3 show the macromodel results for houses with forced-air or wall/floor furnaces without gas stoves and with gas stoves, respectively. No other sources were included in these macromodel runs. Results from using 0% leaky furnaces reflect the impact of outdoor NO_2 on indoor concentrations.

Results of average indoor NO_2 concentrations (average of bedroom and kitchen values) from the SoCal study (Volume 3 of Wilson *et al.*, 1986) show that houses with forced-air furnaces and an electric stove had, during the January sampling period, a median concentration of 0.023 ppm, a 90th-percentile concentration of 0.033 ppm, and a 99th-percentile concentration of 0.046 ppm. The GM of the SoCal study is higher than the macromodel results for all percentages of leaky furnaces modeled. However, the 90th- and 99th-percentile results of the SoCal study are lower than all modeled results. One possible interpretation is that if there are forced-air furnaces that leak in the SoCal study houses, they did not leak very much (i.e., they had much lower vent factors than assumed in the macromodel). Figure IV-3 shows a similar comparison to houses with forced-air furnaces, wall/floor furnaces and gas stoves. Again, the GMs of the SoCal study are higher than the macromodel results. The SoCal results indicate that wall/floor furnaces leak more pollutants indoors than forced-air furnaces. The 99th-percentile results of the macromodel for 6.8% to 10% leaky furnaces are in good agreement with the 99th-percentile results of the SoCal study for wall/floor furnaces. These results may indicate that the vent-factor distribution used in the macromodel is not correct; however, there is not sufficient information available to alter it.

There are numerous problems associated with any assumed vent-factor distribution and readers are cautioned against using the results of the above analysis. At present, these results are very rough "estimates" and have not been scientifically validated.

2. Indoor NO_2 versus gas-stove usage.

Figure IV-4 shows the sensitivity-analysis results of indoor NO_2 concentration versus gas-oven/range usage rates. The analysis was performed using the RGE region (during a summer week when no space heating was required) and the outdoor data reported in Spengler *et al.* (1983). This analysis can be compared with Spengler's annual GM results, i.e., GM of 0.030 ppm for the kitchen and 0.017 ppm for the bedroom. Geometrically averaging these bedroom and kitchen values yields an annual whole-house GM of 0.023 ppm. A GSD of 1.6 was estimated using an AM/ASD ratio of 0.5 taken from Spengler and from Eq.(16) in Chapter II. The percentiles reported for Spengler in Fig. IV-4 are then derived from the log-normal distribution using a GM 0.023 ppm and a GSD of 1.6. From Spengler it appears that the summer-only GM was approximately 0.017 ppm. The implied distribution from these results is shown in Fig. IV-4. The summer results compare favorably to the macromodel results using a gas-usage rate of 1750 kJ/h. In the macromodel (see Chapter III or Appendix A), an average gas-stove usage of approximately 1130 kJ/h is used for the RGE region, whereas

Spengler's results were from Portage, WI. There are several potential reasons why the macromodel results do not agree with Spengler's results; one is that there may have been other NO_2 sources in the houses studied by Spengler *et al.* (1983).

3. Indoor NO_2 from kerosene heaters versus outside temperature.

Figure IV-5 shows indoor NO_2 concentrations in houses with kerosene heaters in the RGE region versus the outdoor temperature. The outdoor NO_2 distribution was taken from Leaderer *et al.* (1986). The kerosene heaters were assumed to be 50% radiant and 50% convective. As expected, the higher the outdoor temperature, the lower the indoor NO_2 concentration. It is interesting to note the wide distribution of NO_2 concentrations in the transition-temperature region from 5 to 15℃, where not all houses need to be heated.

The results shown in Figure IV-5 can be compared to the results of a study conducted in Connecticut (Leaderer *et al.*, 1986). The average outdoor temperatures during the Leaderer study ranged from -3.3℃ to 5.6℃ (Leaderer *et al.*, 1987). The Leaderer NO_2 results, converted to geometric statistics, were a GM of 0.014 ppm (GSD = 2.1) for houses with one kerosene heater and no gas stove and a GM of 0.031 ppm (GSD = 1.7) for houses with two kerosene heaters and no gas stove. The Leaderer results for houses with two kerosene heaters--houses that are more likely to use kerosene as a primary heat source--are somewhat similar to the macromodel results with an outdoor temperature of 10℃. The macromodel results at 0℃ and 5℃ are much higher than the Leaderer results in houses with two kerosene heaters, possibly because the kerosene heaters used in the Leaderer study may have been predominantly used as a secondary heat source, whereas the macromodel assumes kerosene heaters are the only source of heat. The macromodel cannot currently handle secondary heat sources. If we assume that other heat sources raise the indoor temperature 5-10℃, then the macromodel results are in rough agreement with the Leaderer study.

4. Indoor NO_2 concentration from kerosene heaters and gas ranges/ovens versus specific leakage area.

Figure IV-6 shows the impact of specific leakage area (SLA) on the air exchange rate of houses in the RGE region with an outdoor temperature of -5℃. It also shows the impact of SLA on the indoor NO_2 concentrations in houses using kerosene heaters as their only source of heat in the RGE region, with an outdoor temperature of -5℃. The GM of the SLA from Chapter III is 2.84 x 10^{-4} m^2/m^2 of floor area. It is interesting to note that the GM of the air exchange rate rose from 0.25 h^{-1} to 0.80 h^{-1} over the SLA range used, but the GM of the NO_2 distribution dropped only 11 % from 0.224 to 0.200 ppm.

Figure IV-7 is similar to Figure IV-6 except that the outdoor temperature is +10℃ and the effect of changes in SLA on NO_2 from gas ranges/ovens is shown. At this outside temperature, the air exchange rate GM dropped from 0.35 h^{-1} to 0.11 h^{-1}, while the GM of the kerosene-heater NO_2 distribution also dropped from 0.037 to 0.024 ppm. This is because at an outdoor temperature of +10℃, only 75% of the houses in RGE region need any heat at all, and those houses need very little. Lowering the air exchange rate reduces the need for heat and reduces the impact of outdoor NO_2. These two effects caused the GM of the kerosene-heater NO_2 distribution to drop 35% (for 0.037 ppm to 0.027 ppm) as the air exchange rate was lowered. The 90th percentile of the NO_2 distribution dropped on 5% (from 0.136 ppm to 0.129 ppm) throughout the SLA range, but the 99th-percentile did increase 12% (from 0.326 ppm to 0.365 ppm).

The analysis of the effect of SLA on indoor NO_2 from gas ranges/ovens showed surprising results. The GM of the NO_2 distribution from gas ranges/ovens rose only 9% (from 0.011 ppm to 0.012 ppm) as the air exchange rate dropped 69% (from 0.35 h^{-1} to 0.11 h^{-1}). There are two reasons for this result: (1) the effect of the reduction in air exchange rate is severely dampened by the NO_2 reactivity rate (GM = 0.77 h^{-1}), e.g., a 69% reduction in air exchange rate caused only a 21% reduction in the NO_2 removal rate, and (2) reducing the air exchange rate reduces the impact of outdoor air pollution on background indoor air-pollution levels if the pollutant is reactive. These two effects severely dampened the impact of reduced SLA and air exchange rates on the NO_2 concentration distribution from gas ranges/ovens.

5. Indoor CO concentrations from convective unvented gas space heaters (UVGSH) and gas ranges/ovens versus SLA.

Figure IV-8 shows the impact of changes in the SLA GM on the air exchange rate, on the CO-concentration distribution of houses with gas ranges/ovens, and on the CO-concentration distribution of houses with convective UVGSHs. The analysis was modeled in the LPL region with an outdoor temperature of 7℃--the lowest temperature used in the LPL region. The SLA used in the macromodel for the LPL region was 7.68 x 10^{-4} m^2/m^2. The air exchange rate GM dropped 56% (from 1.21 h^{-1} to 0.53 h^{-1}) over the range of SLAs modeled. Over the same range, the GM of the CO distribution from convective UVGSHs rose 40% (from 1.86 ppm to 2.60 ppm), and the 99th percentile rose 69% (from 9.47 ppm to 16.0 ppm). The GM of the CO distribution from gas ranges/ovens rose 32% (from 0.95 ppm to 1.25 ppm) and the 99th percentile rose 50% (from 4.48 ppm to 6.70 ppm).

6. Indoor CO concentration from convective UVGSH versus CO emission rate.

Figure IV-9 shows the impact of the convective UVGSH CO emission rate on the indoor CO-concentration distribution at an outdoor temperature of 7℃. As expected, the greater the emission rate, the higher the indoor concentration.

7. Indoor RSP concentrations versus smoking rate.

Figure IV-10 shows, in the LPL region, the impact of the indoor smoking rate on the indoor RSP concentration distribution in houses with smokers. A summer week was used for this analysis, and the air exchange rates were low (see Appendix C). As expected, the more cigarettes smoked per hour, the higher the indoor RSP concentration. Dockery and Spengler (1981) estimated that each cigarette smoked increases the average indoor RSP concentration by 0.88 to 2.11 $\mu g/m^3$ per cigarette smoked, depending upon the air exchange rate of the house (indirectly correlated with the presence of air conditioning). If we use the higher value, 2.11 $\mu g/m^3$ per cigarette, we can calculate the increase in indoor concentration of 40.5 $\mu g/m^3$ due to smoking 0.8 cigarettes per hour. Even adding an outdoor concentration of 20 $\mu g/m^3$ does not bring us up to the GM of 88 $\mu g/m^3$ shown in Figure IV-10 for 0.8 cigarettes/h. The apparent discrepancy disappears if we assume that the air exchange rates of the modeled houses are less than the rates of the Dockery and Spengler houses; however, Dockery and Spengler did not report direct air exchange rate measurements.

References for Chapter IV

Dockery, D.W. and Spengler, J.D. (1981) Indoor-outdoor relationships of respirable sulfates and particles. *Atmos. Environ.* **15**:335-343.

Leaderer, B.P., Zagranski, R.T., Berwick, M., and Stolwijk, J.A.J. (1986) Assessment of exposure to indoor air contaminants from combustion sources: methodology and application. *Am. J. Epid.* **124**:275-289.

Leaderer, B.P., Zagranski, R.T., Berwick, M., and Stolwijk, J.A.J. (1987) Predicting NO_2 levels in residences based upon sources and source use: a multivariate model. *Atmos. Environ.* 21:361-368.

Spengler, J.D., Duffy, C.P., Letz, R., Tibbitts, T.W., and Ferris, B.G., Jr. (1983) Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research. *Environ. Sci. Technol.* **17**:164-168.

State of California (1977) California Administrative Code, Title 17, Subchapter 1.5, Section 70100.

U.S. Government (1987) *National primary and secondary ambient air quality standards*, Code of Federal Regulations, Title 40, Part 50.

Wilson, A.L., Colome, S.D., Baker, P.E., and Becker, E.W. (1986) *Residential Indoor Air Quality Characterization Study of Nitrogen Dioxide, Phase I: Volume 1, 2 and 3.* Southern California Gas Company, Los Angeles, CA.

Table IV-1. Outdoor Air-Pollution Standards[a]

Pollutant	Standard Type	Standard	Averaging Time
CO	Short-term	35 ppm	1 h
	Long-term	9 ppm	8 h
NO_2	Short-term	0.25 ppm[b]	1 h
	Long-term	0.05 ppm	1 yr
RSP[c]	Short-term	150 $\mu g/m^3$	24 hr
	Long-term	50 $\mu g/m^3$	1 yr

[a]Except where noted, standards are from U.S. Government (1987).

[b]From State of California (1977).

[c]Actual standard is for particles with an aerodynamic diameter less than, or equal to, a nominal 10 μm.

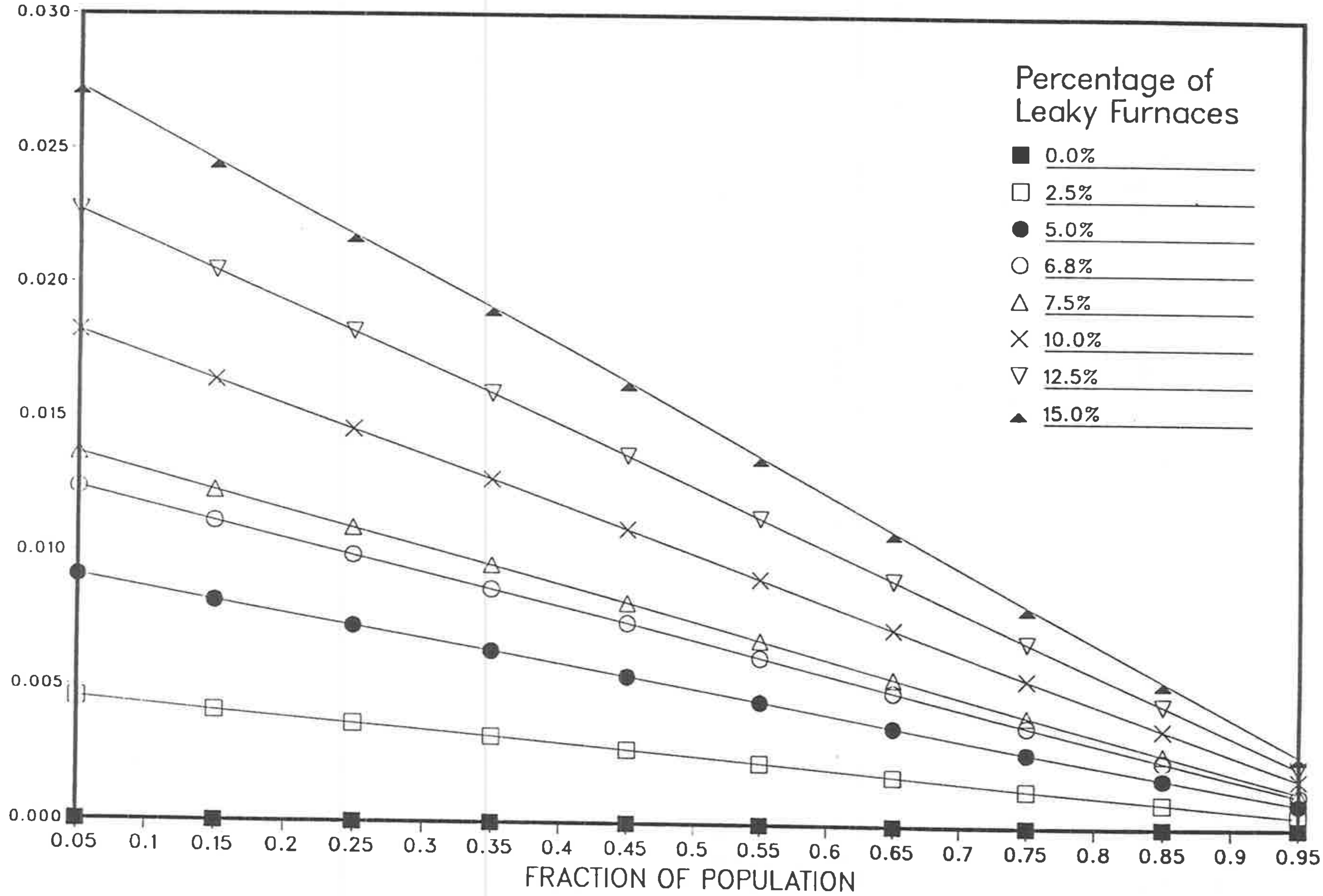


Figure IV-1. Vent-factor distributions for subsequent selected model results for gas forced-air, wall/floor furnaces. Linear distributions are assumed for the percentage of furnaces that leak some pollutants indoors. The percentage of "leaky" furnaces range from 0% to 15%--6.8% is used in the macromodel.

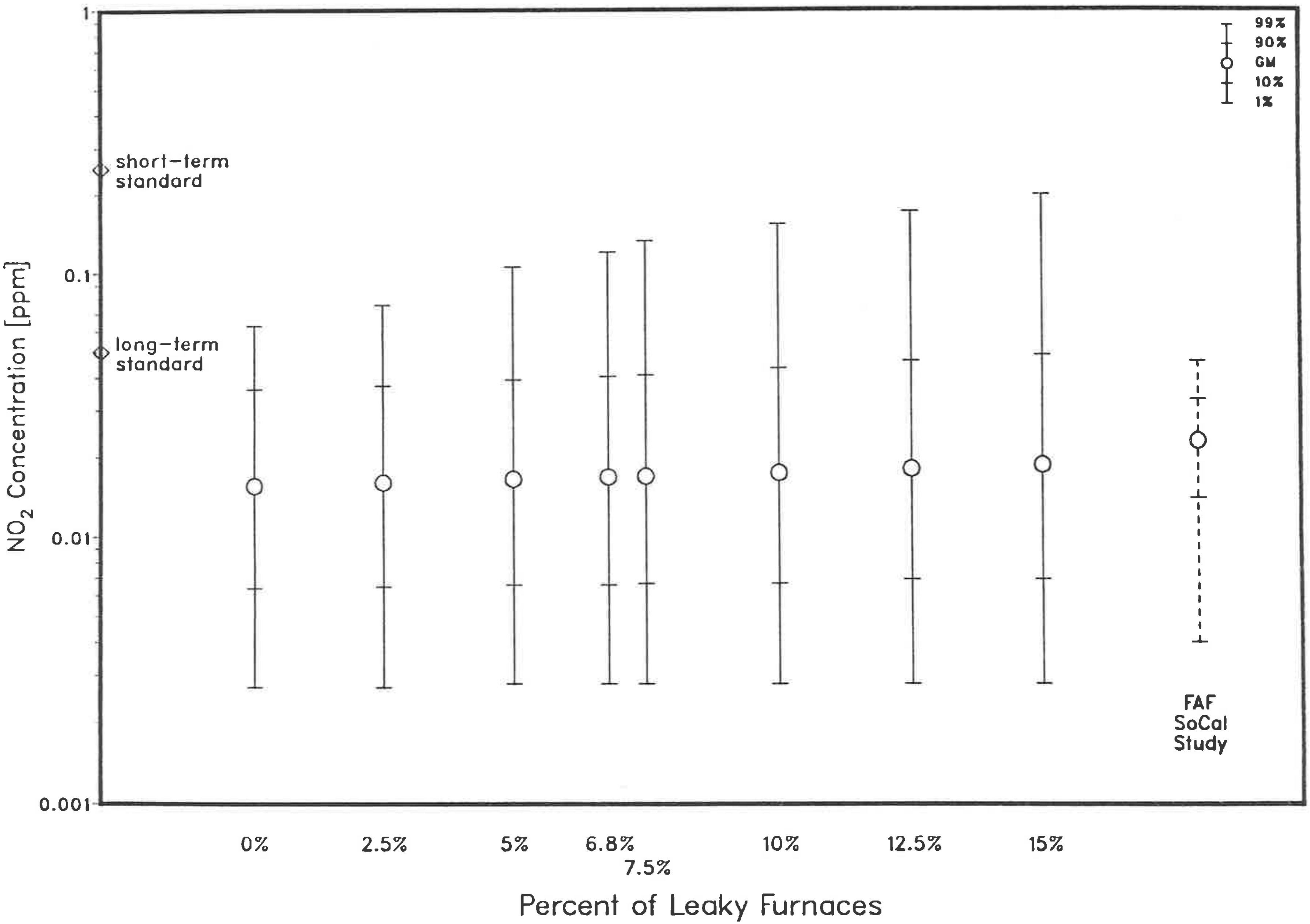


Figure IV-2. Indoor NO_2 concentrations vs. percentage of leaky furnaces (see Fig. IV-1) for houses with gas forced-air, wall/floor furnaces in the PGE region with an outdoor temperature of 11°C and an outdoor pollutant concentration GM of 0.055 ppm (GSD = 1.5). The results are compared with forced-air furnace (FAF) results of a Southern California study (Wilson *et al.*, 1986).

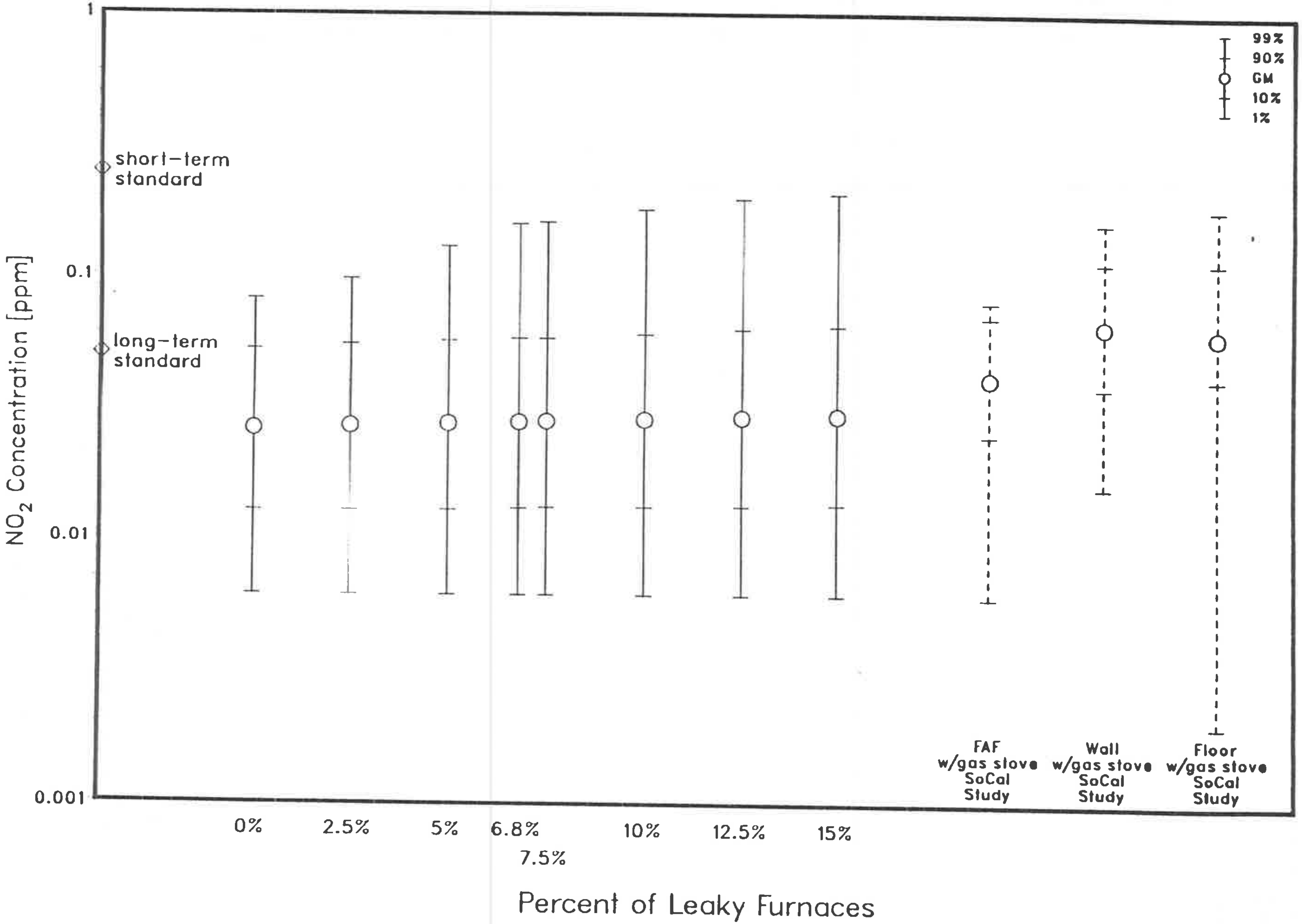


Figure IV-3. Indoor NO_2 concentrations vs. percentage of leaky furnaces (see Fig. IV-1) for houses with gas forced-air, wall/floor furnaces and gas stoves in the PGE region, with an outdoor temperature of 11°C and an outdoor pollutant concentration GM of 0.055 ppm (GSD = 1.5). The results are compared with results from a Southern California study (Wilson *et al.*, 1986).

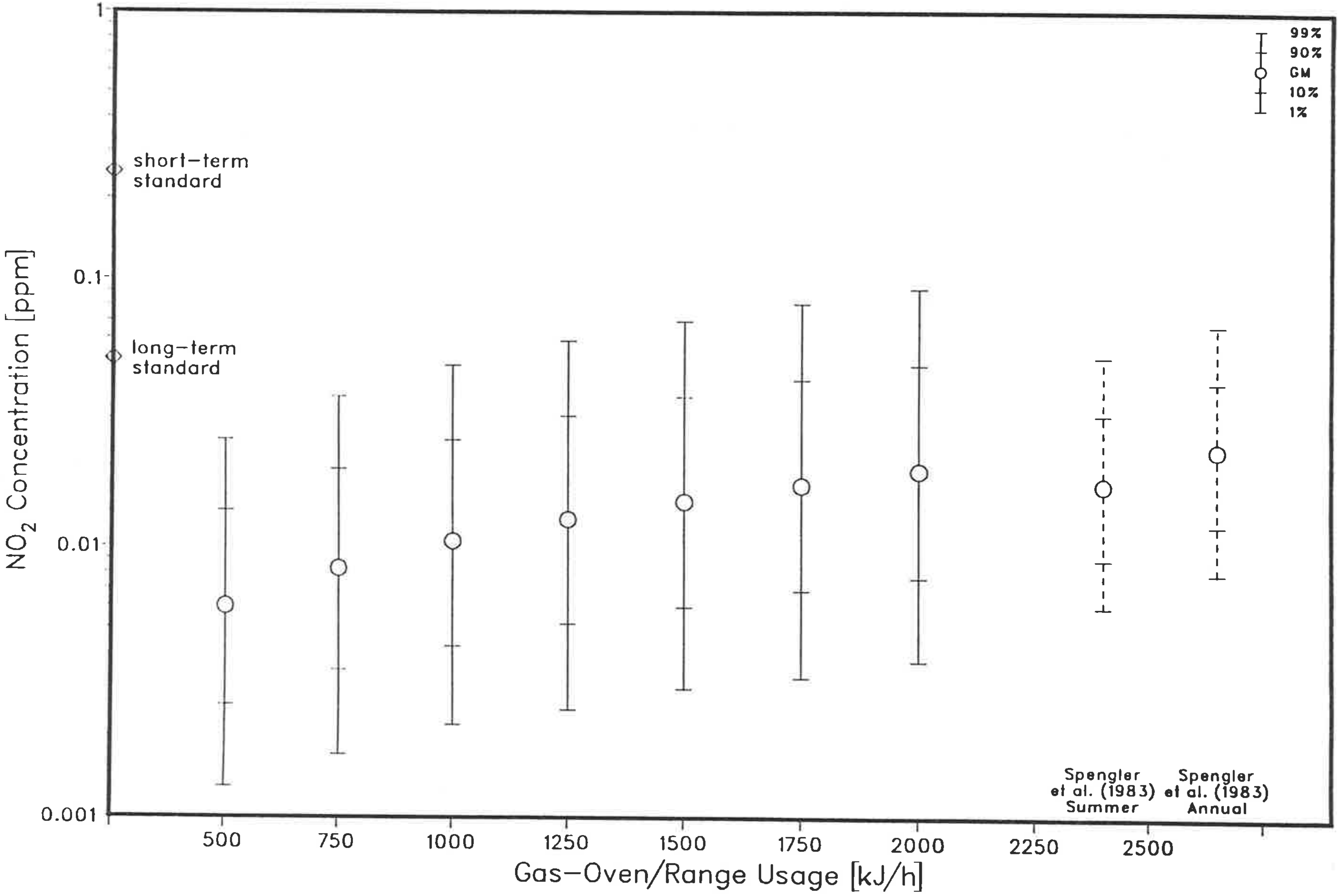


Figure IV-4. Indoor NO_2 concentration vs. gas-range/oven usage rate (GSD = 1.5) in houses with gas stoves in the RGE region, with an outdoor NO_2 concentration GM of 0.008 ppm (GSD = 1.5).

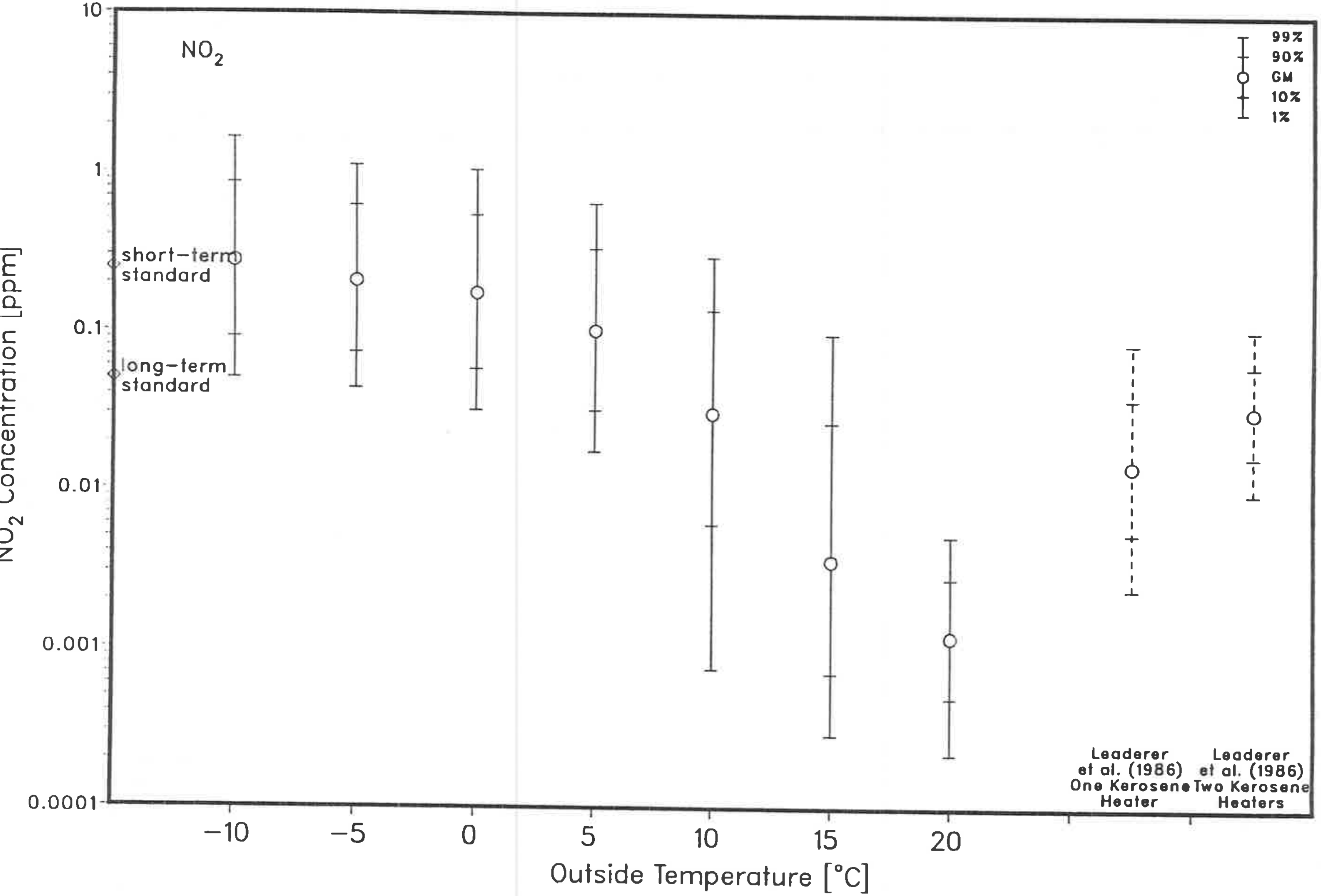


Figure IV-5. Indoor NO_2 concentration vs. outside temperature in houses with kerosene heaters in the RGE region, with an outdoor NO_2 concentration of 0.008 ppm (GSD = 1.4).

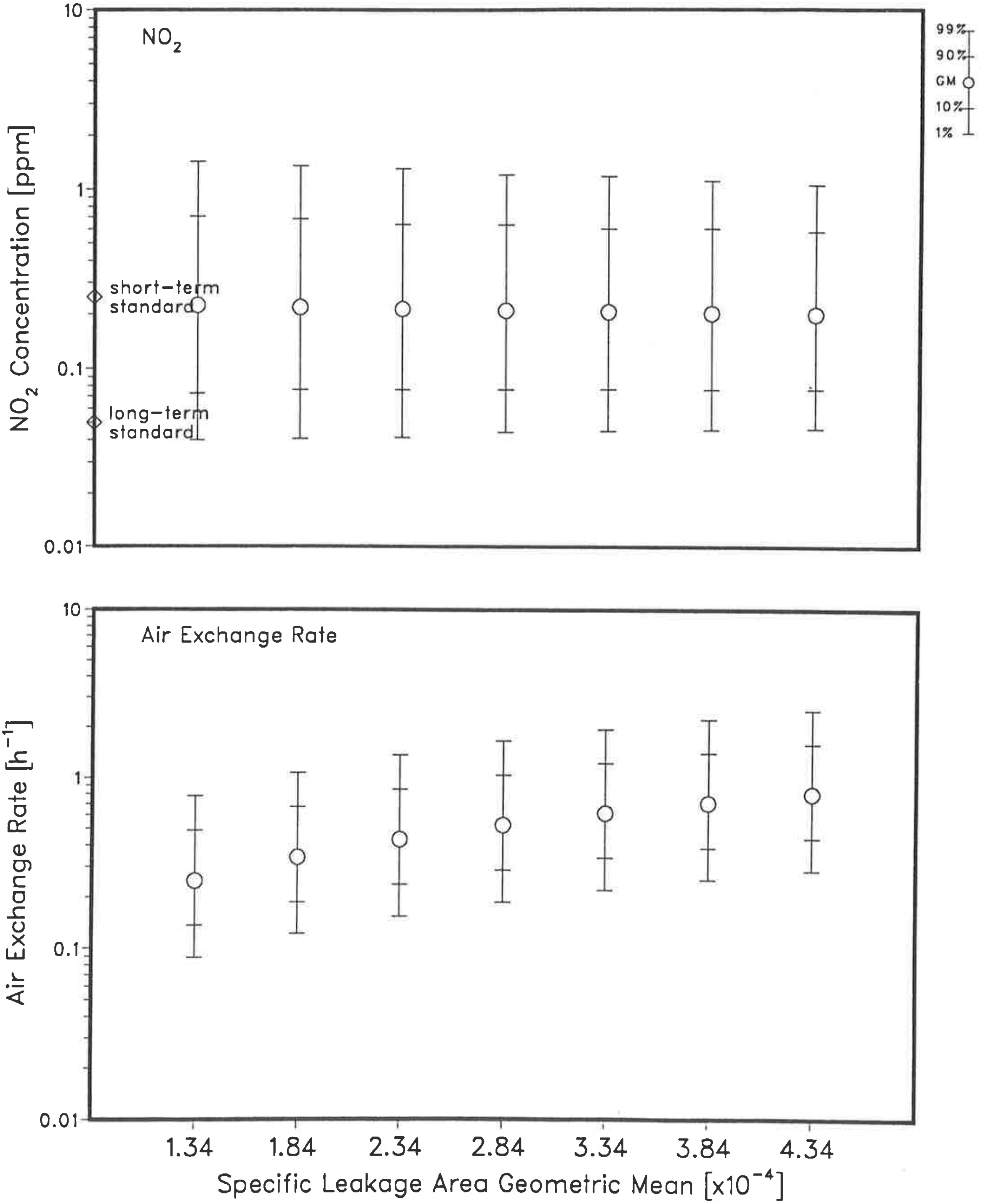


Figure IV-6. Air exchange rate and indoor NO_2-concentration distribution in houses with kerosene heaters vs. specific leakage area (GSD = 1.44) in the RGE region, with an outdoor temperature of -5°C.

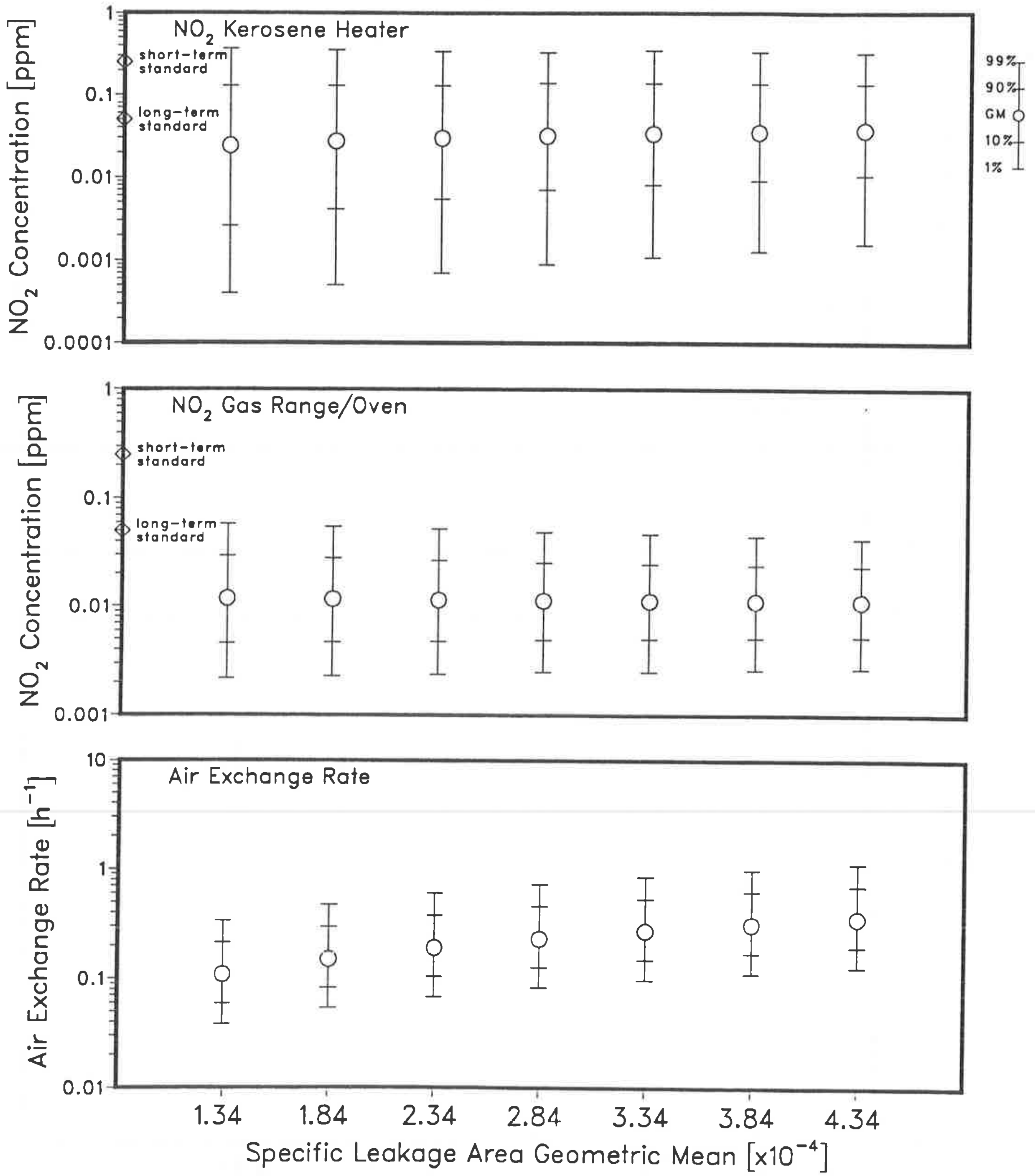


Figure IV-7. **Air exchange rate, indoor NO_2-concentration distributions in houses with gas ranges/ovens, and indoor NO_2-concentration distributions in houses with kerosene heaters vs. specific leakage area in the RGE region, with an outdoor temperature of 10°C.**

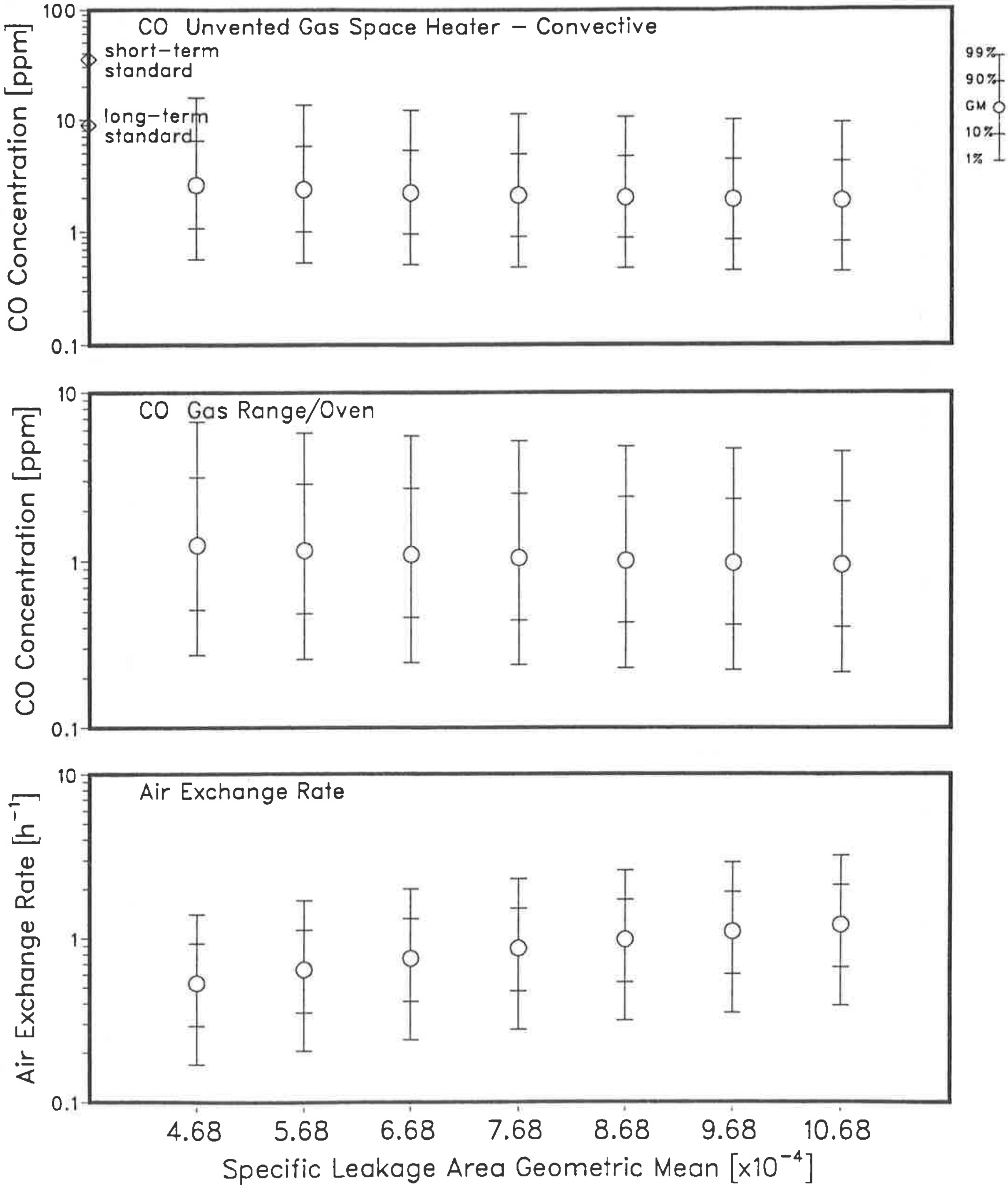


Figure IV-8. Air exchange rate, indoor CO-concentration distribution in houses with gas ranges/ovens, and indoor CO-concentration distribution in houses with convective unvented gas space heaters vs. specific leakage area (GSD = 1.45) in the LPL region, with an outdoor temperature of 7°C and an outdoor CO concentration of 0.7 ppm (GSD = 1.9).

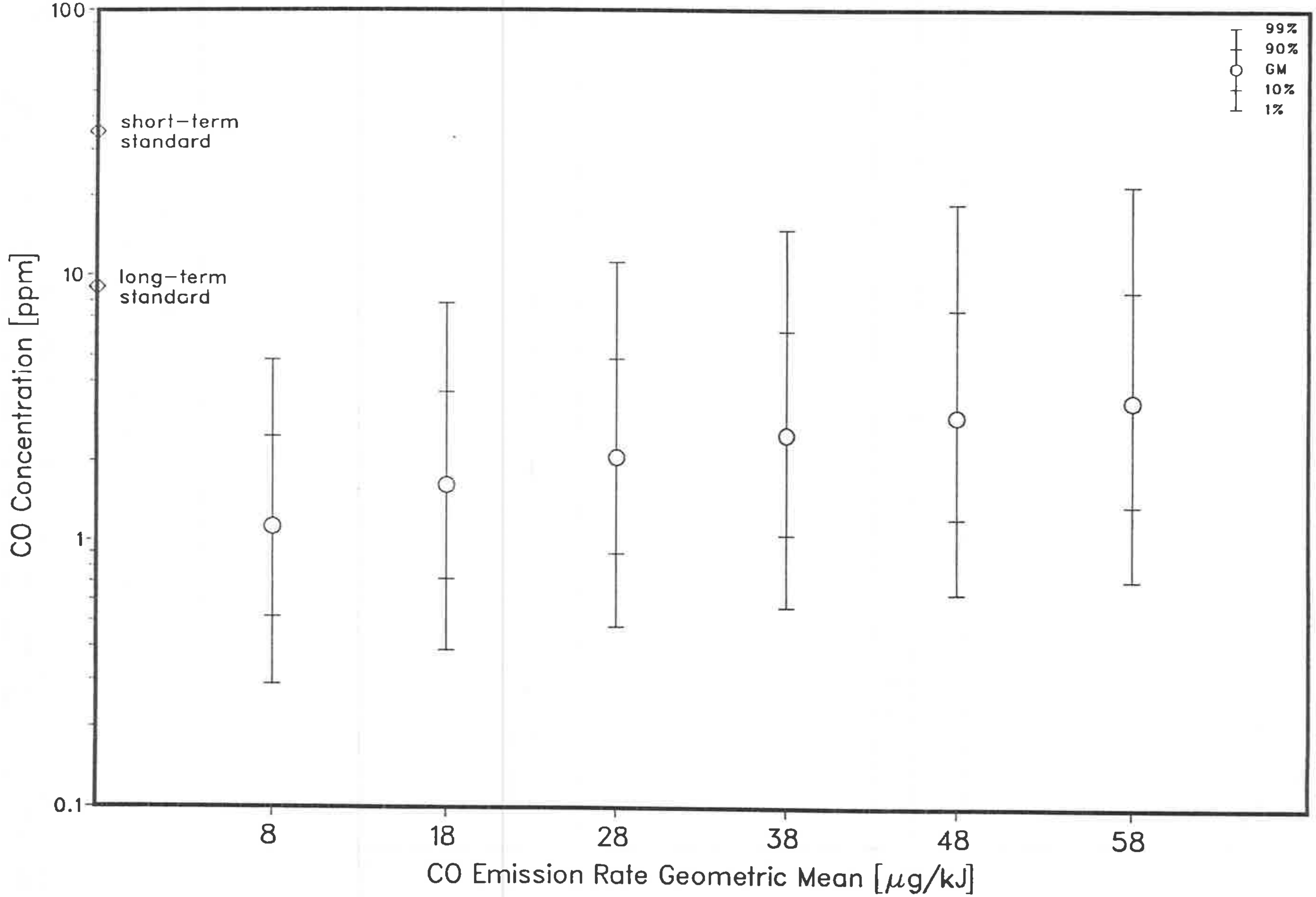


Figure IV-9. Indoor CO concentration vs. CO emission rate (GSD = 2.4) in houses with convective unvented gas space heaters in the LPL region, with an outdoor temperature of 7°C and an outdoor CO concentration of 0.7 ppm (GSD = 2.1).

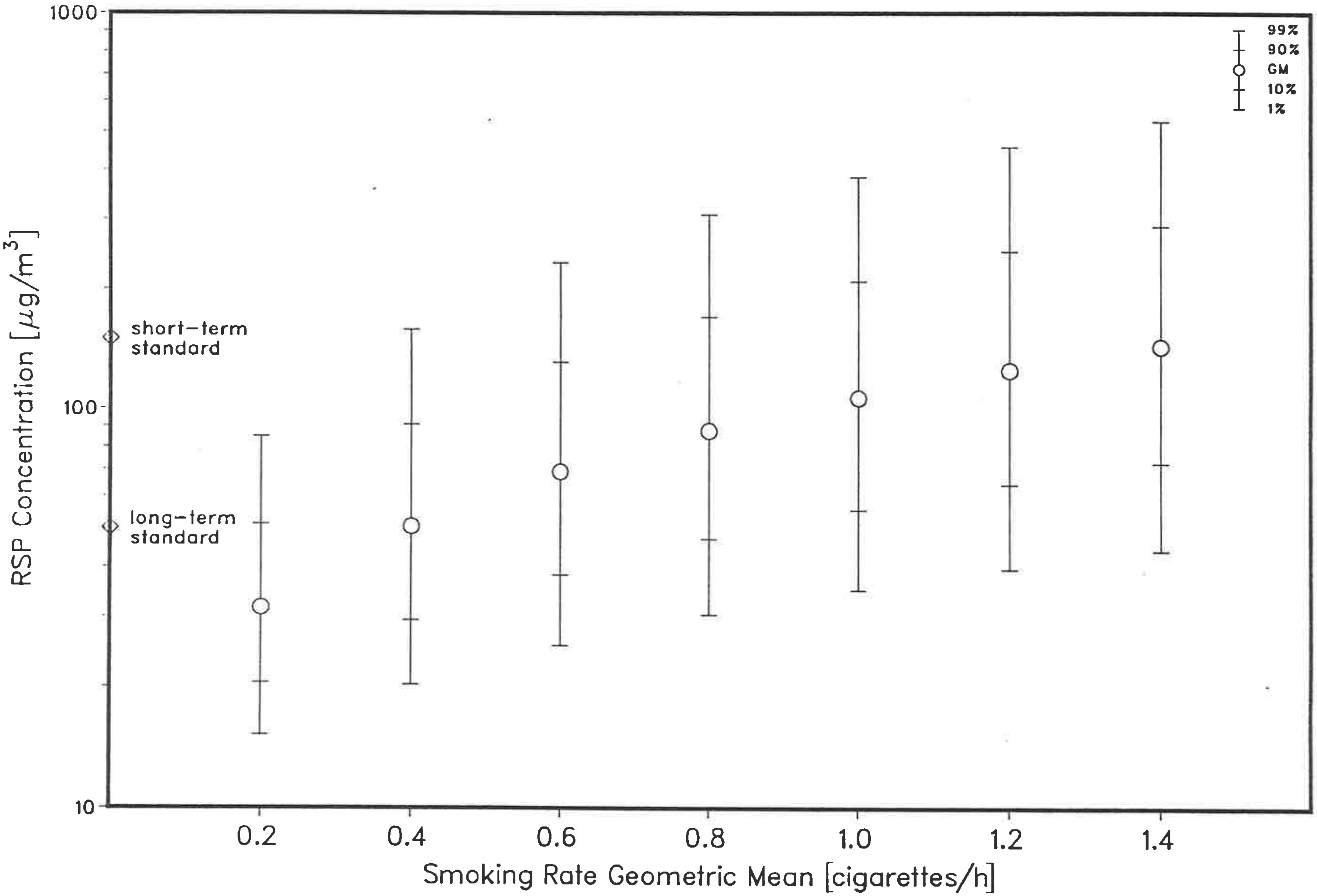


Figure IV-10. Indoor RSP-concentration distribution vs. smoking rate (GSD = 1.5) in houses with smokers in the LPL region, with no space heating and an outdoor RSP concentration of 20 $\mu g/m^3$ (GSD = 1.2).

V. SINGLE-SOURCE AND REGIONAL RESULTS

1. Single-source Results

Multiple macromodel simulations were run for the RGE housing stock with a single source in each of the 3500 houses simulated. These runs were designed to make comparisons of the relative impact of each combustion source on the IAQ of a housing stock.

Figures V-1, 2, and 3 show the modeled indoor concentration distributions of CO, NO_2, and RSP, respectively, in houses with only one indoor combustion-pollutant source. For consistency, the RGE region was used for these analyses, and the outdoor temperature used was 0℃. The indoor pollutant-distributions in houses with electric heaters represent the indoor background concentration due to outdoor air pollution. The indoor-background concentration distribution is the same as the outdoor distribution for CO but is lower for NO_2 and RSP, since these pollutants are reactive, and some outdoor RSP are removed by the building shell.

For CO, kerosene heaters, unvented gas space heaters, and gas oven/ranges used for heating caused the highest indoor concentrations. The same sources were also responsible for the highest indoor NO_2 levels. For RSP, the highest 99th-percentile concentrations were due to non-airtight wood stoves, oil forced-air furnaces, radiant kerosene heaters, and convective unvented gas space heaters. The highest GMs were also due to these sources, except oil forced-air furnaces, and smoking. As mentioned throughout this report, these results are modeled "predictions" based on the macromodeling concept and input parameters with a wide variation in their accuracy, precision, and applicability. However, these results do give us a sense of which sources can cause the highest indoor air pollution levels.

Comparison of the airtight and non-airtight wood stove RSP results shows the effect of the indoor-pollutant emission rate on indoor RSP concentrations (see Fig. V-3). Sexton *et al.* (1984) reported an indoor AM minus outdoor AM of 7 $\mu g/m^3$ for houses with wood stoves. Our modeled results show an indoor GM minus outdoor GM of 9 $\mu g/m^3$ for airtight wood stoves and 37 $\mu g/m^3$ for non-airtight wood stoves. The value measured by Sexton compares well with the macromodel results for airtight wood stoves. Further comparison is difficult since the number of airtight and non-airtight wood stoves and the outdoor temperatures are not reported by Sexton.

The previous single-source analyses shows the relative impact of various sources at a single outdoor temperature during a single week of the year. For space-heating appliances, there is a large dependence of the source-usage rate on the outdoor temperature and, thus, the time of year. Figures V-4 to V-12 show this seasonal dependence for selected space-heating appliances in regions where they are popular.

Figures V-4 to V-12 are largely self-explanatory; however, some interesting observations can be made. The seasonal effects of vented appliances that only emit pollutants indoors if malfunctioning (e.g., gas and oil forced-air furnaces and wall/floor furnaces--see Figs. V-4 to V-6) significantly affect only the 99th-percentile results and do not significantly affect the 90th percentiles or the GMs. This is a result of the model using a 6.8% malfunction rate. When an appliance always emits pollutants indoors--such as kerosene heaters, unvented gas space heaters, and wood stoves--all of the distributional percentiles are affected (see Figs. V-7 to V-12).

2. Regional Results

Regional indoor air-pollution-concentration distributions were obtained by combining all sources using their market-penetration levels discussed in Appendix A.

Figures V-13 to V-15 summarize the macromodel results for indoor concentration distributions of CO, NO_2, and RSP, respectively, for the four regions studied. The figures include houses that use only one space heating source. The use of a gas range/oven for space heating was eliminated for the analysis because the prevelance of this behavior is not well known. The houses can have multiple non-space-heating sources as simulated by the Monte Carlo technique. No provisions for using supplemental heat are included in the model. More summary graphs separated by pollutant, space heating appliance, and season are included in Appendix C.

Comparing the results with the long-term outdoor air quality standards discussed in Chapter IV (9 ppm for CO, 0.05 ppm for NO_2, and 50 $\mu g/m^3$ for RSP) shows that, in general, more houses exceed the RSP standard than either the CO or NO_2 standard, and more houses exceed the NO_2 standard than the CO standard.

A comparison of the CO concentration distributions (Fig. V-13) from the four regions shows that the indoor GM CO levels are highest in the WWP Region. However, the outdoor CO concentrations are also high in this region, effecting the indoor CO levels. Indoors and outdoors, the high CO levels in the WWP region are due to the widespread use of woodstoves. The highest 99th-percentile CO concentrations occur in the winter in the RGE region, presumably due to the use of kerosene heaters.

The distributions of indoor NO_2 concentrations (Fig. V-14) indicate that the LPL Region has the highest annual-average and winter-week concentrations, due to the use of unvented gas appliances and relatively high NO_2 outdoor levels.

RSP levels are highest in the WWP Region (Fig. V-15), again due to the use of woodstoves.

For CO, there is an annual poisoning death rate that can provide some insight to the distribution of indoor CO concentrations in U.S. residences. There are approximately 700 to 1000 CO poisoning deaths per year in the U.S. (NSC, 1986; USDHHS, 1986). Some of these deaths are suicides and some are associated with running cars and burning charcoal indoors--sources not modeled here. It appears that there may be 114 to 343 reported accidental deaths per year due to combustion appliances. If it is assumed that these deaths occur during the winter months, we can use the range of winter GMs shown in Fig. V-13 as a surrogate for the U.S. indoor winter CO GM. The modeled winter CO GMs (and GSDs) for WWP, RGE, PGE, and LPL were 2.3 ppm (GSD = 1.4), 1.4 ppm (GSD = 2.0), 1.6 ppm (GSD = 1.9), and 1.2 (GSD = 2.1), respectively. Using an average GM of 1.6 and a 400 ppm CO level required to induce death (McFarland, 1953), a GSD can be calculated to account for the accidental CO deaths. The implied GSD's are 3.1 for 114 deaths per year and 3.3 for 343 deaths per year. These GSDs are larger than the modeled results. If a GM of 1.6 ppm and a GSD of 2.0 are used, no household in the U.S. would have an indoor CO level above 400 ppm.

There are at least four possible interpretations for the discrepancy in this very crude analysis. One, the actual CO-concentration distributions are not log-normal; therefore, this type of analysis is inappropriate. The CO results for WWP and RGE, the two modeled regions with the coldest climates, do show deviations from the log-normal distribution. Two, the analysis is just too crude to make any real conclusions regarding the consistency of the modeled results and the annual CO poisoning death rate, which can be considered "catastrophic" events. Three, the CO emission rate distributions are not sufficiently characterized, especially with regard to maltuned and malfunctioning appliances, to make inferences regarding the extreme tail of the indoor CO-concentration distribution. And four, there are other indoor CO sources that are important such as the burning charcoal indoors. In fact, all four may be true and more research is needed if we are to characterize the extreme tail of the indoor CO concentration distribution.

References for Chapter V

McFarland, R.A. (1953) *Human Factors in Air Transportation*, McGraw-Hill.

NSC (1986) *Accident Facts: 1986 Edition, National Safety Council,* Chicago, IL.

Sexton, K., Spengler, J.D., and Treitman, R.D. (1984) Effects of residential wood combustion on indoor air quality: a case study in Waterbury, Vermont. *Atmos. Environ. 18*: 1371-1383.

USDHHS (1986) *Vital Statistics of the United States 1982: Volume II - Mortality Part A.* U.S. Department of Health and Human Services, Public Health Service, National Center for Health Statistics, Hyattsville, MD.

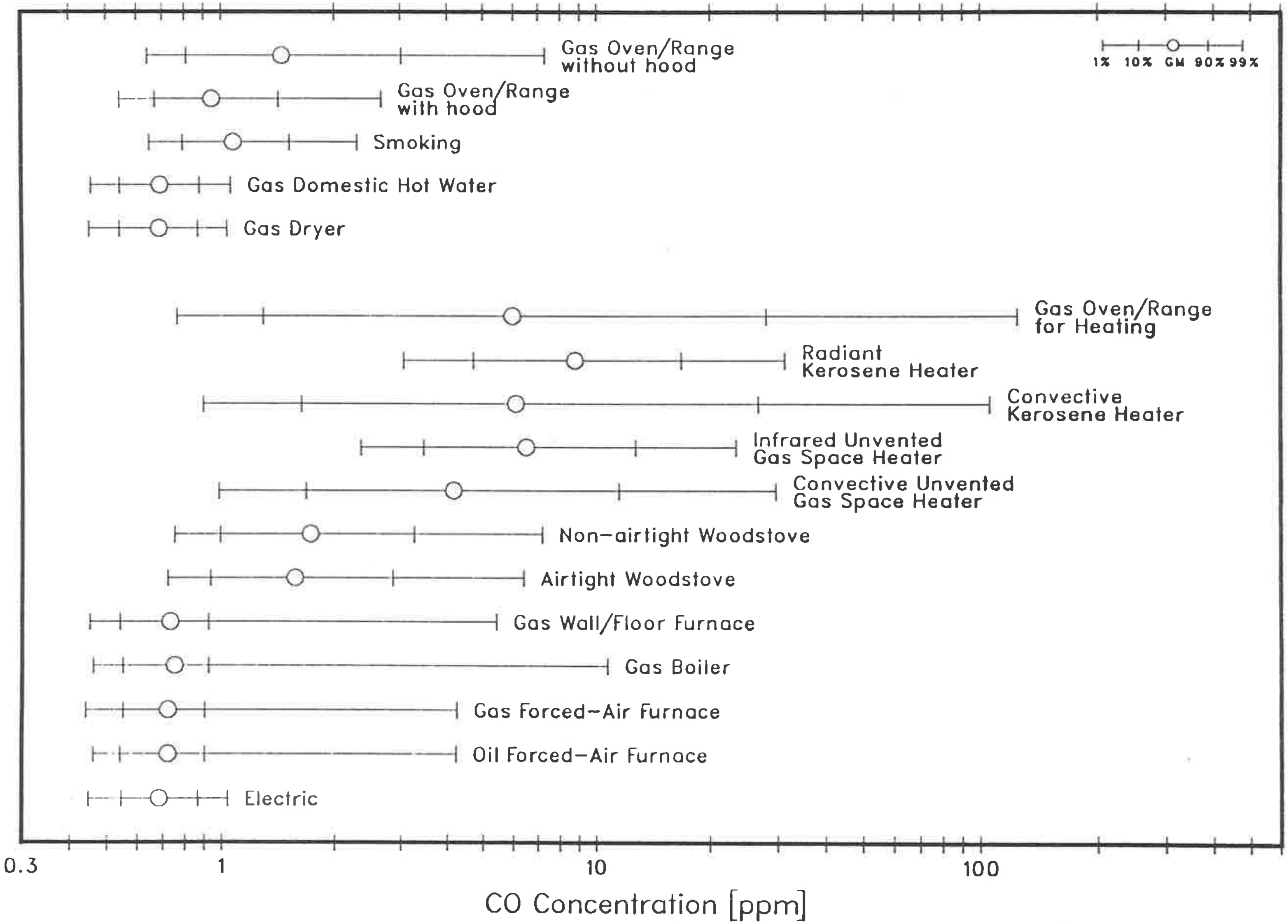


Figure V-1. Modeled indoor CO-concentration distributions in houses with only one indoor combustion pollutant source. The RGE region was used for the analyses, with an outdoor temperature of 0°C. Outdoor CO concentration GM was 0.7 ppm (GSD = 1.2).

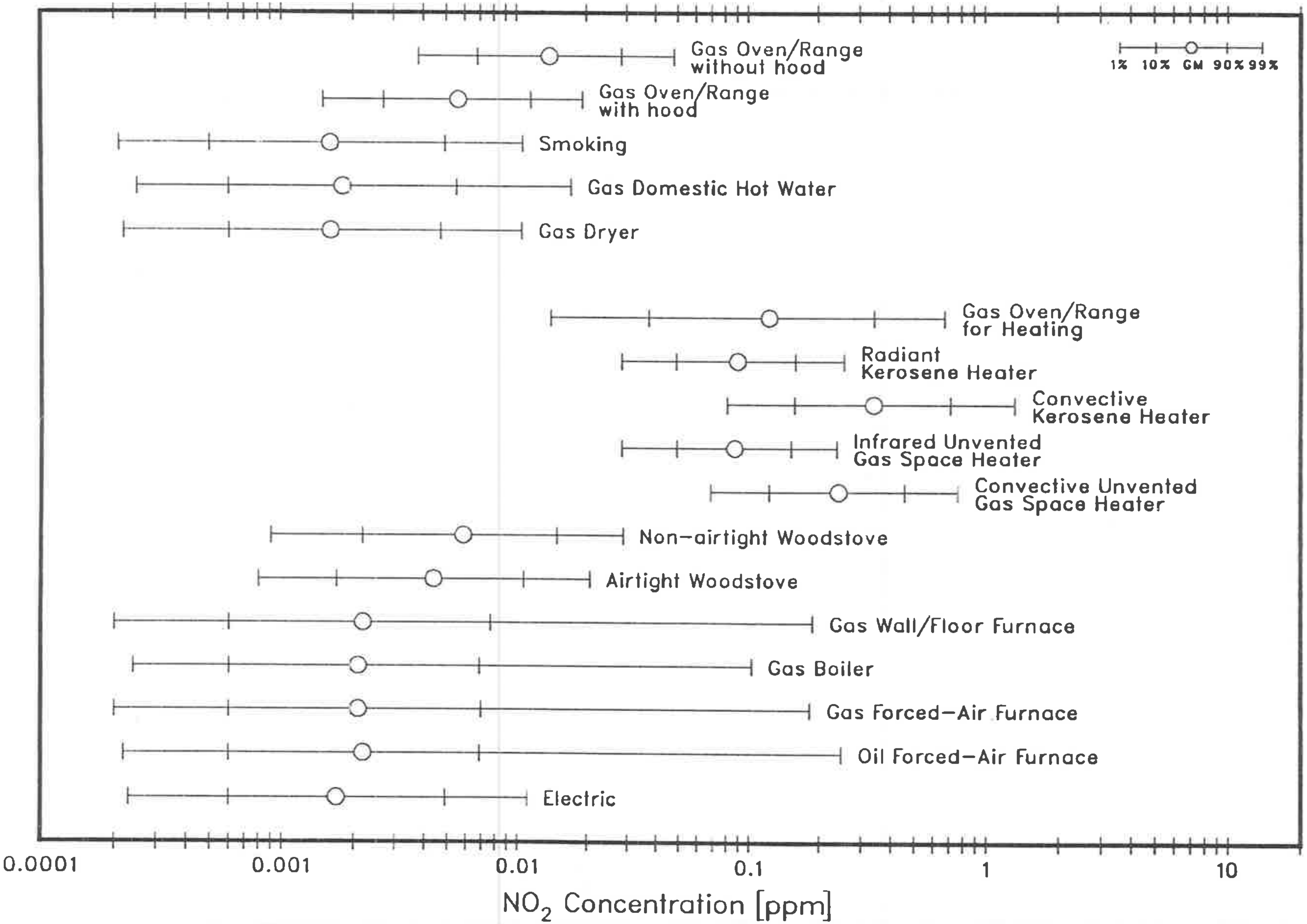


Figure V-2. Modeled indoor NO_2 concentration distributions in houses with only one indoor combustion pollutant source. The RGE region was used for the analyses, with an outdoor temperature of 0°C. Outdoor NO_2 concentrations GM was 0.006 ppm (GSD = 1.95).

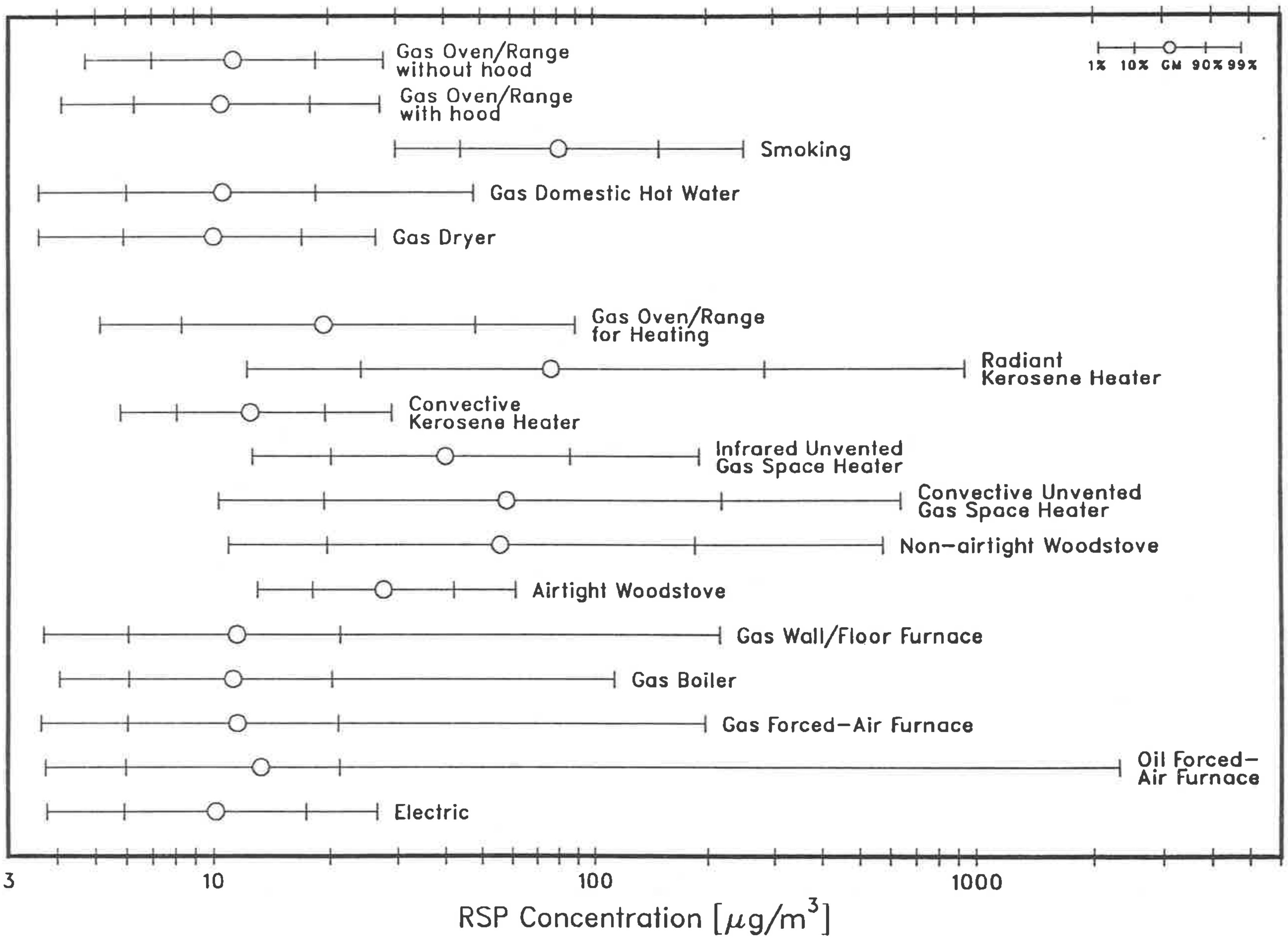


Figure V-3. Modeled indoor RSP-concentration distributions in houses with only one indoor combustion pollutant source. The RGE region was used for the analyses, with an outdoor temperature of 0°C. Outdoor RSP concentration GM was 19 $\mu g/m^3$ (GSD = 1.5).

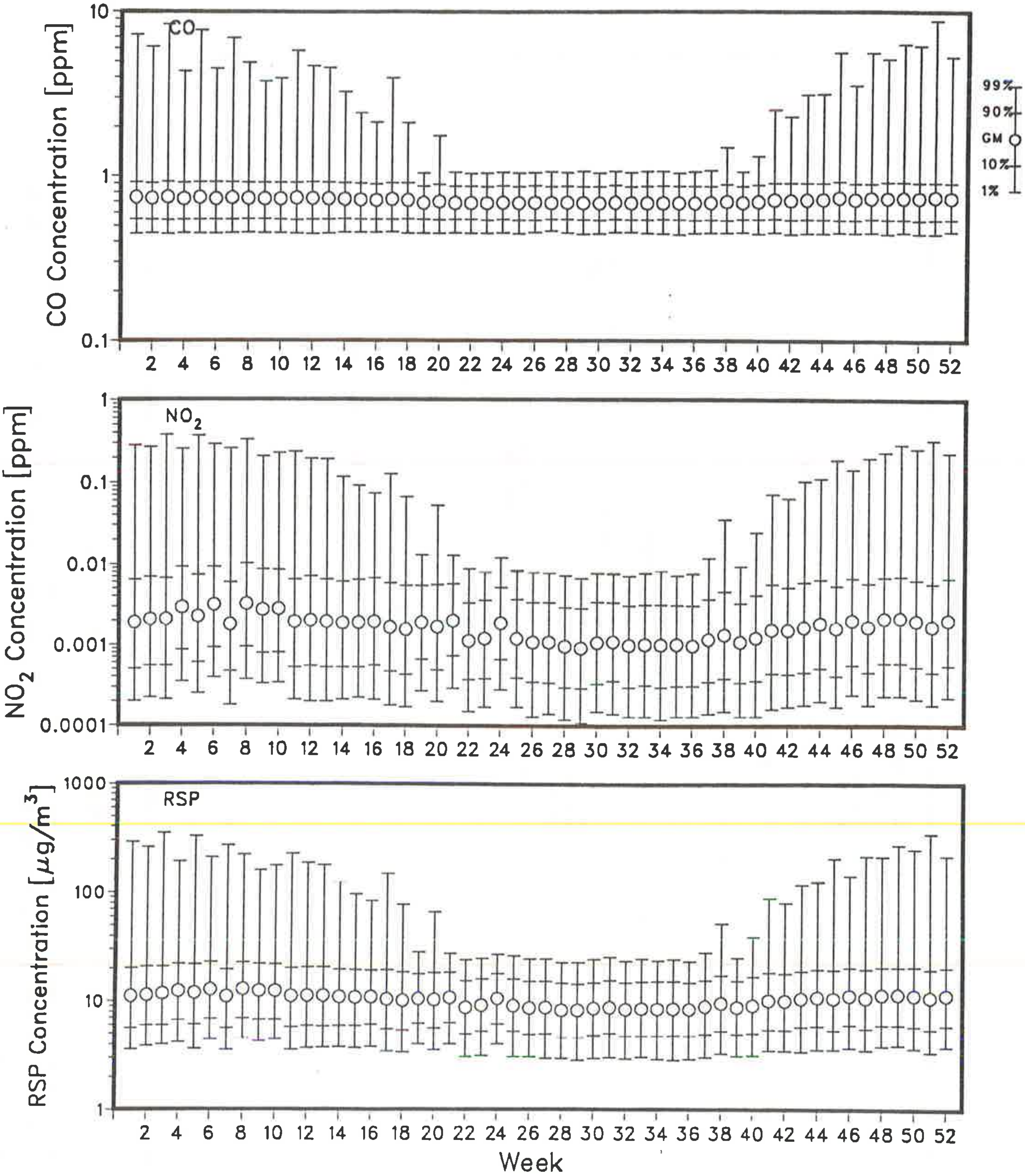


Figure V-4. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the RGE region, with gas forced-air furnaces.

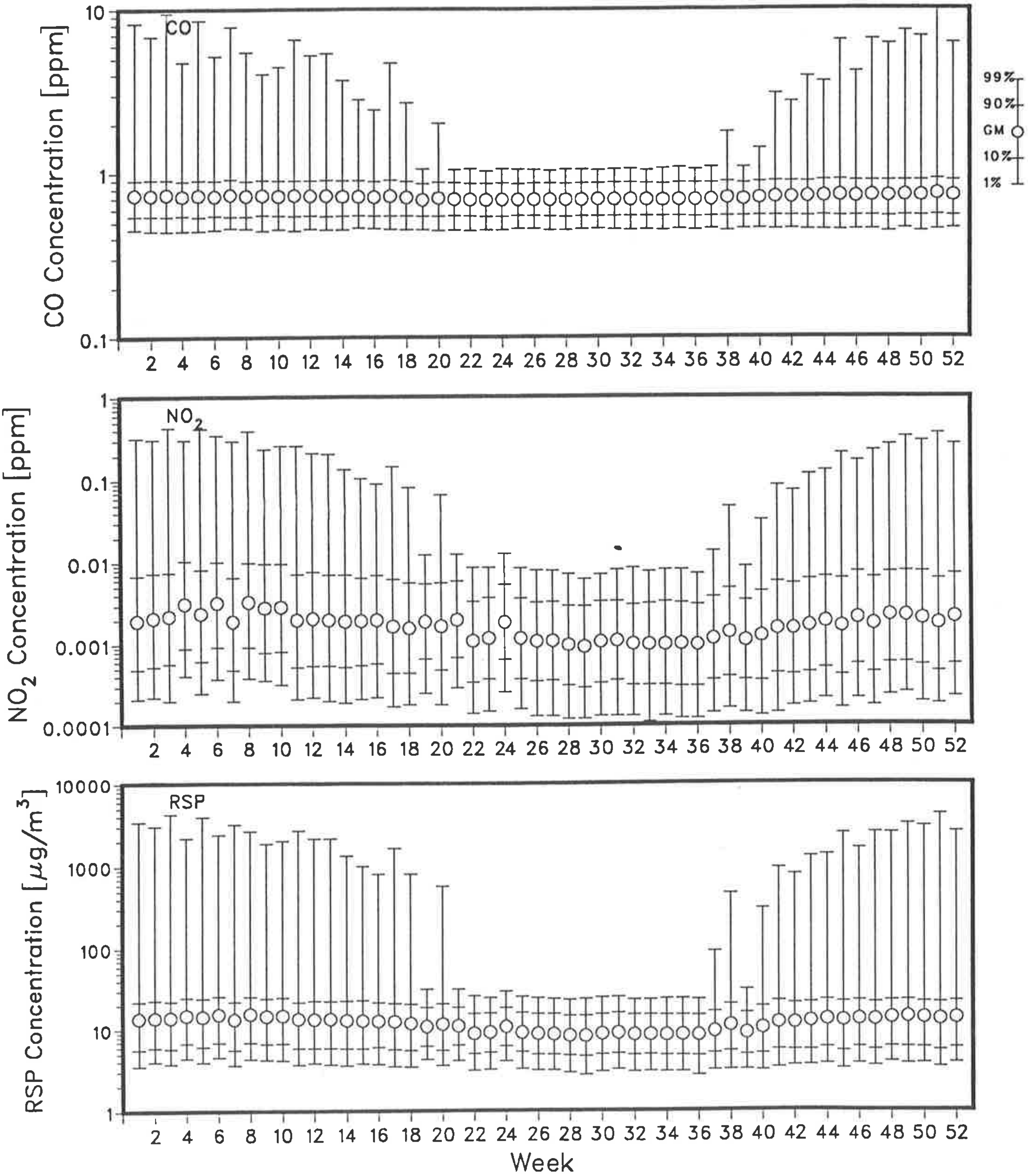


Figure V-5. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the RGE region, with oil forced-air furnaces.

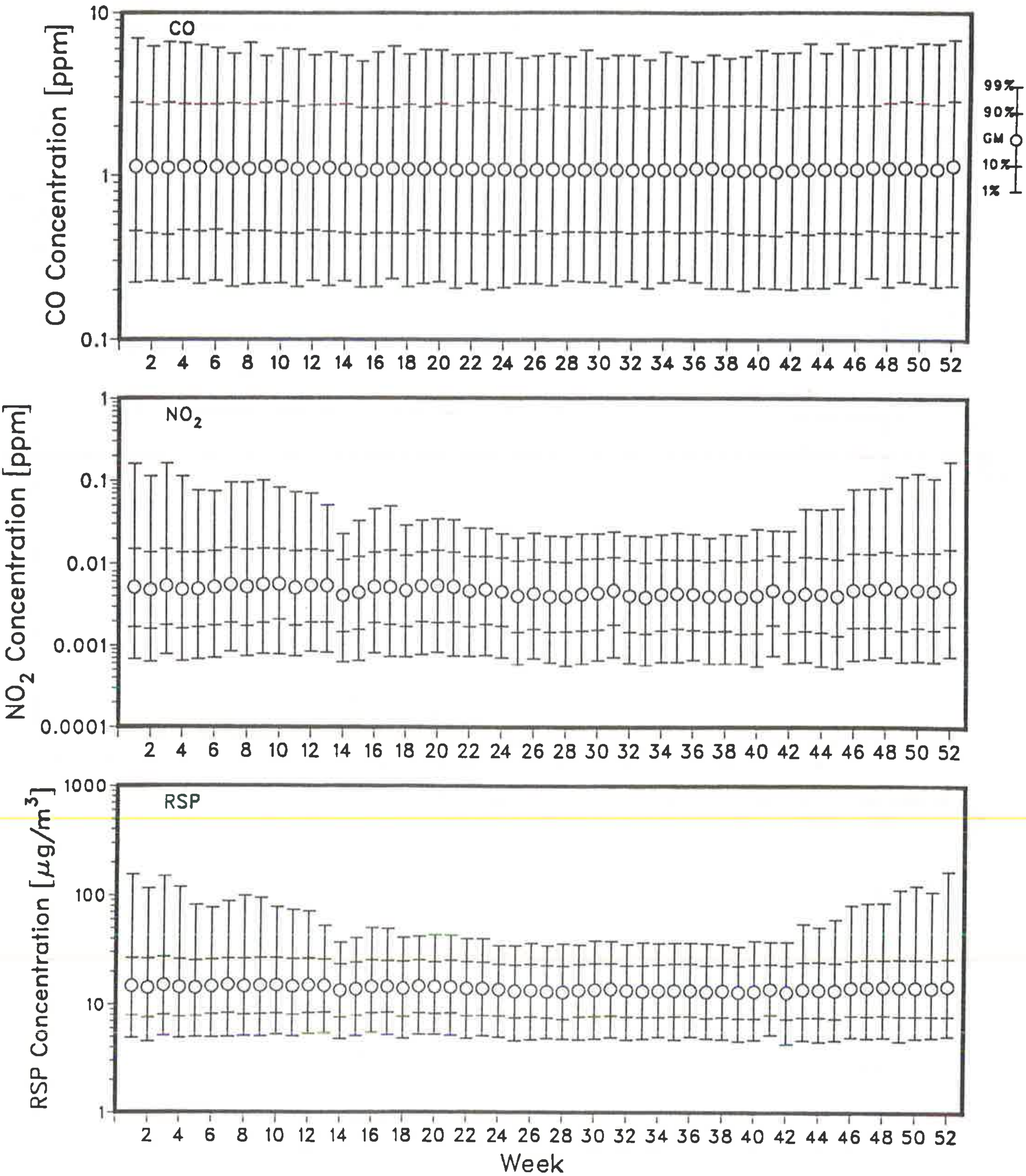


Figure V-6. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the PGE region, with wall/floor furnaces.

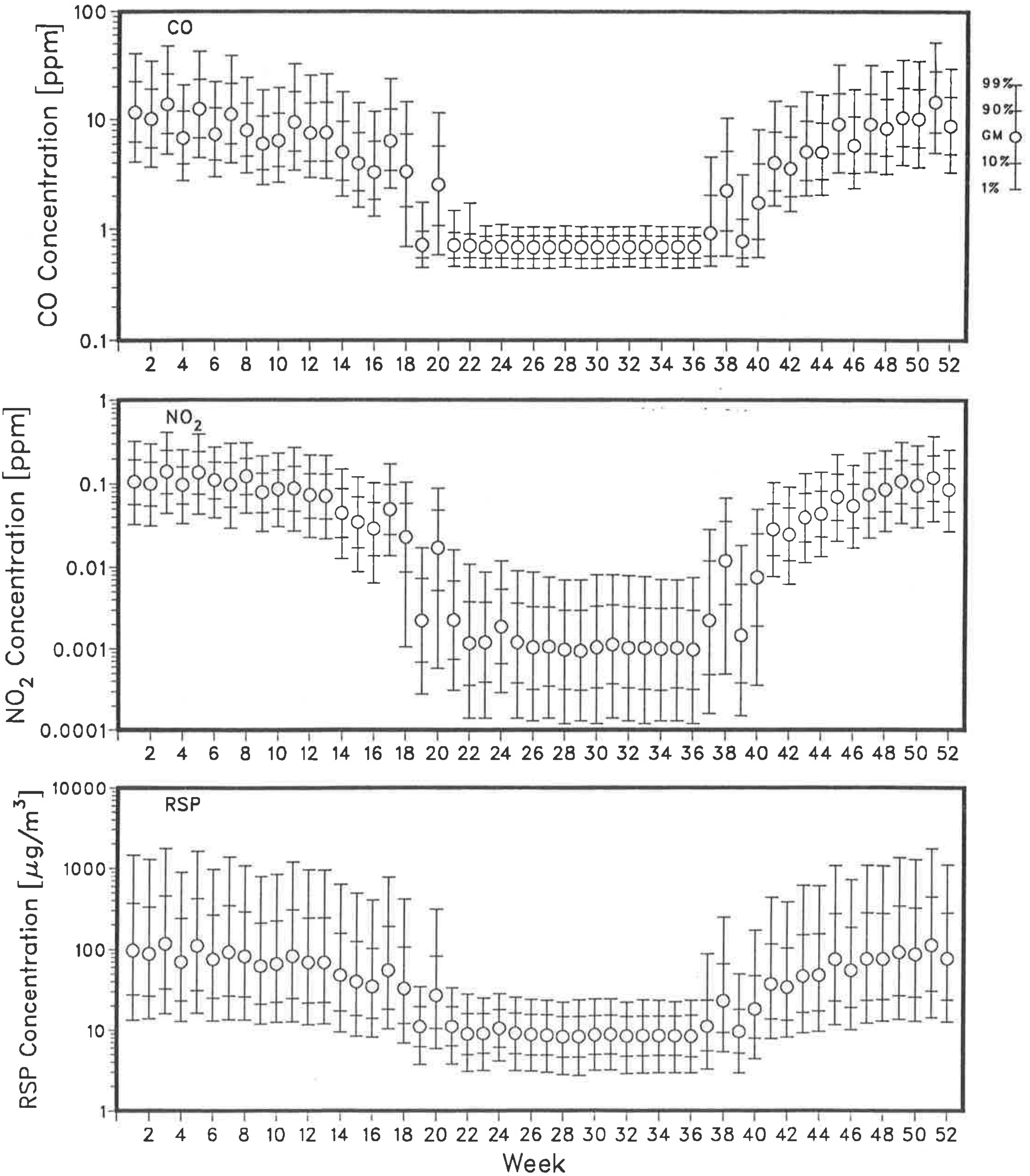


Figure V-7. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the RGE region, with radiant kerosene heaters.

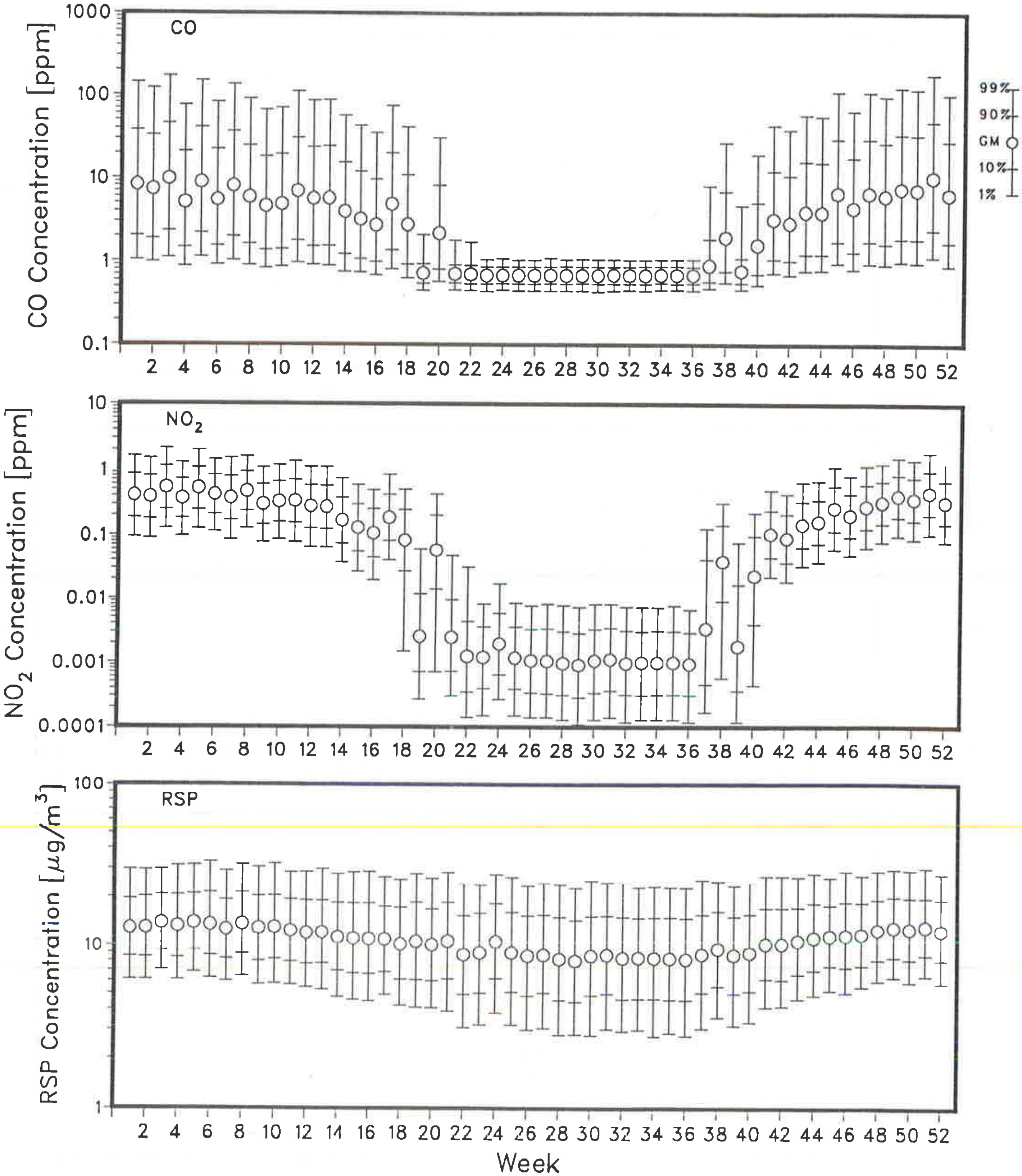


Figure V-8. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the RGE region, with convective kerosene heaters.

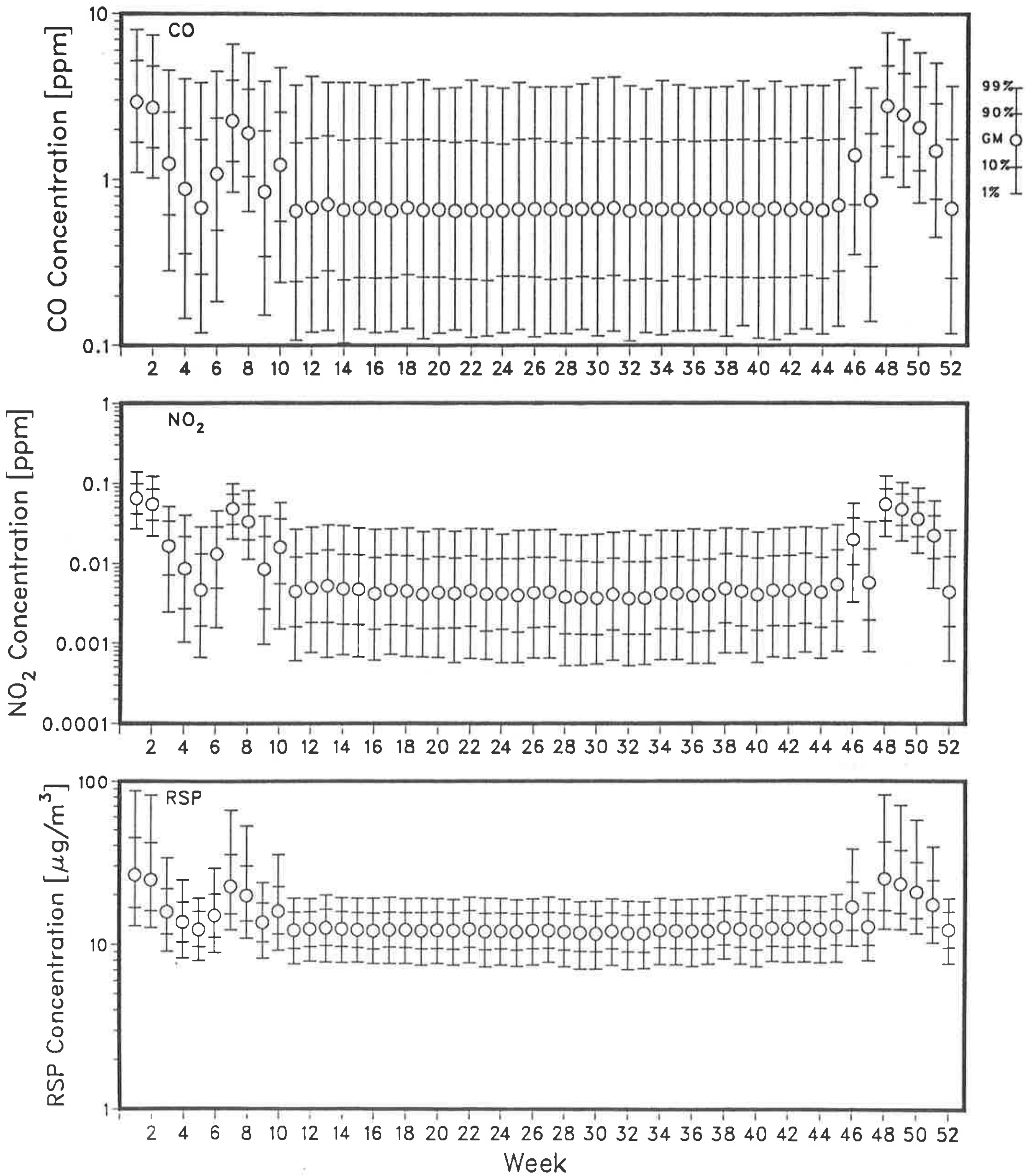


Figure V-9. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the LPL region, with infrared unvented gas space heaters.

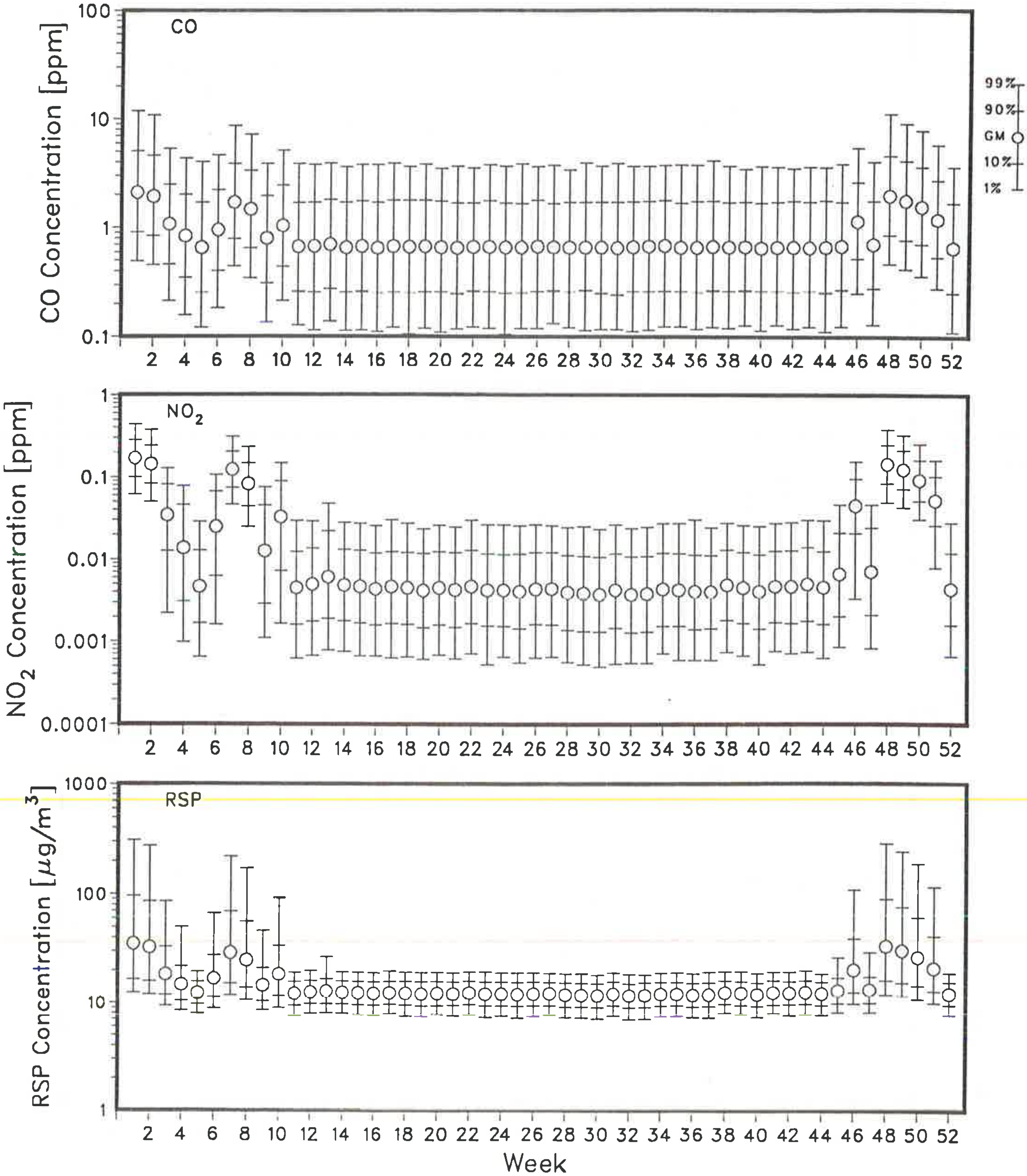


Figure V–10

Figure V-10. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the LPL region, with convective unvented gas space heaters.

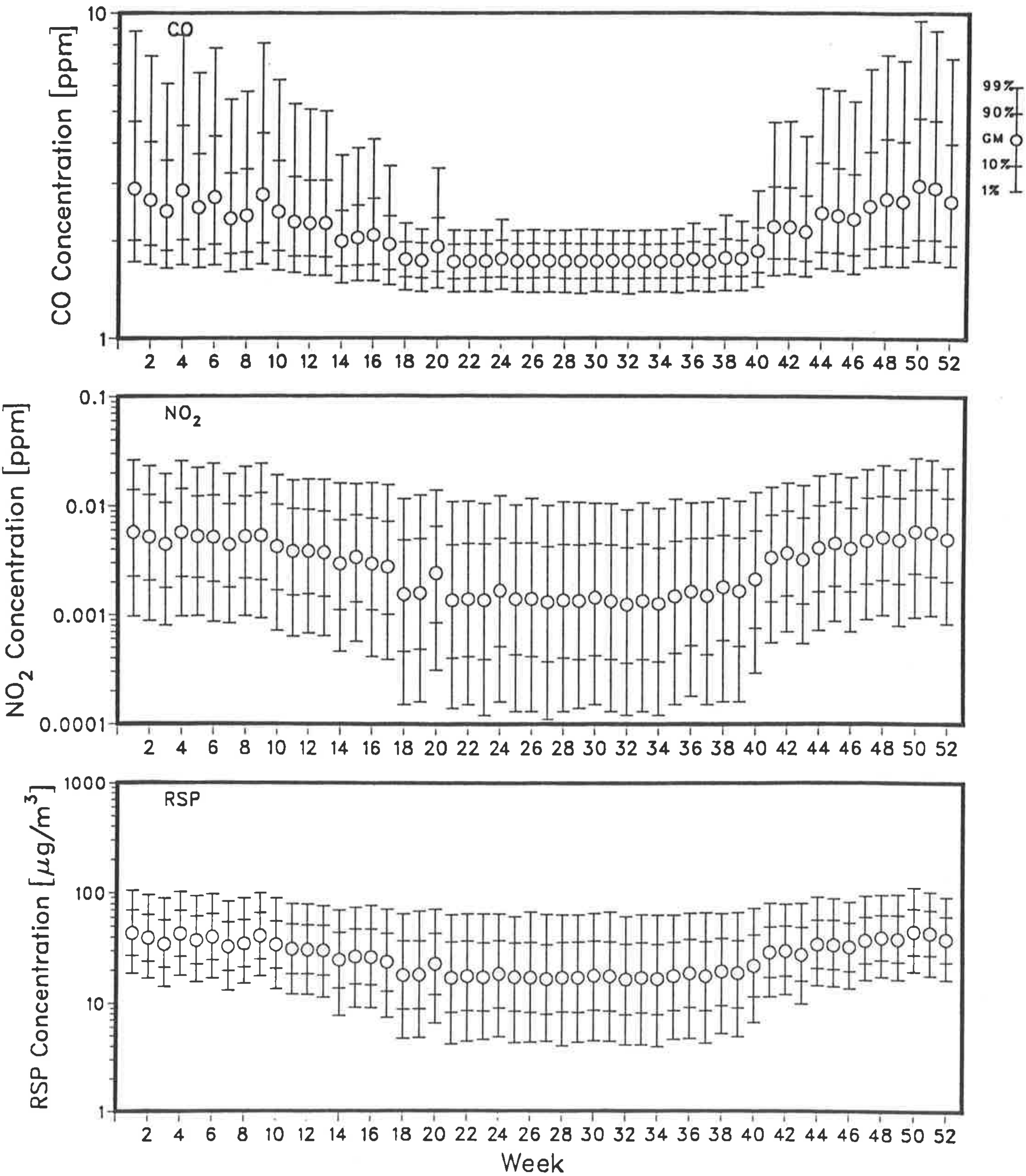


Figure V-11. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the WWP region, with airtight wood stoves.

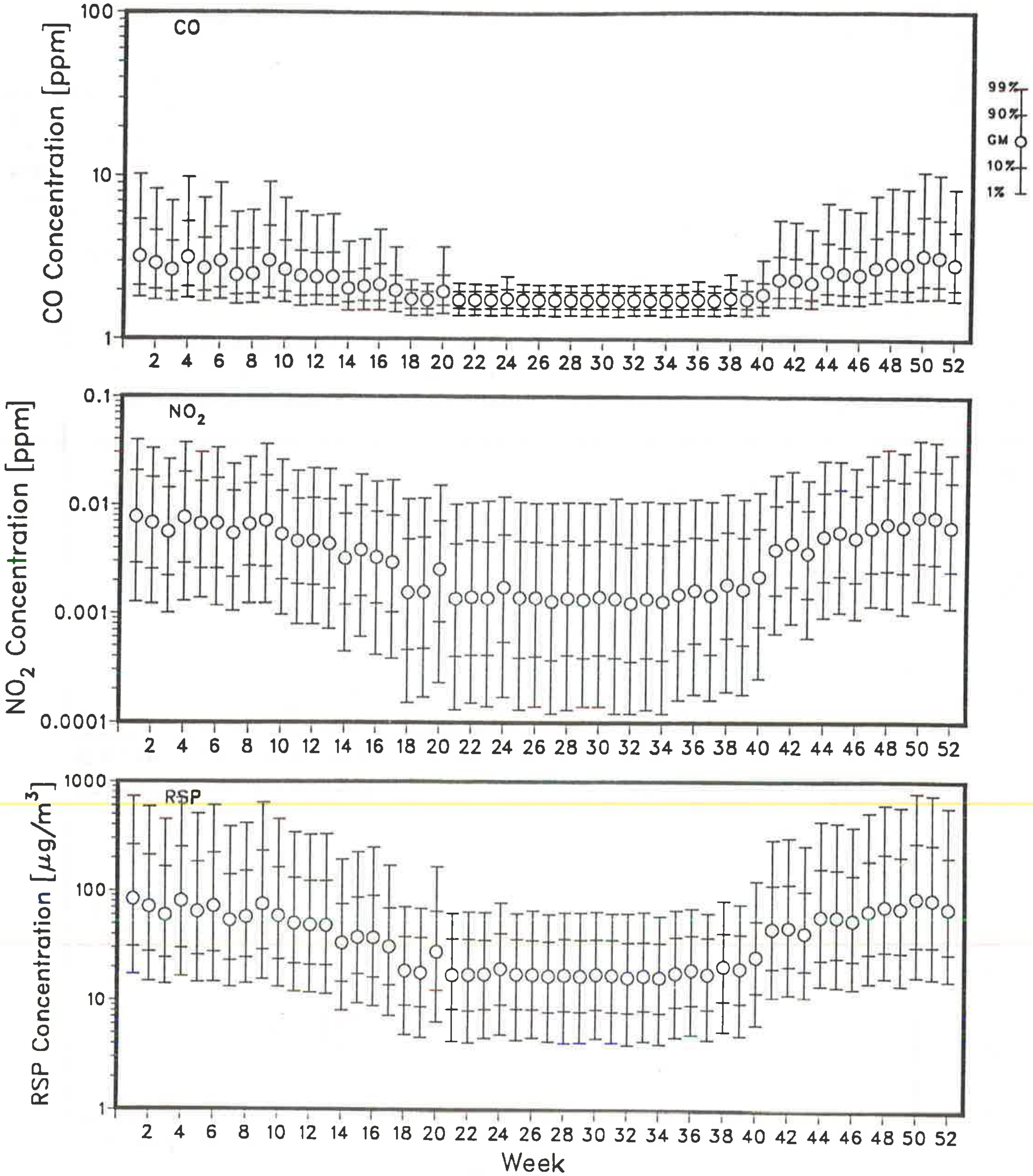


Figure V-12. Modeled indoor CO-, NO_2-, and RSP-concentration distributions versus week of year for houses in the WWP region, with non-airtight wood stoves.

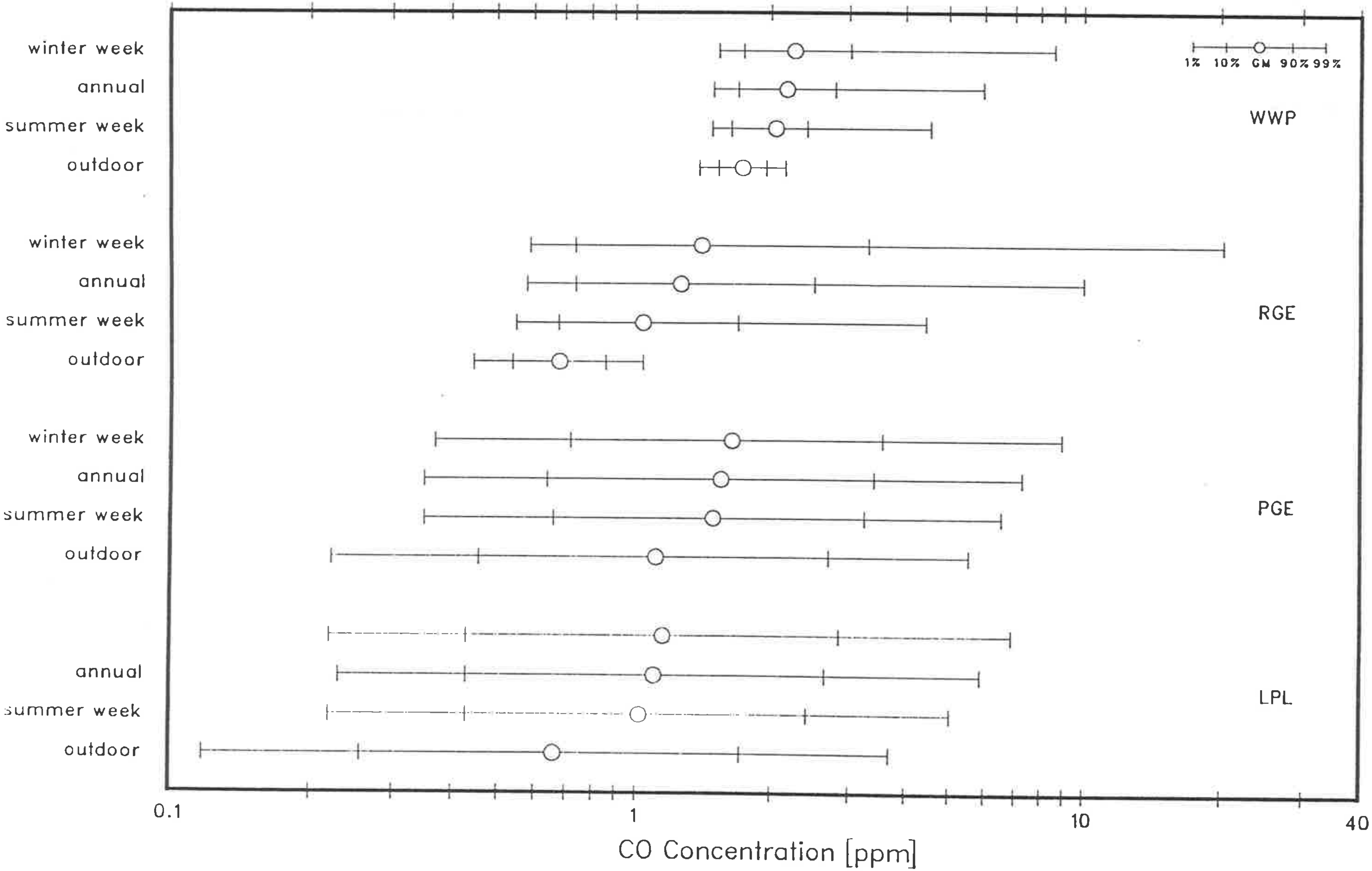


Figure V-13. Modeled indoor and measured outdoor CO-concentration distributions for four regions in the U.S. Indoor winter and summer results are taken from selected weeks and are not seasonal averages.

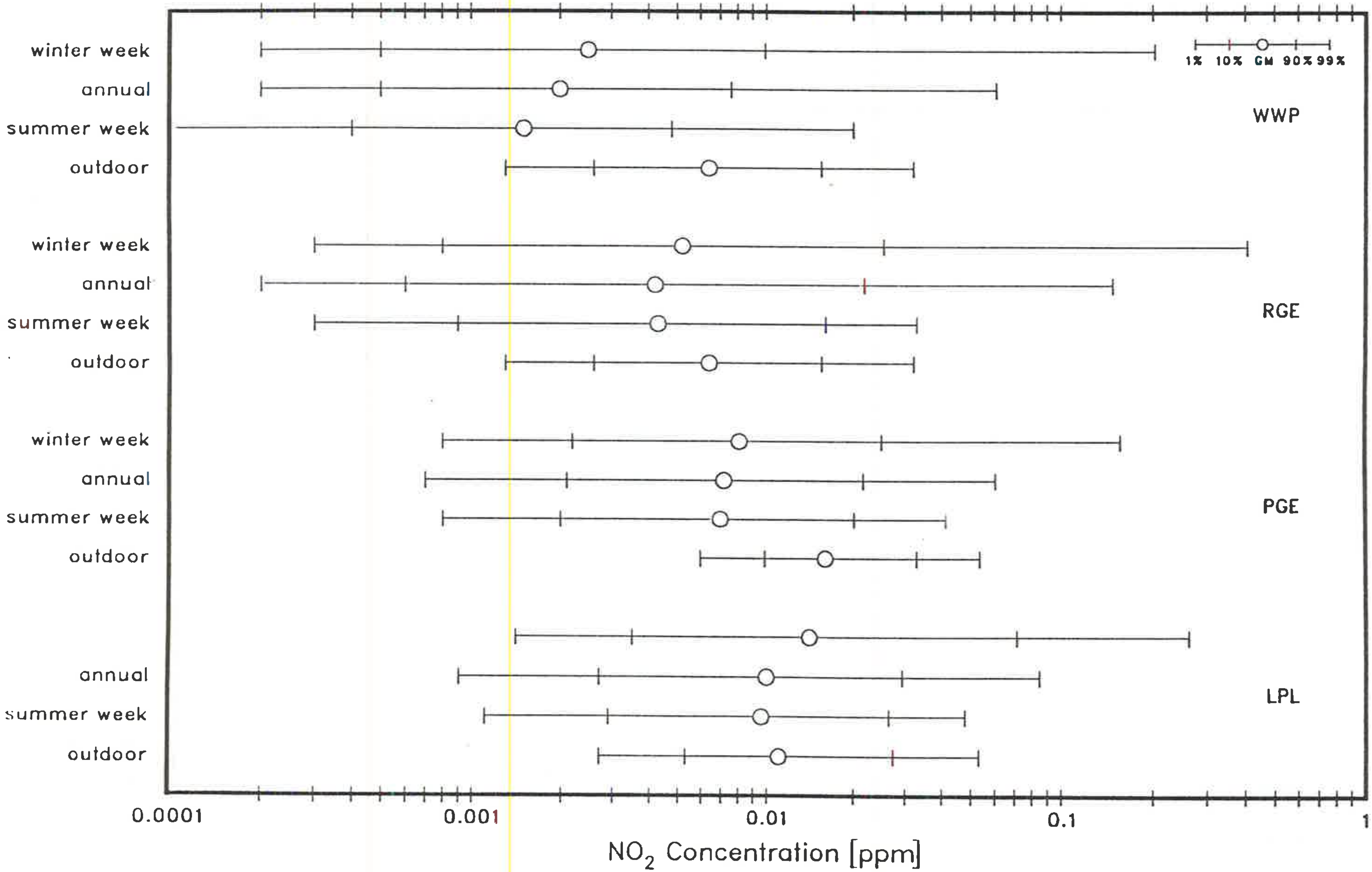


Figure V-14. Modeled indoor and measured outdoor NO_2-concentration distributions for four regions of the U.S. Indoor winter and summer results are taken from selected weeks and are not seasonal averages.

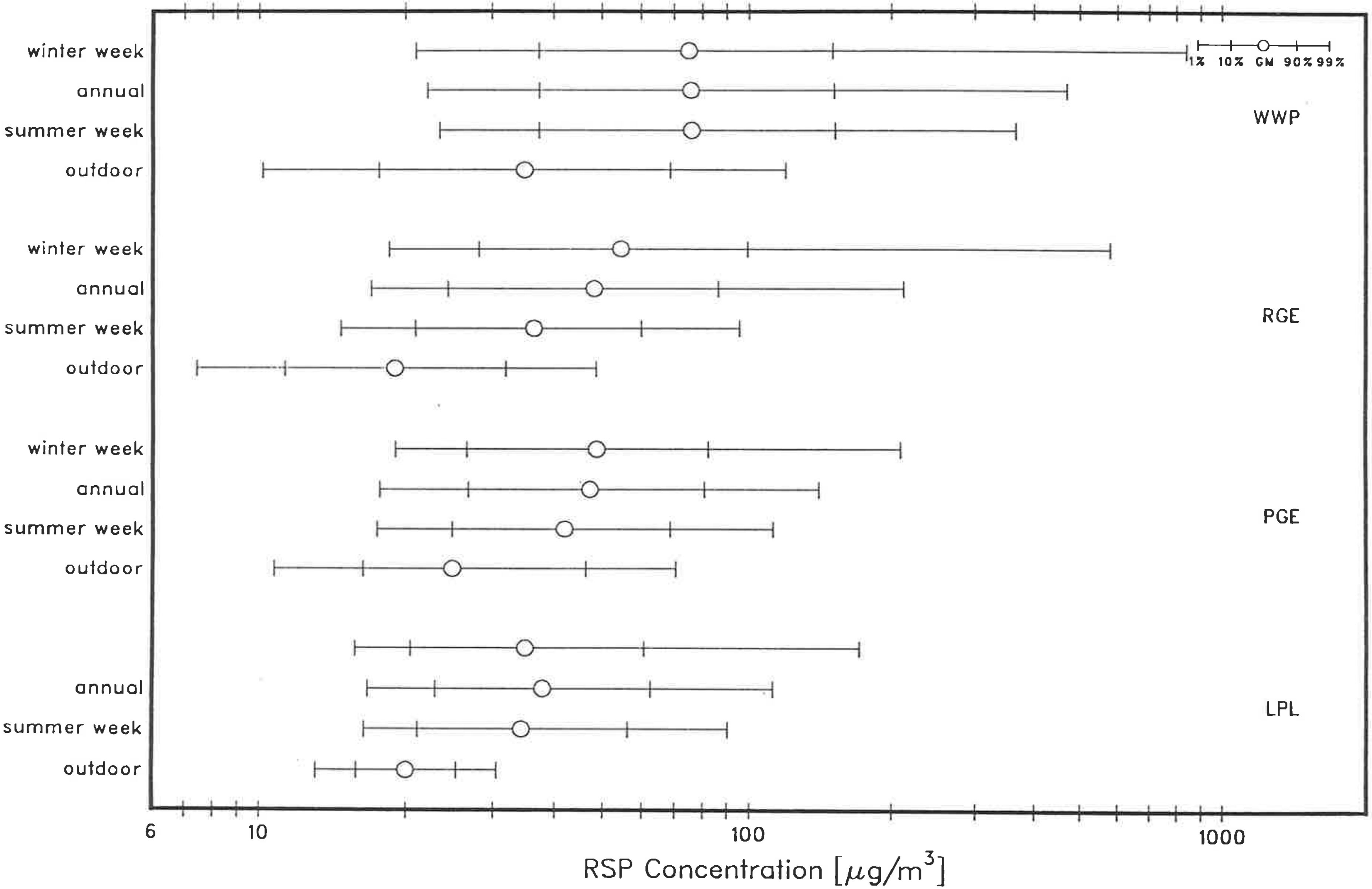


Figure V-15. Modeled indoor and measured outdoor RSP-concentration distributions for four regions of the U.S. Indoor winter and summer results are taken from selected weeks and are not seasonal averages.

VI. CONCLUSIONS AND RECOMMENDATIONS

Use of simulation models, also called a macromodel in this report, to assess indoor air-pollution concentrations in the U.S. housing stock appears to be a very promising approach. The effects of sources, geographic region, and time of year are all incorporated into the model. The model can be used to quantify the influence of numerous parameters on the indoor air-pollutant concentrations in residences. The macromodeling concept was successfully used to assess indoor air-pollutant concentrations from combustion sources and to delineate the relative impact on IAQ of several sources of indoor combustion pollutants. High predicted residential CO and NO_2 concentrations were associated with the winter-time use of unvented gas and kerosene space heaters. High predicted RSP concentrations were associated with indoor smoking and the winter-time use of non-airtight wood stoves, oil forced-air furnaces, radiant kerosene heaters, and convective unvented gas space heaters.

More research is needed related to improve the model algorithms and extent and reliability of the input data. At a minimum, improved model algorithms are needed to account for the use of secondary heat sources and for the opening of doors and windows during mild weather.

There is a great need for improved data in three categories. First, improved information on field emission-rates for sources already included in the model is needed. In many cases, the emission rates used in the model are derived from laboratory studies, and these data need, at a minimum, to be verified by field studies or replaced by new field-study data. A few examples of data needs in this category include RSP emission-rate distributions for airtight and non-airtight wood stoves, prevalence and magnitude of malfunctioning vented appliances, CO emission rates for almost all sources, indoor smoking frequency, and prevalence of use, and degree of venting of range hoods. Second, data on the market penetration and emission rates of sources not presently included in this model is needed. Such sources include fireplaces, attached garages, indoor charcoal cooking, and pipe/cigar smoking. And third, data on the influence of lifestyle on indoor air pollution concentrations are needed. Research in this area could result in improved data or improved/new model algorithms. A sensitivity analysis of this model will be conducted in the future and will more explicitly address research needs, especially with regard to improved data.

Despite current limitations of the model, comparisons of the macromodel results with data from field studies indicate that the current state of the model is good, at least, for "order-of-magnitude" assessments, and GMs may be accurate to within a factor 2 or 3 or better in specific instances where the input data are relatively well known (e.g., NO_2 from unvented gas-fired space heaters or kerosene heaters used as the only source of heat). However, conclusions regarding the number of households above a given standard cannot be made at this time, and the model needs further verification.

A future macromodel report will address combustion pollutants other than CO, NO_2, and RSP. Pollutants such as organic compounds (volatile, semivolatile, and nonvolatile), many of which are mutagenic, and sulfur dioxide will be addressed because of the adverse health effects associated with these pollutants. It appears that the macromodeling concept can also be applied to other pollutant categories such as organics from consumer products and building materials and radon from ground soil, but more research is needed in these areas.

One key recommendation for other researchers in this field is that future field studies need to take into account the macromodeling parameters to maximize the usefulness of their results. It is extremely important that future field studies (1) fill the information gaps identified in this report and (2) collect sufficient information on the housing stock under study to allow proper interpretation of the results. It is almost more important to measure the parameters that affect indoor concentrations than it is to measure the concentrations themselves.

ACKNOWLEDGMENTS

The authors thank Kevin Teichman of the U.S. Environmental Protection Agency (EPA); John Talbott of the U.S. Department of Energy; Kailash Gupta, Warren Porter, and Sandra Eberle of the U.S. Consumer Product Safety Commission; and Tom King of EA-Muller, Inc. for their moral and/or financial support of this project. The authors also thank Edie Canfield, Nancy Powers, Sandy Sampson, and Ted Gartner for "processing" the manuscript and Bryan Cowley for his assistance in data processing. Finally, we thank Dave Grimsrud, Max Sherman, and Ashok Gadgil of the Lawrence Berkeley Laboratory and Les Sparks of the U.S. EPA for their reviews of the manuscript.

APPENDIX A: DETAILED DESCRIPTION OF MODEL INPUT PARAMETERS

Table of Contents

1 Introduction

This appendix contains a detailed description of the macromodel input parameters. The data have been organized by parameter type. The parameters are divided into two categories. The first consists of global parameters, i.e., those parameters that are common to the entire housing stock. The second category consists of region-specific parameters.

Since the results generated by the macromodel are only as good as the input data supplied, it is important that the data sources are carefully chosen and their origins well documented. The quality and applicability of the input data collected for this project varied widely. Many input parameters are well understood, and a wealth of good data exists for them. Unfortunately, many input parameters have very little data available in the literature. In many cases a "best-guess" approach has been taken using small data sets to form tentative parameter distributions.

Sufficient data exist, or can be estimated, to provide reasonable inputs to the macromodel. Weak areas in the input data can only be remedied by further research. However, sensitivity analyses of the macromodel, which will be conducted in a later phase of this project, will provide a priority ranking of the current information gaps or weaknesses and thus provide direction for future field studies in this area.

2 Global Input Parameters

2.1 Heating-Appliance Efficiencies

Most furnaces and boilers are rated according to their seasonal "first-law" efficiency, known as the annual fuel utilization efficiency (AFUE). The procedure for determining the AFUE includes laboratory measurements during "warm-up", steady-state operation, "cool-down", and the "off" period. The AFUE accounts for losses from cyclic effects, exhausted latent and sensible heat, infiltration, and pilot-burner usage. Determination of the AFUE does not account for any heat loss in the hot-air or hot-water distribution systems (ASHRAE, 1985).

Little data on field-measured efficiencies of heating appliances were available in the literature. Empirical distributions of appliance efficiencies were estimated from laboratory-measured efficiency ranges given in the literature. The distributions were constructed with a bias towards the lower efficiencies, reflecting the assumptions that the newer, more-efficient appliances are not widely used and that laboratory-measured appliance efficiencies are most probably higher than the actual efficiencies of the same units after a few years of service.

Unvented space heaters are assumed to have an efficiency of 100%, since all of the heat produced enters the house.

AFUE efficiencies for gas forced-air furnaces (FAF) range from the typical model efficiencies available on the market in the early 1970s to the efficiency of the top-rated model sold in 1985, as compiled by the American Council for an Energy Efficient Economy (Geller, 1985). A similar range of values is reported by others (AIP, 1985). The range used in this report is 55% to 90%. The efficiency range of new gas boilers reported by GAMA (1987) is 60% to 90%.

Gas wall/floor-furnace efficiencies were only available as steady-state efficiency ratings (Geller, 1985). A range of 75% to 80% was used.

Traditionally, oil-fired heating systems have been more efficient than gas-fired systems because they do not use a standing pilot and because latent heat losses are lower with fuel oil than with natural gas (Geller, 1985). Annual-shipment-weighted average AFUE ranged from 73% in the early 1970s to 88% in the most-efficient oil furnaces manufactured in 1987 (AIP,1985; GAMA, 1987). The range of efficiency used for the oil FAF was 70% to 90%.

Wood-stove efficiency is reported in the literature as an "overall efficiency," defined as the percentage of the total energy content of the fuel that is delivered as useful heat to a house and derived from the combustion and heat-transfer efficiencies reported by Shelton Research (Shelton, 1985; Shelton, 1987). The efficiency ranges used for airtight and non-airtight wood stoves are 45% to 65% and 35% to 45%, respectively.

2.2 Smoking Frequency

Nationwide, 40% of U.S. homes have at least one smoker (Bureau of Census, 1985). Modeling smoking behavior is difficult since there are regional variations in the percentage of homes with smokers, and the number of cigarettes consumed per hour varies at different times of day, etc. (USDHHS, 1986). For simplicity, we have assumed that 40% of residences have a single smoker. The number of cigarettes smoked indoors has been estimated to have a geometric mean (GM) of 0.8 cigarette/h (Repace and Lowrey, 1985) with an assumed geometric standard deviation (GSD) of 1.5.

2.3 Pollutant Emission Rates

Pollutant emission rates were compiled for cigarettes and all appliances that emit carbon monoxide (CO), nitrogen dioxide (NO_2), and respirable suspended particles (RSP). Emission-rate units are in μg/kJ for appliances and μg/cigarette for smoking. Because the state of tune and other operating factors may significantly affect appliance emission rates, field measurements on appliances were used, when available, in preference to laboratory data. In a number of cases, laboratory measurements of emission rates for both well-tuned and maltuned appliances were combined and used if no field data were available. No data on the distribution of field appliance tuning were available, so no attempt was made to weight the emission-rate data according to a distribution of tuning that might be expected in the field.

A maximum NO_2 emission rate has been calculated for each appliance. This is a ceiling value and is used to prevent the model from randomly picking an NO_2 emission rate higher than the theoretical value, where all of the NO_x is NO_2. The value is based on the highest NO_x emission rate measured in the literature for a particular appliance.

2.3.1 Gas

2.3.1.1 Forced-air furnaces

Carbon monoxide emission rates for gas FAF were derived from measurements made by Levy *et al.* (1971), Surprenant *et al.* (1979), and Szydlowski (1987).

Nitrogen dioxide emissions rates were derived from Levy *et al.* (1971) and Surprenant *et al.* (1979). Data collected from two furnaces in the "as-found" condition by Battelle were reported as NO_x(as NO_2), so an NO_2/NO_x (as NO_2) ratio of 0.34 was used to convert from NO_x to NO_2. This ratio was chosen because emissions from unvented convective gas space heater (the burner type most similar to a gas FAF) showed a NO_2/NO_x (as NO_2) ratio of approximately 0.34 (Apte and Traynor, 1986).

Surprenant *et al.* (1979) and Levy *et al.* (1971) reported data on particle emission rates for gas forced-air furnaces. Since only total-suspended-particle (TSP) emission-rate data were available from these reports, they were used as a surrogate for RSP data. Since the particles generated by combustion sources are in the submicron range (Stern *et al.* 1973), the TSP emission rates should equal the RSP emission rates. The Surprenant measurements were for a 50-minute-on/10-minute-off cycle, and the Levy measurements were for a 10-minute-on/20-minute-off cycle. Investigators have reported that CO and particle emission rates are higher in the 10-minute-on/20-minute-off cycle, which more accurately represents normal household operating conditions. We have used measurements made under these conditions whenever possible.

The GM emission rates used for the gas FAF are 11.4 μg/kJ (GSD=6.4), 8.4 μg/kJ (GSD=2.3), and 1.1 μg/kJ (GSD=3.0) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used is 66.0 μg/kJ.

2.3.1.2 Boilers

Hot-water-boiler steady-state laboratory emission-rate data for NO_2 and CO for 16 boilers were available from the Institute of Gas Technology (IGT) for well-tuned and maltuned appliances (GRI, 1985a). Since particulate emission rate data were not available, the RSP emission rate distribution used for the infrared unvented gas space heater (UVGSH) was selected as a surrogate because it has the most similar CO and NO_2 emission rates.

The GM emission rates used for the gas boiler were 24.5 μg/kJ (GSD=7.4), 4.4 μg/kJ (GSD=1.8), and 0.3 μg/kJ (GSD=2.1) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used is 108.4 μg/kJ.

2.3.1.3 Wall/floor furnaces

No emission rate data for gas wall/floor furnaces were found. Since wall/floor furnace burners are similar to those used in forced-air furnaces, we have used the same emission rates. These were 11.4 μg/kJ (GSD=6.4), 8.4 μg/kJ (GSD=2.3), and 1.1 μg/kJ (GSD=3.0) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 66.0 μg/kJ.

2.3.1.4 Unvented gas space heaters

Unvented gas space heaters (UVGSH) are classified by their burner type: convective and infrared. Emissions from convective UVGSHs were reported by Moschandreas *et al.* (1983 and 1986), Zawacki *et al.* (1984), and Traynor *et al.* (1985). Infrared UVGSH emission-rate data were reported by Moschandreas *et al.* (1983 and 1986) and Traynor *et al.* (1984). All of the heaters were tested in a laboratory setting. Emissions-rate data from a total of twelve well-tuned convective heaters and six well-tuned radiant heaters were included.

The GMs of the CO, NO_2, and RSP emission rates were 27.9 μg/kJ (GSD=2.4), 13.0 μg/kJ (GSD=1.3), and 0.4 μg/kJ (GSD=3.3), respectively, for the convective UVGSH. They were 49.5 μg/kJ (GSD=1.5), 4.6 μg/kJ (GSD=1.1), and 0.3 μg/kJ (GSD=2.1), respectively, for the infrared UVGSHs. The maximum allowable NO_2 emission rate used is 57.5 μg/kJ for the convective heaters. The maximum allowable NO_2 emission rate for the infrared heaters was 6.2 μg/kJ.

2.3.1.5 Stove range tops

CO and NO_2 emission-rate distributions from gas range-top burners were constructed from laboratory and field measurements. Laboratory emission rates were taken from measurements on three stoves tested by Moschandreas *et al.* (1986); eighteen stoves tested by Himmel and Dewerth (1974); two tested by Cote *et al.* (1974) in both well-tuned and maltuned conditions; two tested by Fortmann *et al.* (1984); and one each tested by Traynor *et al.* (1982a), Traynor *et al.* (1982b), and MIT (1976). In additions, two stoves tested in the field were used (Goto and Tamura, 1984). Stoves tested under two distinct tuning conditions were considered to be two different stoves, so an effective total of fifty-three burners were included. The stove emission-rate data was not weighted by population or by state of tune. All of the stoves were tested with water-filled cooking pots on the burners (loaded conditions). The fuel input settings varied.

The RSP GM was determined using one range tested by Traynor *et al.* (1982a) and an average laboratory measurement for 3 well-tuned ranges (GRI, 1985a). The GSD was conservatively assumed to be 1.5.

The GMs of the emission rates used for the gas range top were 81.3 μg/kJ (GSD=3.1), 11.8 μg/kJ (GSD=1.4), and 0.27 μg/kJ (GSD=1.5) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 71.4 μg/kJ.

2.3.1.6 Stove ovens

Emission-rate distributions for CO and NO_2 from gas ovens were constructed from data compiled from laboratory studies. One oven each was measured by Traynor *et al.* (1982a), Moschandreas *et al.* (1986), Traynor *et al.* (1982b), and Fortmann *et al.* (1984). In addition, twenty-seven oven burners were tested under "blue-flame" conditions and then twenty-five of them were tested again under "yellow-tipping-flame" conditions by Himmel and Dewerth (1974).

Burners that were tested under two distinct tuning conditions were counted as two different burners. An effective total of fifty-six ovens were included. Again, the oven emission-rate data was not weighted by population or state of tune since no data on these subjects were found in the literature.

An RSP emission-rate distribution for gas ovens was taken from only one oven tested twice by Traynor *et al.* (1982a). The GSD was conservatively assumed to be 1.5.

The GM of the emission rates used for the gas ovens were 38.6 μg/kJ (GSD=4.1), 7.4 μg/kJ (GSD=1.8), and 0.015 μg/kJ (GSD=1.5) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 57.6 μg/kJ.

2.3.1.7 Dryers

Steady-state CO and NO_2 emission rates for gas dryers were measured in the laboratory by GRI (1985a).

RSP emission rates were not available so, as a surrogate, the RSP emission-rate distribution from the gas range top was used. This appliance was chosen for it's similar CO and NO_2 emission rates. The scrubbing effect of the clothes in the dryer on the emissions of combustion-generated particles is unknown.

The GM of the emission rates used for the gas dryers were 52.0 μg/kJ (GSD=1.5), 8.5 μg/kJ (GSD=1.3), and 0.27 μg/kJ (GSD=1.5) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used are 40.0 μg/kJ.

2.3.1.8 Domestic water heaters

A steady-state CO emission rate for gas domestic hot-water heaters (DHWs) was derived from measurements made on 55 DHWs in an "as-found" condition by Szydlowski (1987). The DHWs ranged in age from 1 to 30 years. Carbon monoxide concentration measurements were made over a period of 1.5 hours, from a cold start to the peak hot-water temperature. In each case, the CO concentration measured at the 45-minute mark was used to calculate a CO emission rate appropriate for typical water temperatures maintained in the appliance.

The NO_2 emission rate is calculated from 32 steady-state appliance measurements made in Thrasher and Dewerth (1977). Approximately one-half of the appliances were well tuned and one-half were maltuned. RSP emission-rate data were not available, so the gas FAF RSP emission rates were used as a surrogate.

The GMs of the emission rates used for the gas DHWs are 5.8 μg/kJ (GSD=1.9), 3.1 μg/kJ (GSD=1.9), and 1.1 μg/kJ (GSD=3.0) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 135.0 μg/kJ.

2.3.2 Oil

2.3.2.1 Forced-air furnaces

Carbon monoxide and RSP emission-rate data on FAFs were available from Surprenant *et al.* (1979), Barrett *et al.* (1973) and Levy *et al.* (1971). NO_x emission rate data were provided by Barrett and Levy. Sufficient information was given so that NO_2/NO_x ratios for each furnace measurement could be calculated. These ratios were used to convert NO_x emission rates to NO_2 emission rates. The volumetric NO_2/NO_x ratios ranged from 0.02 to 0.90.

The GM of the emission rates used for the oil FAFs were 6.3 μg/kJ (GSD=11.7), 10.6 μg/kJ (GSD=2.9), and 17.9 μg/kJ (GSD=2.4) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 106.3 μg/kJ.

2.3.3 Wood

All emissions rates for wood appliances are indoor emission rates determined by empirical measurement, rather than stack emission rates coupled with a vent-factor distribution (used for most of the vented appliances presented in this study). This is because wood stove vent factor information was extremely limited.

2.3.3.1 Airtight wood stoves

Pollutant emission rates from airtight wood stoves were obtained from field measurements by Traynor *et al.* (1987) and TVA (1983 and 1985b). Data were available for a total of twelve airtight stoves, although emissions of NO_2 for three of them and RSP emissions for four of them were not reported.

The TSP source-strength data presented in Traynor *et al.* (1987) were converted to RSP emission rates using an RSP/TSP ratio if 0.54. This ratio was calculated from RSP/TSP ratios presented by TVA (1985a)--the ratios had an AM of 0.54 ± 0.11. Also, the volumetric CO source strengths reported in Traynor *et al.* (1987) were converted to mass emission rates using an atmospheric pressure of 0.8 atm, since these tests were conducted at 1800 m. The heat content of wood was 16,250 kJ/kg for the wood used in TVA (1985a) and 15,100 kJ/kg for the wood used in Traynor *et al.* (1987).

The GMs of the emission rates used for the airtight wood stoves were 3.9 μg/kJ (GSD=2.1), 0.07 μg/kJ (GSD=2.9), and 0.09 μg/kJ (GSD=1.4) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 0.28 μg/kJ.

2.3.3.2 Non-airtight wood stoves

Pollutant emission rates from non-airtight wood stoves were obtained from field measurements by Traynor *et al.* (1987) and TVA (1985a). Data were available for a total of four non-airtight stoves, although emissions of NO_2 for one of them and RSP emissions for one of them were not reported.

Emission rates were calculated from the source strengths presented in the manner discussed in the airtight-wood-stove section above. Data reported for non-airtight wood stoves operating under the "worst-case" conditions were not included in the emission-rate distributions. Both the Traynor and TVA reports state that it was possible to operate the non-airtight wood stoves without producing the high concentrations observed in the "worst-case" mode, so it is likely that most wood-stove operators would soon learn how to avoid using their stoves this way or would discontinue wood stove use.

The GMs of the emission rates used for the non-airtight wood stoves were 3.2 μg/kJ (GSD=2.0), 0.09 μg/kJ (GSD=3.0), and 0.15 μg/kJ (GSD=3.0) for CO, NO_2, and RSP, respectively. The maximum allowable NO_2 emission rate used was 0.31 μg/kJ.

2.3.4 Kerosene

2.3.4.1 Unvented kerosene space heaters

The two types of unvented kerosene space heaters that are most widely used, convective and radiant, have very different emission rates of CO, NO_2, and RSP. Four convective and seven radiant heaters were used to generate emission-rate distributions. The data for both types of heaters came from Traynor *et al.* (1983), Leaderer (1982), and Woodring *et al.* (1985). All of the studies presented laboratory results. RSP emission rate measurements for the convective heaters were only available from Traynor *et al.* and were found to be below their limit of detection of 0.04 μg/kJ. The GM, therefore, of the RSP emission rate was assumed to be 0.02 μg/kJ (GSD=1.0).

All of the emission rates were measured with kerosene heaters operating with low-sulfur fuel (grade 1-K, maximum 0.04% sulfur by weight). The heater age ranged from new (but "burned in" for several days) to five years old.

The GM CO, NO_2, and RSP emission rates were 42.1 μg/kJ (GSD=3.4), 18.4 μg/kJ (GSD=1.5), and 0.02 μg/kJ (GSD=1.0), respectively for the convective kerosene heaters. The maximum allowable NO_2 emission rate used was 52.6 μg/kJ for the convective heaters. They were 67.9 μg/kJ (GSD=1.4), 4.7 μg/kJ (GSD=1.2), and 0.59 μg/kJ (GSD=3.1) for CO, NO_2 and RSP, respectively for the radiant kerosene heaters. The maximum allowable NO_2 emission rate used was 8.2 μg/kJ for the radiant heaters.

2.3.5 Electric

Electric heating systems do not emit combustion pollutants into the indoor environment.

2.3.6 Smoking

Pollutant emission rates for sidestream and exhaled mainstream cigarette smoking were obtained from several sources. CO emission rates were reported by Woods and Crawford (1983), Rickert *et al.* (1984), GRI (1985b), Apte (1988), NRC (1981), and Girman *et al.* (1982). The RSP emission rate for sidestream plus exhaled mainstream tobacco smoke is based on measurements made by Leaderer (1987) on 12 brands of cigarettes under actual smoking conditions.

The reported NO_2 emission rates from exhaled and sidestream cigarette smoke are not reliable, since there is at least one other pollutant in cigarette smoke (hydrogen cyanide) that acts as a positive interferent to chemiluminescent NO_x analyzers. The reported values were very low, even with the possible interference, and a value of zero is used for the NO_2 emission rate.

The GM emission rates used for cigarettes are 71400 μg/cigarette (GSD=1.3), 0.0 μg/cigarette (GSD=1.0), and 15900 μg/cigarette (GSD=1.2) for CO, NO_2, and RSP, respectively.

2.4 Venting Factors

The venting factor defines the fraction of the combustion products that enter the living space. The range is from 0 (no combustion products enter) to 1 (all combustion products enter). Very little is known about the actual venting-factor distribution of malfunctioning vented gas appliances. Proctor (1984) states that approximately 11% of the gas furnaces in 400 low-income Colorado households leaked combustion products into the living space. Quackenboss (1984) states that 3 of 50 Wisconsin houses had a gas FAF that injected NO_2 into the living space. SoCal (1987) found 2% of 110 homes with wall furnaces and 9% of 120 homes with floor furnaces inspected in a southern California study had "the potential for significant quantities of combustion products to enter the living space." (The SoCal study also noted up to 12% of the wall heaters and up to 37% of the floor heaters had potential for injecting some pollutants into the house; however, these percentages were not used in this report.) Finally, AGA (1980) reported that 6% of 2000 homes had FAFs that were "in unsafe condition, primarily due to cracked heat exchangers and faulty vents and flues."

A simulated venting-factor distribution has been constructed, using this limited data. Since these data only address the number of appliances that might be leaking, and not how much they are leaking, the constructed vent-factor distribution is a guess. The arithmetic mean of the frequencies of leaking vented space heaters reported above is 6.8%. In other words, 6.8% of the vented appliances are leaking some pollutants into the house. We assume, therefore, that 93.2% of the homes have a vent factor of zero. A venting-factor distribution of the remaining population was calculated by dividing 6.8% into ten vent-factor bins from 0.05 to 0.95. A linear approach was taken, so the first vent-factor bin had ten times the population of the tenth bin, the second bin had nine times the population of the tenth, etc. (See Chapter IV, Figure IV-1.) This vent-factor distribution has been assumed for all of the vented gas and oil appliances.

A vent factor of one was used for gas range tops and ovens without range hoods. The vent factor used for gas range tops and ovens with outside-venting range hoods that were operated was 0.3 (Traynor *et al.*, 1982b). It was assumed that only 30% of gas oven/range users had and used their range hood based on a rough estimate of the market penetration and usage rate of range hoods. In the absence of appliance-specific data, the venting-factor estimates for central furnaces are used for gas dryers and domestic gas water heaters as well. They reflect the possibility of leaky flue connections and collars and, in some cases, the possibility of having no flue system at all.

No venting factors are given for wood stoves because the emission rates for these sources are derived from empirical measurements of pollutants actually leaking into the indoor environment (i.e., the pollutant emission rates already include the vent factors).

2.5 Pollutant Penetration Factors

The pollutant penetration factor (PPF) is that fraction of the outdoor contaminants that penetrates the building envelope. No field data on the removal of outdoor pollutants by the building shell have been found in the literature for NO_2 or CO, and, therefore, the PPFs for NO_2 and CO were assumed to be one. Laboratory data by Traynor *et al.* (1982a) corroborate this assumption. An approximate PPF of 0.7 was used for respirable particles (Dockery and Spengler, 1981). There are other PPFs published in the literature, but they are derived from measurements taken over short periods of time. Dockery and Spengler's value is an average taken over a one-year period of normal occupancy and incorporates the effects of changing infiltration rates and the opening of doors and windows.

2.6 Pollutant Reactivity

Particle and NO_2 emissions from indoor sources are removed from the air by deposition or reaction with indoor surfaces at various rates. For RSPs, the literature gives one value derived from field measurements of 0.08 h^{-1} (Traynor *et al.* 1987). A GSD of 1.26 was derived from 3 laboratory measurements on different surfaces (Leaderer *et al.* 1986). For NO_2, seven values were available: two measured in houses and five in laboratory settings (Ryan *et al.*, 1983; Ozkaynak *et al.*, 1982; Traynor *et al.*, 1982b; Wade *et al.*, 1975; Moschandreas and Stark, 1978; Goto and Tamura, 1984). The seven values were used to derive a GM and GSD of 0.77 h^{-1} and 1.69, respectively.

3 Region-Specific Parameters

The four regions modeled (see Figs. A-1 to A-4) are areas falling within the boundaries of the following utility company service areas: Rochester Gas and Electric Corporation (New York), Washington Water Power Company (Washington, Idaho), Pacific Gas and Electric Company (California), and Louisiana Power and Light Company (Louisiana). They will hereafter be referred to as RGE, WWP, PGE, and LPL, respectively.

The parameters discussed in this section depend directly or indirectly on such regional variables as climate, market penetration of appliances, and local housing construction practices.

3.1 Validation of Utility Survey Data

Since most of the region-specific parameters were derived from utility residential appliance saturation surveys, and the entire utility regions were not modeled in 3 of the 4 regions, it was important to verify that the utility survey samples accurately represent each area's general population. This was done by comparing selected survey results for demographic, occupancy, and building characteristics and for appliance market penetration to values for the same parameters in the 1980 Census Summary Tape File 3 (STF3) (see Tables A-1 to A-3).

STF3 does not contain cross tabulations for single-family homes, so in each case survey results across all dwelling types were compared to the census data. If we assume that the survey results for all dwelling types are representative, then the results for single-family homes will most likely be representative as well.

In the case of RGE and PGE, the utility data (also referred to as the "sample" data) are compared to a wider (Set 1) and a narrower (Set 2) geographical area. WWP is divided into two parts by state, and the sample for each part, as well as for the whole region, is compared to census data for the appropriate counties. Figs. A-5 to A-7 show the counties used in each census comparison. Unlike the other regions where only part of the utility's region was modeled, the entire LPL service area was modeled; therefore, a census comparison was not deemed useful.

3.1.1 RGE

Comparison of sample and census data suggests a reasonable match (see Table A-1). The sampled households in the RGE survey appear to be of somewhat higher income. In general, Set 1 data are the closest match to the sample data. The RGE service territory actually includes parts of Orleans, Genesee, and Wyoming counties (see Fig. A-1). If census data for these counties had been included in the comparison, we would expect the match to be better still. Comparison with the Set 2 data is also good, even though their geographic coverage is not entirely inclusive of the sample area.

3.1.2 WWP

The WWP region represented by our input data is not the entire service area of the utility (see Fig. A-2). Since the weather in the Lewiston-Clarkston division is quite different from the rest of the utility's territory, the Lewiston-Clarkston division was not included in our modeling effort. Our data represent the Spokane, Coeur D'Alene, and Palouse divisions. The original utility data have been reaggregated to represent the households in the reduced region. The demographic, occupancy, and building characteristics presented in Table A-2 have not been reaggregated for the reduced region because exploratory calculations show that there is never more than a percentage-point difference between any given value of a distribution for the original region and the value for the reduced region. The one exception to this is the use of air conditioners, where omitting the Lewiston-Clarkston region decreases the number of households with air conditioners by 4%.

In general there is a high degree of comparability between the sample results and the census results. This is the case for both the region as a whole and also for parts of Washington and Idaho, if they are individually analyzed.

3.1.3 PGE

The PGE region represented by our input data does not include the entire PGE service area. The PGE input parameters refer to Baseline Territory X (2500-4000 degree-days/yr), which is shown in Fig. A-3 and which contains 50% (1,134,559) of PGE-single-family-customer households. In general, the PGE survey results for Baseline Territory X compare very well with both sets of data (see Table A-3). Set 1 includes all of the survey area, whereas Set 2 does not contain 3 counties (Marin, San Mateo, and Santa Cruz) that are only partly within Baseline Territory X (see Fig. A-7). Because the PGE survey contained nonresponses, and the census data did not, large differences seen in the distributions may not be completely accurate. Also, there were differences in the subgrouping of categories.

3.1.4 LPL

The LPL region includes the entire service area of Louisiana Power and Light. No comparison with Census data was made for this region. LPL's 1984 Residential Customer Survey did not disaggregate responses by housing types, but we have assumed that, since 74% of those surveyed lived in single-family homes, response percentages indicating market penetration of appliances, housing size, etc., are indicative of single-family homes.

3.2 Individual Region-Specific Parameters

3.2.1 Market Penetration of Appliances

For all four regions, the utility companies provided residential appliance saturation surveys from which appliance market penetrations were derived [WWP (1981), PGE (1984), RGE (1985), LPL (1984]. These data are presented in Figs. A-8 and A-9 for primary space-heating appliances and other combustion appliances, respectively.

3.2.1.1 Primary heating-appliance distribution

3.2.1.1.1 RGE

Single-family homes in the RGE service area are heated by gas and oil FAFs, gas boilers, wood stoves, kerosene heaters, and electric heaters (RGE, 1985). In the gas FAF category we have also included small numbers of gas-assisted heat pumps, dual fuel solar hot water/gas heating systems, vented radiant gas heaters, and propane-gas central hot-air furnaces. Natural-gas and propane water boilers and natural-gas steam boilers make up the gas-boiler category. The oil FAF category includes small numbers of oil-assisted heat pumps and steam and water boilers, as well as central hot-air systems. The relative market penetrations of airtight and non-airtight wood stoves have been estimated for all regions (including RGE) to be 75% airtight and 25% non-airtight (Shelton, 1988).

3.2.1.1.2 WWP

Single-family homes in the WWP service area are heated primarily by gas FAFs, electricity, and oil FAFs in addition to a large number of homes using wood stoves (WWP, 1981). Gas radiators were included in the gas-boiler category; oil radiators were included under oil FAFs; and central wood furnaces were included under airtight wood stoves.

3.2.1.1.3 PGE

As is the case in the RGE and WWP areas, the predominant method of heating California single-family homes in PGE Baseline Territory X is with central gas FAFs (PGE, 1984). However, wall/floor furnaces are also used as primary heating appliances. There are also a small number of households that use wood stoves and electric heat for primary heat.

3.2.1.1.4 LPL

Gas FAFs are the primary heating system in Louisiana, supplemented by a significant use of gas room heaters (LPL, 1984). Gas room heaters, also known as gas space heaters, are noncentral heating appliances that may be vented or unvented. The LPL survey market penetration of gas room heaters (18%) did not distinguish between the vented and unvented types. The 1980 census indicated that 60% of room heaters in Louisiana are unvented. We assume that this fraction holds for the LPL region; therefore, approximately 11% of LPL customers heat their homes with UVGSHs.

Discussions with Louisiana utility officials indicated that the 40% of gas space heaters that are vented are likely to be wall/floor furnaces of the type used in PGE's territory (Trauth, 1987); therefore, about 7% of LPL customers are assumed to heat their homes with wall/floor furnaces.

3.2.1.2 Non-space-heating gas-appliance distributions

In addition to a high percentage of gas heating appliances, the RGE service territory also has significant percentages of gas stoves (45.1%), gas dryers (34%), and gas DHWs (84.3%). Although these percentages are for the entire RGE housing stock, we have assumed that they also represent the market penetration of non-space-heating appliances in single-family houses relatively well. We have assumed that 50% of the gas DHWs are located in the house's living space, where occupants could be exposed to combustion gas leakage.

There is very little use of gas in non-space-heating appliances in the WWP region. Sixteen percent of households have gas DHWs, and 61% of these heaters are located in the living space of the house, based on WWP (1981). Therefore, region-wide, 10% of households have gas DHWs indoors.

In the PGE region, 25% of the households have gas stoves and ovens, 8% have gas dryers, and 88.4% have gas DHWs, and half of the gas DHWs are assumed to be located in the living space.

In the LPL region, 59% of the households have gas stoves and 43% have gas ovens. Gas is also used widely for domestic water heating (75%) and clothes drying (30%). The LPL survey reports that 50% of DHWs are in the living space.

3.2.2 Fuel Usage by Non-space-heating Appliance

The American Gas Association provided 1982 data on average gas consumption for residential appliances by census division (AGA, 1985). Data from the following divisions were used for the utility service areas: Middle Atlantic for RGE; West South Central for LPL; and Pacific for WWP and PGE. Gas-range fuel usage is assumed to be split evenly between the range top and the oven (Thrasher and Dewerth, 1977). To account for variations in life style, we have assumed that each usage rate can be represented by a log-normal distribution, with a GM given below and an assumed GSD of 1.5. Although the gas-consumption data provided by GRI are AMs, the fairly small GSD we have chosen to represent the distributions implies that the GM and the AM are very close.

The GMs of non-heating-appliance usage-rate distributions for RGE, WWP, PGE, and LPL, respectively, are as follows: range-top--566 kJ/h, 499 kJ/h, 499 kJ/h, and 626 kJ/h; oven--566 kJ/h, 499 kJ/h, 499 kJ/h, and 626 kJ/h; DHW--3920 kJ/h, 2880 kJ/h, 2880 kJ/h, and 2980 kJ/h; gas dryer with gas pilot--686 kJ/h, 578 kJ/h, 578 kJ/h, and 926 kJ/h.

3.3 House Volumes

The frequency distribution of various house volumes is indicated in Figs. A-10 and A-11 for WWP, PGE, LPL, and RGE. This information for single-family detached homes was available in the residential surveys carried out by WWP and PGE and for the entire housing stock in the LPL survey [WWP (1981), PGE (1984), LPL (1984)]. The data were given in multiple bins of floor-area ranges. The midpoints of the ranges were multiplied by a 2.4-m (8-ft) ceiling height to calculate a typical volume for each floor-area range.

For the RGE service territory, volume measurements of 48 New York single-family homes (Grimsrud *et al.*, 1982) were used to generate an empirical distribution for house volume. The majority of houses in this data set were less than 20 years old.

3.4 Outdoor-Pollutant Concentrations

3.4.1 RGE

The outdoor concentrations of CO and RSP in the RGE region were obtained from the New York Department of Environmental Conservation's 1985 Air Quality Report (DAR, 1986). The CO and RSP concentrations presented are the GM and GSD of the annual means recorded by all sampling stations within the RGE region. No attempt to weight by population density was made. RSPs were estimated to be one-half the mass of the TSPs based on the following. Whitby *et al.* (1975) reported an average ambient RSP/TSP ratio of 0.3, whereas Knight and Humphreys (1984) found a 0.7 outdoor RSP/TSP ratio in a wood-heating area of Tennessee; therefore, we have chosen a 0.5 RSP/TSP ratio for converting outdoor TSP concentrations to RSP concentrations.

NO_2 levels are not regularly measured in the Rochester area, so an outdoor NO_2 value from a pilot indoor-pollutant modeling study done in upstate New York was used (Nitschke *et al.* 1985). The value is based on NO_2 concentration measurements made during the winter months outside of thirty homes in the northeast and central regions of New York. Most of the homes are within thirty miles of cities such as Syracuse, Albany, Oswego, and Utica.

The GM of the CO, NO_2, and RSP outdoor concentrations used for this region were 0.7 ppm (GSD=1.2), 0.006 ppm (GSD=1.95), and 19.0 $\mu g/m^3$ (GSD=1.5), respectively.

3.4.2 WWP

The outdoor-concentration data for CO and TSP in the WWP region were obtained on computer tape from the Washington State Department of Ecology, Olympia, WA. The CO and RSP data presented are the GM and GSD of the annual means recorded by all sampling stations within the WWP region during 1986. No attempt to weight by population density was made. RSPs were calculated to be one-half of TSPs. No sampling stations reported values for NO_2 in the WWP region, so the RGE data were used. Conversations with U.S. EPA Region 10 officials confirmed that this is a reasonable estimate for the Spokane area (Schweiss, 1986).

The GM of the CO, NO_2, and RSP outdoor concentrations used for this region were 1.7 ppm (GSD=1.1), 0.006 (GSD=1.95), and 34.9 $\mu g/m^3$ (GSD=1.7), respectively.

3.4.3 PGE

The outdoor concentrations of the pollutants in California were obtained from the California Air Resources Board Annual Summary for 1985 (CARB, 1986). County-specific average annual hourly concentrations for CO and NO_2 and daily averages for RSP for those counties located within the PGE Baseline Territory X were averaged to obtain the GMs and GSDs. RSPs were assumed to be one-half of TSPs. No attempt to weight by population was made.

The GM of the CO, NO_2, and RSP outdoor concentrations used for this region were 1.1 ppm (GSD=2.0), 0.016 ppm (GSD=1.7), and 24.8 $\mu g/m^3$ (GSD=1.5), respectively.

3.4.4 LPL

The outdoor concentrations of pollutants in Louisiana were obtained from the Louisiana Department of Environmental Quality Ambient Air Quality Data Report (1985). RSP data are the GM and GSD of the annual means recorded by all sampling stations within the LPL region. Carbon monoxide values are the average GM and GSD of annual means reported by the only two stations (New Orleans and Baton Rouge) in Louisiana that record CO concentrations. The NO_2 concentration is the annual mean reported by the only station (Kenner) in Louisiana that monitors NO_2.

The GM of the CO, NO_2, and RSP outdoor concentrations used for this region were 0.7 ppm (GSD=2.1), .011 ppm (GSD=2.0), and 20.0 $\mu g/m^3$ (GSD=1.2), respectively.

3.5 Building-Component U-values

U-values, in units of $kJ/hm^2{}^\circ C$, are a measure of the rate of conductive heat loss though building components. U-values are primarily determined by the amount and kind of insulation in a building component. In general, homes in colder climates tend to be better insulated and, therefore, have lower building-component U-values.

The RGE residential appliance saturation survey presented a multitude of information about exterior siding materials and types and thicknesses of insulation used in floors, walls, and ceilings. To ensure that the number of combinations was reasonable, we grouped together walls with similar types of siding and aggregated some of the insulation levels. It was assumed that every house has an attic.

The U-values for the WWP region were calculated using data on housing type and ceiling-insulation thickness from the WWP survey. A distribution of siding types was reported by a Bonneville Power Administration survey (BPA, 1983) that included the

WWP service area. Ten percent of households had sidings of brick or stone, and 90% had sidings of wood, aluminum, etc. The WWP survey reported that 70% of households have wall insulation. There was no information indicating the amount or kind of this insulation, so the presence of insulation was calculated to lower wall U-values by 2.2 kJ/hm²°C, representing a typical installation of 8.9 cm (3.5in.) of R11 blanket insulation. For ceiling insulation, the WWP survey reported a distribution in inches that was converted to U-values. The WWP survey presented information on floor types but not on floor insulation levels. BPA gave data on percent of floor space insulated for single-family homes (BPA, 1983). By assuming that U = 1.8 kJ/hm²°C represents a typical floor-insulation level, we calculated a weighted floor U-value for the different segments of the population, depending upon the fraction of floor area that they had insulated.

The U-values for PGE Baseline Territory X were obtained from a weatherization survey done by the California Public Utilities Commission (CPUC, 1986). The data presented are for all of California. For wall and floor insulation, the survey indicated only whether they were present or absent. An assumption of a 8.9-cm (3.5in.) wall space and R11 blanket insulation for insulated walls was made. The U-value for slab floors was taken from ASHRAE (1985) using an example of a slab with stucco perimeter and metal-stud walls. (The metal-stud walls are certainly not characteristic of the PGE housing stock; however, it is assumed that the heat loss from slab floors with wood-stud wall construction would not be much different). The ceiling-insulation distribution was broken down according to thickness of insulation. These were subsequently converted to U-values.

The LPL residential survey (LPL, 1984) gave for the entire housing stock average ceiling, wall, and floor R-values that were used to calculate corresponding U-values. The information presented was not sufficient to construct distributions of U-values for these building components.

3.5.1 Walls and Ceilings

The basis for the wall and ceiling U-values used in the model were values calculated for prototypical wood-frame walls and ceilings (Callender, 1982). The values were then adjusted to account for different levels of insulation, different types of siding, and the presence of attics, in the case of ceilings (ASHRAE, 1985). Figs. A-12 and A-13 indicate the distribution of households with various U-values for their walls and ceilings in the RGE, WWP, and PGE regions. The LPL survey reported average wall and ceiling insulation levels for the housing stock that correspond to approximate U-values of 2.5 and 1.5 kJ/hm²°C, respectively.

3.5.2 Floors

Heat losses through four different floor types were calculated: floors with crawl-spaces beneath them; floors with unheated basements beneath them; concrete slab floors; and raised frame floors. Data on market penetration of floor types were obtained from utility surveys for WWP and LPL (WWP, 1981; LPL, 1984), from the California Public Utilities Commission for PGE (CPUC, 1986), and from discussions with utility officials for RGE (Fogg, 1987). Regional distributions of floor type are displayed in Fig. A-14.

3.5.2.1 Floors with basements and crawl spaces beneath them

CIRA (Computerized Instrumented Residential Audit) provides an algorithm for calculating heat loss through unheated basements and crawlspaces (Sonderegger *et al.* 1982; BHKRA, 1984). The algorithm, which treats a crawlspace as a small basement, calculates an effective U-value for the combined house floor (ceiling of the basement or crawlspace) and subfloor system. The heat loss through the house floor/subfloor system is a function of the effective U-value, the floor area, and the indoor-outdoor temperature difference.

Factors that determine the effective U-value are wall U-values above and below grade; U-values of the house floor; soil thermal conductivity; and the relative wall areas above and below grade. CIRA default values based on various assumptions were used for the majority of these parameters. We assumed that the subfloor walls above and below grade are uninsulated; that there are no wall vents, penetrations, or windows; and that basements have a concrete slab floor; and that crawlspaces have a dirt floor. Distributions of U-values for house floors above basements and crawlspaces were based on values calculated for prototypical wood-frame floors (Callender, 1982). The values were then adjusted to account for different levels of insulation. These distributions are displayed in Fig. A-15.

To simplify the heat-loss calculation, we have assumed that all basements are unheated. While BPA data show that about 50% of basements in the WWP region are heated, the small increase in pollutant emission due to increased appliance use should be offset by the added volume of the occupied basement. In addition, the algorithm that we have adapted for use in the model treats all crawlspaces as enclosed rather than vented. BPA data indicate that this is true of colder climates.

3.5.2.2 Concrete-slab floors

Slab-floor heat loss occurs primarily around the perimeter of the floor, so the heat loss is calculated using a slab heat-loss coefficient that varies depending on the severity of a region's climate. The values used are 13.2, 13.2, 8.4, and 4.5 kJ/h°C per m of perimeter for the RGE, WWP, PGE, and LPL regions, respectively (ASHRAE 1985).

3.5.2.3 Raised-frame floors

About one-half of the residences in the LPL region are built on stilts, so that the floor is raised above the ground. The LPL survey reported an average floor U-value for the housing stock of 3.6 kJ/hm^2°C.

3.5.3 Windows

We made the following assumptions in our determination of heat loss through windows: (1) only two types of windows exist--single pane (U = 22 kJ/hm^2°C) and single pane with storm window (U = 10 kJ/hm^2°C) [see Callender (1982)], and (2) only a single window covering is used--drapes, shades, or blinds, and they are in use only at night. The R-value of the window covering is multiplied by 0.67 to account for its part-time use (BHKRA, 1984). The U-values calculated for the windows plus window covering are 18 and 9 kJ/hm^2°C for single pane and single pane with storm window, respectively. The Residential Energy Consumption Survey (RECS) (EIA, 1984) and some of the utility surveys reported information on the percent of window area with storm windows. These percentages were applied to the total glass area, including sliding glass doors. RGE was the only region that reported the area of the predominantly sized window, 1 m^2, and picture window, 2.5 m^2 (RGE, 1985), so these values were used for all regions. RGE also reported that, on the average, each home has one picture window. This also was assumed to be true of the other regions. The area of a typical sliding glass door was estimated to be 4 m^2. It is likely that average area per window is greater in California than in New York for instance, but no data for the other regions were available.

Data on number of windows, percent window area with storm windows and number of sliding glass doors were obtained from the utility survey, where possible. Otherwise data from EIA (1984), which lists values by census division and climate zone, were used. The numbers of windows and outside doors were derived from the census region that best matched the utility being modeled. RGE data come from the northeast, with 5,500 heating degree days (HDD) or more, WWP data come from the pacific northwest, with 4,000 HDD or more, and PGE data come from the far west, with fewer than 4,000 HDD. LPL data comes from the south, with 2,000 or more cooling degree days. The regional data used in the model are shown in Figs. A-16 to A-18.

We used CIRA to estimate solar gain through windows in the four regions for each week of the year (BHKRA, 1984; Sonderegger *et al.*, 1982). CIRA asks for inputs concerning window orientation, area, and type of glazing and calculates solar gain using solar-insolation data for the appropriate region. We assumed that window area is evenly distributed on the four sides of the house. CIRA also calculates solar gain through the walls and ceiling using default values for wall and ceiling U-values, and for a window-area/wall-area ratio, and adds that to the solar gain through the windows. Generally, solar gain through the walls and ceiling is only a few percent of the solar gain through the windows, so any discrepancy between the wall and ceiling U-values used by CIRA and by the model should not be important. The weekly values used in the macromodel include solar gain through windows, walls, and ceilings and are in units of kJ/h per m^2 of window area. Radiative heat losses through walls and ceilings were not accounted for in the model.

3.5.4 Doors

The following assumptions were made to determine heat loss through outside doors: (1) the area of a typical outside door is 1.7 m^2 (BHRKA, 1984; Sonderegger *et al.*, 1982); (2) all outside doors are assumed to be 3.8 cm (1.5in.) solid wood with no glass area in them; and (3) all storm doors are assumed to be metal. The U-values for a door with and without a storm door are 7 and 10 kJ/hm^2°C, respectively (Callender, 1982). The data sources for number of outside doors and percent door area with storm doors are RECS (EIA, 1984) and the utility surveys for windows as described above. Regional distributions are shown in Figs. A-19 and A-20.

3.6 Surface Areas and Number of Stories

Research done in the Department of Mechanical Engineering at the University of Alberta, Canada, used empirical measurements from about one hundred homes of differing shapes to show that most houses have a length-to-width ratio between 1 and 2 and that the actual perimeter and surface area can be closely approximated using a ratio of 1.5 (Wilson, 1987).

House perimeter is calculated using the volume, the number of stories, an assumed house length-to-width ratio of 1.5, and a ceiling height of 2.4 m (8 ft). We assumed that houses with one story constituted the lower end of the house volume distribution and houses with two stories had the higher house volumes. The surface areas of building components were calculated using the perimeter and a 2.4-m (8-ft) ceiling height. The window and outside-door areas were subtracted from total wall-surface area to get actual wall area.

Data on the distribution of one- and two-story dwellings were available for the entire housing stock of RGE (RGE, 1985) and for single-family homes in the WWP region (WWP, 1981) and were estimated for PGE and LPL using National Association of Home Builder (NAHB) information for 1979 and 1980 (NAHB, 1981). The data were assumed to refer to the number of floors above grade, although the RGE survey reported number of occupied stories, which could include basements. Split-level homes were considered two-story. These regional distributions are displayed in Fig. A-21.

3.7 Outdoor Temperature/Windspeed

Outdoor temperature and windspeed data for the RGE, WWP, and LPL regions were obtained from the Typical Meteorological Year weather data tapes (National Oceanic and Atmospheric Administration, Asheville, NC). The Rochester, Spokane, and Baton Rouge measurement sites, respectively, were considered to be fairly representative of their areas. Since the PGE Baseline Territory X is so large, it was impossible to identify a representative station for that area. Therefore, we used a set of climatic regions, geographically congruent with Baseline Territory X, for which representative weather-measurement stations had been identified (Buhl, 1986). We weighted the weather data according to the geographical distribution of PGE's customer households.

3.8 Specific Leakage Areas

Specific leakage area (SLA) is the total leakage area of a house normalized to floor area. A large database containing SLA measurements from houses throughout the U.S. and Canada was available from Sherman (1988) and Sherman *et al.*, (1984). A SLA distribution with a GM of 2.84×10^{-4} m^2/m^2 (GSD=1.44) was constructed from fifty houses measured in the RGE region. Similarly, the GM SLAs for WWP and PGE were 3.15×10^{-4} m^2/m^2 (GSD=1.92) from 61 houses, and 6.10×10^{-4} m^2/m^2 (GSD=1.59) from 80 houses, respectively. No data were available for houses in the LPL region. However, 37 houses from Georgia and Alabama, also in the south, had a GM of 7.68×10^{-4} m^2/m^2 (GSD=1.45), and this value was used as a surrogate for the LPL region.

3.9 Heating-Requirements Validation

Building-component U-values, surface areas, and indoor-outdoor temperature differences determine the heating requirements of a house. To test whether the heat-loss calculations in the model were accurate, we calculated house-heating requirements for several hypothetical houses using both the macromodel and CIRA. These included tight, well-insulated houses, with crawlspaces and basements, in New York, and a leaky, uninsulated house with a slab foundation in California. Macromodel and CIRA results of space heating measurements showed close agreement, often within a few percent.

4 References for Appendix A

AGA (1980) *Space Heating Efficiency Program: 1978-79 Heating Season Status Report.* AGA Catalog No. 560080, American Gas Association, Washington, D.C.

AGA (1985) *Gas Facts 1985 Data.* American Gas Association, Arlington, Virginia.

AIP (1985) *Energy Sources: Conservation and Renewables.* Chapter 16, Conference Proceedings #135. American Institute of Physics, New York, NY.

Apte, M.G. (1988) Personal communication, Indoor Environment Program, Lawrence Berkeley Laboratory, Berkeley, CA. 94720

Apte, M. and Traynor, G. (1986) Comparison of pollutant emissions from unvented kerosene and gas space heaters. In *Proceedings, IAQ'86: Managing Indoor Air for Health and Energy Conservation*, ASHRAE, Atlanta, GA.

ASHRAE (1985) *Handbook of Fundamentals.* American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA.

Barrett, R., Miller, F. and Locklin, D. (1973) *Field Investigation of Emissions from Combustion Equipment for Space Heating.* EPA-R2-73-084A, Battelle-Columbus Laboratories. Prepared for the US Environmental Protection Agency, Washington, DC.

BHKRA (1984) *EEDO: Energy Economics of Design Options.* Burt Hill Kosar Rittelman Associates, Butler, PA.

BPA (1983) *Pacific Northwest Residential Energy Survey.* Bonneville Power Administration, Portland, OR.

Buhl, F., (1986) Residential California Temperature Zone Weather Tapes. Lawrence Berkeley Laboratory, Berkeley, CA.

Bureau of the Census (1985) *Current Population Survey.* U.S. Department of Commerce, Washington, DC.

Callender, J.H. ed. (1982) *Time-Saver Standards for Architectural Design Data.* Sixth Edition, McGraw-Hill Book Company, New York, NY.

CARB (1985) *California Air Quality Data; Summary of 1984 Air Quality Data Gaseous and Particulate Pollutants.* Aerometric Data Division, California Air Resources Board, Sacramento, CA.

Cote, W.A., Wade, W.A. III, and Yocum, J.E. (1974) *A Study of Indoor Air Quality.* Prepared for the Environmental Protection Agency. The Research Corporation of New England, EPA-650/4-74-042 NTIS No. PB 238 556.

CPUC (1986) *Statewide Saturation Survey on Weatherized Dwelling Units.* Energy Branch, Evaluation and Compliance Division, California Public Utilities Commission, Sacramento, CA.

DAR (1986) *New York State Air Quality Report.* DAR-86-1, Division of Air Resources, New York State Department of Environmental Conservation, Albany, NY.

Dockery, D.W. and Spengler, JD, (1981) Indoor-outdoor relationships of respirable sulfates and particles. *Atmos. Environ.* **15**:335-343.

EIA (1984) *Residential Energy Consumption Survey: Housing Characteristics.* Energy Information Administration, Washington, DC.

Fogg, T.T. (1987) Personal communication. Rate and Economic Research Department, Rochester Gas and Electric Corporation, Rochester, NY.

Fortmann, R.C., Borrazzo, J.E., and Davidson, C.I. (1984) Characterization of parameters influencing indoor pollutant concentrations. *Proceedings of the 3rd. International Conference on Indoor Air Quality and Climate, August 20-24, 1984, Stockholm, Sweden* **4**:259-264. Published by the Swedish Council for Building Research.

GAMA (1987) *Consumers Directory of Certified Furnace And Boiler Efficiency Ratings,* Gas Appliance Manufacturers Association, Arlington, VA.

Geller, H. (1985) *Progress in the Energy Efficiency of Residential Appliances and Space Conditioning Equipment.* American Council for an Energy Efficient Economy, Washington, DC.

Girman, J.R., Apte, M.G., Traynor, G.W., Allen, J.R., and Hollowell, C.D. (1982) Pollutant emission rates from indoor combustion appliances and sidestream cigarette smoke. *Environ. Intern.* **8**:213-221.

Goto, Y. and Tamura, G.T. (1984) Measurement of combustion products from a gas cooking stove in a two story house. Presented at 77th Annual Meeting of APCA, San Francisco, CA. June 24-29, 1984.

GRI (1985a) *Emissions from Residential Gas-fired Appliances.* GRI-84/0164, Gas Research Institute, Chicago, IL.

GRI (1985b) *Characterization of Emission Rates from Indoor Combustion Sources.* GRI-85/0075, Gas Research Institute, Chicago, IL.

Grimsrud, D.T., Sherman, M.H., and Sonderegger, R.C. (1982) Calculating infiltration: implications for a construction quality standard. *Thermal Performance of the Exterior Envelopes of Buildings II*, ASHRAE sp38, ASHRAE Publications, Atlanta, GA, pp. 422-452.

Himmel, R.L. and Dewerth, D.W. (1974) *Evaluation of the Pollutant Emissions from Gas-Fired Ranges.* American Gas Association Laboratories Research Report No. 1492, Cleveland, OH.

Knight, C.V. and Humphreys, M.P. (1984) Indoor air quality associated with conventional and new technology wood heaters in a weatherized home. Presented at 79th Annual Meeting of APCA, Minneapolis, MN. June 22-27, 1984.

Leaderer, B.P. (1987) Personal communication, John B. Pierce Foundation Laboratory and Yale University School of Medicine, New Haven, CT.

Leaderer, B.P., Renes, S., Bluyssen, P., and Van de Loo, H. (1986) Chamber Studies of NO_2, SO_2, and RSP deposition rates indoors. Presented at the 79th Annual Meeting of APCA, Minneapolis, MN, June 22-27, 1984.

Leaderer, B.P. (1982) Air pollution emissions from kerosene-fired space heaters. *Science* **218**:1113-1115.

Levy, A., Miller, SE, Barrett, RE, Schulz, E.J., Melvin, R.H., Axtman, W.H., and Locklin, D.W. (1971). *Field Investigation of Emissions from Fuel Oil Combustion for Space Heating.* Battelle-Columbus Laboratories. Prepared for the American Petroleum Institute. API Publication 4099, Washington, DC.

Louisiana Department of Environmental Quality (1985) *Ambient Air Quality Data Annual Report.* Baton Rouge, LA.

LPL (1984) *Residential Customer Questionnaire for 1984 Load Profile Samples.* Louisiana Power and Light Co., New Orleans, LA.

MIT (1976) *Experimental Evaluation of Range-Top Burner Modification to Reduce NO_x Formation*, Massachusetts Institute of Technology, Prepared for American Gas Association, No. M40677.

Moschandreas, D.J., Relwani, S., Cole, J.T., Elkins, R.H., and Macriss, R.A. (1983) *Characterization of Emission Sources into the Indoor Environment.* Annual report prepared for Gas Research Institute by Illinois Institute of Technology Research Institute.

Moschandreas, D., Relwani, S., Johnson, D., and Billick, I. (1986) Emission rates from unvented gas appliances. *Environ. Intern.* **12**:247-253.

Moschandreas, D.J. and Stark, W.C. (1978) *The Geomet Indoor-outdoor Air Pollution Model.* EPA 600/7-78-106, Geomet, Inc., Washington, DC.

NAHB (1981) *1981 Research Results.* National Association of Home Builders Research Foundation, Inc., Gaithersburg, MD.

Nitschke, I.A., Clarke, W.A., Clarkin, M.E., Traynor, G.W., and Wadach, J.B. (1985) *Indoor Air Quality, Infiltration and Ventilation in Residential Buildings.* W.S. Fleming & Associates, 5802 Court Street Rd., Syracuse, NY 13206; NYSERDA Report #85-10, New York State Energy Research and Development Authority, Albany, NY 12223.

NRC (1981) *Indoor Pollutants.* National Research Council, Washington, D.C., National Academy Press.

Ozkaynak, H., Ryan, P.B., Allen, G.A., and Turner, W.A. (1982) Indoor air quality modeling: compartmental approach with reactive chemistry. *Environ. Intern.* **8**:461-471.

PGE (1984) *Residential Appliance Saturation Survey, Volume II.* Pacific Gas and Electric Company, San Francisco, CA.

Proctor, J. (1984) Low Cost Furnace Improvements. In *ACEEE Proceedings*, American Council for an Energy Efficient Economy, Washington D.C., 20036.

Quackenboss, J.J. (1984) Personal communication, University of Arizona Medical Center, Tuscon, AZ.

Repace, J.L. and Lowrey, A.H. (1985) A quantitative estimate of non-smoker's lung cancer risk from passive smoking. *Environ. Intern.* 11: 3-22.

RGE (1985) *Home Appliance Survey,* Rochester Gas and Electric Co., Rochester, NY.

Rickert, W.S., Robinson, J.C., and Collishaw, N. (1984) Yields of tar, nicotine, and carbon monoxide in the sidestream smoke from 15 brands of Canadian cigarettes. *Amer. J. Pub. Hlth.* 74 228.

Ryan, P.B., Spengler, J.D., and Letz, R. (1983) The effects of kerosene heaters on indoor pollutant concentrations: A monitoring and modeling study. *Atmos. Environ.* 17:1339-1345.

Schweiss, J. (1986) Personal communication, Air Quality Assurance Coordinator, US EPA Region 10.

Shelton, J. (1988) Personal communication, Shelton Research, Santa Fe, NM.

Shelton, J. (1987) Personal communication, Shelton Research, Santa Fe, NM.

Shelton, J. (1985) *Wood Stoves - A Progress Report.* Shelton Research, Santa Fe, NM.

Sherman, M.H. (1988) Personal communication, Energy Performance of Buildings Group, Indoor Environment Program, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

Sherman, M.H., Wilson, D.J., and Kiel, D.E. (1984) *Variability in Residential in Leakage.* LBL-17587, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

SoCal (1987) *Residential Indoor Air Quality Characterization Study of Nitrogen Dioxide - Phase II - Wall and Floor Furnace Inspection Study,* Southern California Gas Company, Los Angeles, CA, 90051.

Sonderegger, R.C., Garnier, J.Y., and Dixon, JD (1982) *Computerized Instrumental Residential Audit: CIRA.* PUB-425, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

Stern, A.C., Wohlers, H.C., Boubel, R.W. and Lowry, W.P. (1973) *Fundamentals of Air Pollution.* Academic Press, New York, NY.

Surprenant, N.F., Hall, R.R., McGregor, K.T., and Werner, A.S. (1979) *Emissions Assessment of Conventional Stationary Combustion Systems: Volume I, Gas and Oil-fired Residential Heating Sources.* EPA-600/7-79-029b, Environmental Protection Agency, Washington, DC.

Szydlowski, R. (1987) Personal communication, Energy Performance of Buildings Group Lawrence Berkeley Laboratory, Berkeley, CA 94720.

Thrasher, W.H. and Dewerth, D.W. (1977) *Evaluation of the Pollutant Emissions from Gas-fired Water Heaters.* GRI research report No. 1507. American Gas Association Laboratories, Cleveland, OH.

Trauth, J. (1987) Personal communication, Division Marketing Supervisor, New Orleans Public Service, Inc., New Orleans, LA.

Traynor, G.W., Anthon, D.W., and Hollowell, C.D. (1982a) Technique for determining pollutant emissions from a gas-fired range. *Atmos. Environ.* **16**:2979-1987.

Traynor, G.W., Apte, M.G., Dillworth, J.F., Hollowell, C.D., and Sterling, E.M. (1982b) The effects of ventilation on residential air pollution due to emissions from a gas-fired range. *Environ. Intern.* **8**:447-452.

Traynor, G.W., Allen, J.R., Apte, M.G., Girman, J.R., and Hollowell, C.D. (1983) Pollutant emissions from portable kerosene-fired space heaters. *Environ. Sci. Technol.* **17**:369-371.

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.D., and Grimsrud, D.T. (1984) *Pollutant Emission Rates from Unvented Infrared and Convective Gas-Fired Space Heaters.* LBL-18258, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

Traynor, G.W., Girman, J.R., Apte, M.G., Dillworth J.F and White P.D. (1985) Indoor air pollution due to emissions from unvented gas-fired space heaters. *J. Air Pollut. Control Assoc.* **35**:231-237.

Traynor, G.W., Apte, M.G., Carruthers, A.R., Dillworth, J.F., Grimsrud, D.T., and Gundel, L.A. (1987) Indoor air pollution due to emissions from wood-burning stoves. *Environ. Sci. Technol.* **21**:691-697.

TVA (1983) *TVA/BPA: Indoor Air Quality Study - Phase I.* Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, TN.

TVA (1985a) *TVA/CPSC: Indoor Air Quality Study.* Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, TN.

TVA (1985b) *TVA/BPA: Indoor Air Quality Study - Phase II.* Tennessee Valley Authority, Division of Conservation and Energy Management, Chattanooga, TN.

USDHHS (1986) *The Health Consequences of Involuntary Smoking: A Report of the Surgeon General.* US Department of Health and Human Services, Public Health Service, Center for Disease Control, Rockville, MD.

Wade, W.A., Cote, W.A., and Yocum, J.E. (1975) A study of indoor air quality, *J. Air Pollut. Control Assoc.* **25**:933-939.

WWP (1981). *Washington Water Power Residential Survey.* Consumer Services Research and Forecasting Section, Washington Water Power Company, Spokane, WA.

Whitby, K., Clark, W., Marple, V., Sverdrup, G., Sem, G., Willeke, K., Liu, B. and Pui, D. (1975) Characterization of California aerosols I. distributions of freeway aerosol. *Atmos. Environ.* **9**:463-470.

Wilson, David J. (1987) Personal communication, Professor, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada.

Woodring, J.L., Duffy, T.L., Davis, J.T., and Bechtold, R.R. (1985) Measurements of combustion product emission factors of unvented kerosene heaters. *Amer. Ind. Hyg. Assoc. J.* **46**:350-356.

Woods, J.E. and Crawford, R.R. (1983) Calculation methods to assess indoor air quality. *ASHRAE Transactions, Vol. 89, Part 2B,* Paper No. DC-83-12, No. 1.

Zawacki, T.S., Cole, J.T., Huang, V.M., Banasiuk, H., and Macriss, R.A. (1984) *Efficiency and Emissions Improvement of Gas-Fired Space Heaters, Task 2. Unvented Space Heater Emission Reduction.* Institute of Gas Technology, Chicago, IL.

Table A-1. Rochester Gas and Electric survey area comparisons.

Data Item	Sample	Census Set 1	Census Set 2
Demographics			
Total person		1,064,370	927,470
Total households		373,395	328,112
Total year-round housing units		392,637	344,273
Total occupied year-round housing units		372,620	327,472
100% housing units		402,521	351,265
High school grad. (at least)	88.6%	72.1%	72.8%
College grad. (at least)	28.4%	16.4%	17.2%
Median family income	$24,423	$17,026[a]	$17,392[a]
Family income <$10k	11.7%	24.6%[b]	24.0%[b]
Family income $10k-50k	81.0%	70.9%[b]	71.1%[b]
Family income >$50k	7.3%	4.5%[b]	4.9%[b]
Occupancy Characteristics			
Own house/apt.	78.2%	66.6%	65.9%
Rent house/apt.	21.8%	33.4%	34.1%
Number of occupants, median	1.9	2.8	2.8
Occupants 0-5 yrs., median	0.3	0.2	0.2
Occupants 6-17 yrs., median	0.5	0.6	0.6
Occupants 18-64 yrs., median	1.4	1.7	1.7
Occupants 65+ yrs., median	1.5[c]	0.3	0.3
Building Characteristics			
Median building age	36.7 yrs.	N/A	N/A
≤ 10 yrs.	8.8%	18.4%	18.6%
10-20 yrs. old	16.7%	18.5%	19.3%
21-40 yrs. old	28.9%	21.8%	22.8%
40+	44.0%	41.3%	39.3%
Unknown	1.7%	--	--
Number of rooms, not bath, median	5.3	4.6	4.4
Number of bathrooms median	1.1	1.2	1.3
Total rooms		5.8	5.7
Single-family dwelling	78.5%	65.6%	65.4%
Two-, three-family dwelling	10.5%	16.2%[d]	16.2%[d]
Apartment with 4+ units	10.4%	14.8%[e]	15.8%[e]
Mobile home	0.5%	3.4%	2.6%
Space heating fuel in utility gas bill	74.8%	62.6%	65.2%

Table A-1. (continued)

Data Item	Sample	Census Set 1	Census Set 2
HVAC Distribution, Primary			
Forced Air	76.4%	63.4%	53.4%
Baseboards, steam and water radiators and others	19.7%	19.2%	19.3%
N/A or Missing	3.9%	17.4%	16.4%
Water Heating Fuel			
Electric	14.5%	21.9%	19.4%
Natural Gas	81.9%	70.3%	73.6%
Oil	1.5%	3.4%	3.3%
Propane	0.9%	3.9%	3.3%
Other	0.4%	0.3%	0.2%
Don't know/missing	0.8%	0.2%[f]	0.2%[f]

[a] Average of county medians of household not family income.
[b] "Household income" not "family income."
[c] This number seems to be unusually high, perhaps a typo for 0.5.
[d] Two - four family dwelling calculated.
[e] Apartment with 5 or more units only reported.
[f] "No fuel used" not "don't know/missing."

Table A-2. Washington Water and Power 1980 residential survey comparisons.

Data Item	Sample			Census		
	System	Wash.Pt.	Idaho Pt.	System	Wash.Pt.	Idaho Pt.
Demographics						
Total persons				566,648	450,611	116,037
Total households				207,864	166,410	41,454
Total year-round housing units				224,497	178,697	45,800
Total Occ. year-round housing units				207,635	166,173	41,462
100% housing units				230,213	181,069	49,144
Dwelling Type						
One family	75%	75%	73%	69.4%	70.0%	66.7%
Duplex	5%	5%	5%	4.8%	4.8%	4.9%
3-4 Units	4%	4%	3%	3.3%	3.2%	4.0%
5+ Units	7%	8%	6%	14.0%	15.1%	9.7%
Mobile Home	9%	8%	13%	8.5%	6.9%	14.7%
Construction						
Before 1939	26%	27%	19%	27.0%	27.7%	24.2%
1940-49	11%	12%	10%	11.8%	12.3%	9.9%
1950-59	18%	20%	14%	15.9%	16.8%	12.3%
1960-69	13%	12%	17%	12.8%	12.5%	13.9%
1970-79	31%	28%	38%	27.6%	26.1%	33.5%
1980+	1%	1%	2%	5.0%	4.6%	6.3%
Stores in Dwelling						
1-3 Stories	99%	99%	100%	97.9%	97.4%	99.5%
4+ Stories	1%	1%	0%	2.1%	2.6%	0.5%
Median No. Rooms	6	6	5	5.4[a]	5.5[a]	5.2[a]
Dwelling Ownership						
Own	77%	77%	79%	67.4%	66.6%	70.6%
Rent	22%	22%	21%	32.6%	33.4%	29.4%
Other	1%	1%	0%	0%	0%	0%
Time in Residence						
Mean yr. moved in	1970	1970	1971	1971.5	1971.4	1972.1
Size of Household						
Person/Household	2.7	2.7	2.8	2.7	2.6	2.8

Table A-2. (continued)

Data Item	Sample			Census		
	System	Wash.Pt.	Idaho Pt.	System	Wash.Pt.	Idaho Pt.
Income/Household						
Under $4999	9%	9%	10%	14.0%	14.0%	13.9%
$5k-$9999	18%	17%	18%	17.8%	17.4%	19.1%
$10k-$14,999	20%	21%	19%	16.1%	16.2%	15.7%
$15k-$19,999	14%	13%	15%	14.8%	14.6%	15.5%
$20k-$24,999	13%	13%	14%	12.9%	12.9%	12.9%
$25k-$29,999	10%	10%	10%	8.9%	9.0%	8.6%
$30k-$34,999	6%	6%	6%	6.0%	6.0%	6.0%
$35k-$39,999	3%	3%	3%	3.4%	3.5%	3.1%
$40k-$49,999	3%	4%	2%	3.2%	3.2%	2.9%
Over $50k	4%	4%	3%	3.1%	3.2%	2.5%
Seasonal Residence						
Year round	97%	98%	97%	97.5%	98.7%	93.2%
Seasonal	3%	2%	3%	2.5%	1.3%	6.8%
Main Space Heat Fuel						
Natural Gas	31%	34%	22%	30.2%	32.4%	21.4%
Fuel Oil	20%	21%	16%	18.3%	19.4%	14.1%
Electric	36%	35%	40%	43.3%	42.1%	48.4%
Wood	12%	9%	21%	7.0%	4.9%	15.3%
Coal	1%	1%	0%	0.8%	0.9%	0.7%
Solar	0%	0%	0%	---	---	---
Other	0%	0%	1%	0.4%	0.4%	0.2%
Main Space Heat Equipment						
Central Furnace	51%	54%	44%	45.4%	48.4%	33.6%
Baseboards	21%	21%	23%	29.5%	28.2%	34.3%
Radiators	5%	6%	2%	5.9%	6.7%	2.6%
Heat Pump	3%	3%	2%	3.6%	3.9%	2.5%
Oil-Gas Stove	6%	5%	6%	7.3%	6.6%	10.1%
Wood-Coal Stove, Fireplace Insert, or Fireplace	12%	9%	21%	8.1%	5.9%	16.6%
Other	2%	2%	2%	0.2%	0.2%	0.3%
Water Heating Fuel						
Natural Gas	14%	16%	9%	14.7%	15.9%	9.6%
Electricity	84%	82%	88%	83.9%	82.6%	88.9%
Fuel Oil	1%	1%	1%	0.7%	0.8%	0.3%
Wood, Solar, Other	1%	1%	2%	0.7%	0.6%	1.2%

Table A-2. (continued)

Data Item	Sample			Census		
	System	Wash.Pt.	Idaho Pt.	System	Wash.Pt.	Idaho Pt.
<u>Air Condition Type</u>						
None	64%	62%	66%	71.8%	68.2%	85.8%
1 + Wall Units	20%	21%	16%	11.2%	19.0%	5.3%
Central Electric/Gas	14%	15%	15%	17.0%	12.8%	8.9%
Other	2%	2%	3%	---	---	---
<u>Cooking Fuel</u>						
Electricity	97%	98%	96%	95.1%	95.5%	93.8%
Natural Gas	2%	1%	3%	4.0%	3.8%	5.1%
Wood, Other	1%	1%	1%	0.8%	0.7%	1.1%

[a] Number rooms = aggregate number rooms/number housing units.

Table A-3. Pacific Gas and Electric Company survey area comparisons

Data Item	Survey (Baseline) Territory X)	Census Set 1	Census Set 2
<u>Demographics</u>			
Total persons		6,005,404	4,328,392
Total households		2,277,330	1,591,473
Total year-round housing units		2,394,673	1,673,535
Total occupied year-round housing units		2,273,315	1,588,642
100% housing units		2,403,939	1,680,619
<u>Annual Household Income</u>			
<$5000	3.8%	10.8%	10.1%
$5k-9999	7.0%	13.3%	13.1%
$10k-14999	8.5%	13.7%	13.4%
$15k-19999	7.9%	12.9%	12.9%
$20k-24999	8.5%	12.2%	12.5%
$25k-29999	6.3%	7.9%	10.3%
$30k-34999	6.8%	7.9%	8.2%
$35k-39999	4.8%	5.6%	5.9%
$40k-49999	6.9%	6.6%	6.8%
$50k+	9.1%	7.0%	6.8%
Decline to answer	26.0%	---	---
Left blank	4.4%	---	---
<u>Number of Residents</u>			
One	20.4%	26.6%	23.8%
Two	34.5%	32.4%	32.6%
Three	17.8%	16.3%	17.1%
Four	16.2%	13.8%	14.9%
Five	6.7%	6.6%	7.0%
Six +, Left blank	3.8%	4.4%	4.6%
<u>Dwelling Type</u>			
Single family	58.8%	61.6%	65.5%
2-4 Units	13.7%	11.2%	9.9%
5 Units or more	22.7%	23.9%	20.5%
Mobile Home	3.6%	3.3%	4.1%
Other	0.7%	---	---
Left Blank	0.6%	---	

Table A-3. (continued)

Data Item	Survey (Baseline) Territory X)	Census Set 1	Census Set 2
Own or Rent			
Own	56.7%	55.8%	59.0%
Rent	42.6%	44.2%	41.0%
Other	0.5%	---	---
Left Blank	0.3%	---	---
Type of Occupancy			
Full-time	97.1%	94.6%	94.5%
Part-time	1.8%	1.4%[a]	1.5%[a]
Other	0.3%	4.0%[b]	4.0%[b]
Left blank	0.8%	---	---
Length of Occupancy (years)			
One or less	29.7%	26.9%	27.7%
Two to five	28.8%	31.7%	32.0%
6-10	16.6%	15.4%	15.5%
11-20	14.2%	14.9%	14.9%
16-20	4.8%		
21 or more	10.5%	11.0%	10.0%
Number of Bedrooms			
None	2.5%	4.5%	3.0%
One	15.8%	18.9%	16.7%
Two	32.4%	31.4%	31.2%
Three	32.8%	31.2%	33.5%
Four	13.1%	11.8%	13.4%
Five or more	2.9%	2.2%	2.2%
Left blank	0.4%	---	---
Main Space Heating System			
Central	46.7%	51.5%	52.0%
Gas Wall/Floor	31.7%	28.0%	30.4%
Electric Wall/Baseboard	6.7%	9.7%	9.7%
Electric Heat Pump	0.2%	1.3%	1.3%
Portable Heater	0.8%		
Wood Stove	4.1%	3.2%	3.3%
Fireplace	0.9%		

Table A-3. (continued)

Data Item	Survey (Baseline) Territory X)	Census Set 1	Census Set 2
Main Space Heating System (continued)			
Solar	0.1%	---	---
Multi-res. System	4.4%	---	---
Other	1.8%	6.0%[c]	3.0%[c]
None	0.1%	0.4%	0.3%
Not sure	2.8%	---	---
Left blank	1.4%	---	
Space Cooling System			
Central Electric/Gas	9.1%	8.8%	11.4%
Ref. Window/Wall	5.3%	7.2%	9.5%
Evaporative	2.0%	---	---
Multi-res. System	0.3%	---	---
Elec. Heat Pump	0.2%	---	---
Other	0.6%	---	---
Electric Fans	8.0%	---	---
None	70.3%	84.0%	79.1%
Not sure/Blank	4.1%	---	---
Type of Range or Stove			
Natural Gas	39.2%	42.6%	38.8%
Electric	57.6%	54.9%	58.7%
Bottled Gas	1.7%	2.0%	2.2%
Other	0.8%	0.1%	0.1%
None	0.2%	0.4%	0.2%
Not sure/Blank	0.6%	---	---
Water Heating Fuel[d]			
Natural Gas	72.7%	85.6%	85.2%
Electricity	5.7%	10.6%	10.9%
Bottled Gas	1.9%	3.4%	3.5%
Solar	1.9%	---	---
Multiple Fuels	0.2%	0.2%	0.1%
Other	0.1%	0.2%	0.1%
Not sure/Blank	17.6%	0.2%[d]	0.1%[d]

[a] "Not year round housing unit" or "held for occasional use."
[b] "Vacant, for sale or for rent."
[c] Steam.
[d] None.

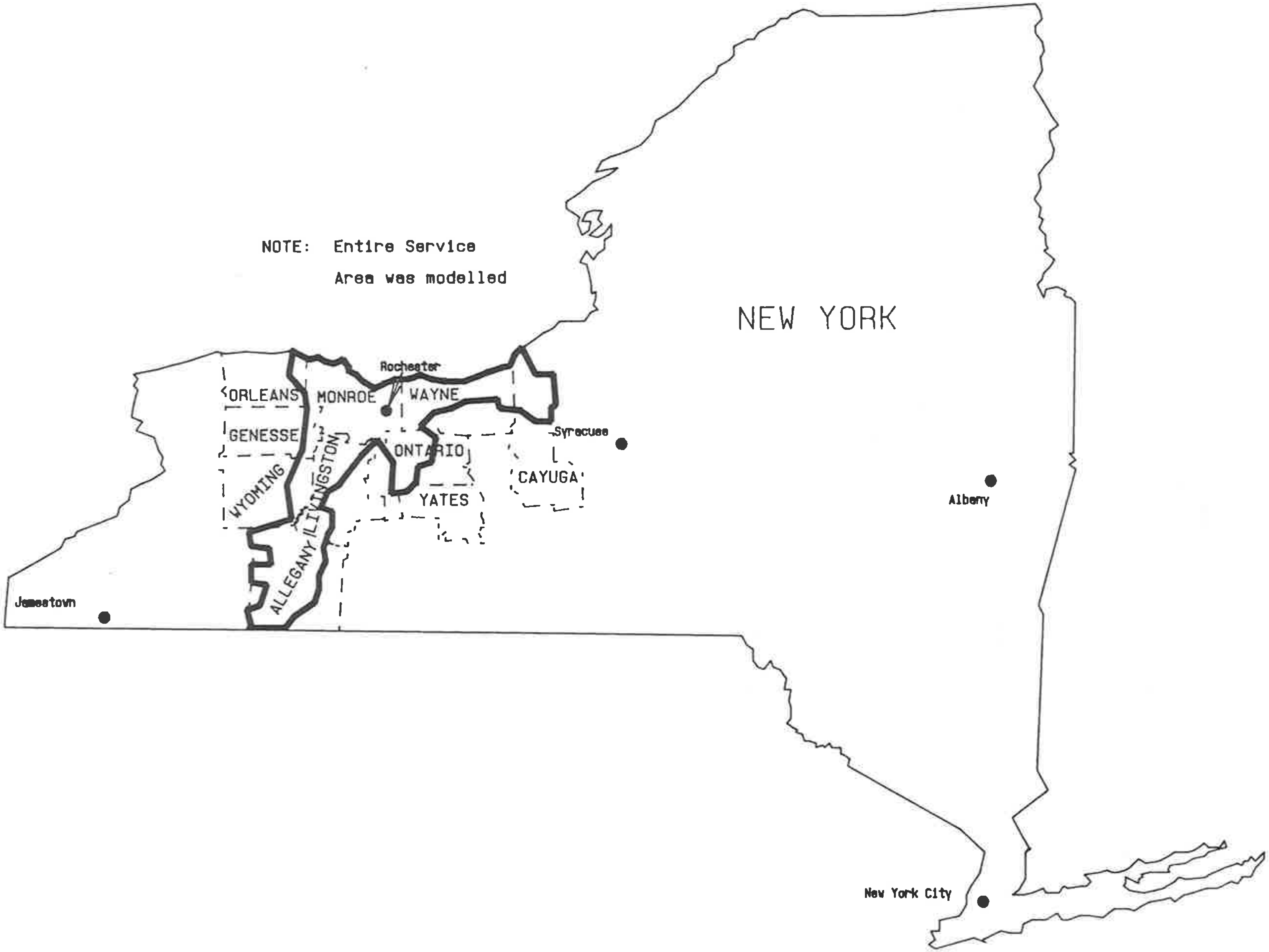


Figure A-1. Rochester Gas and Electric Corporation service territory.

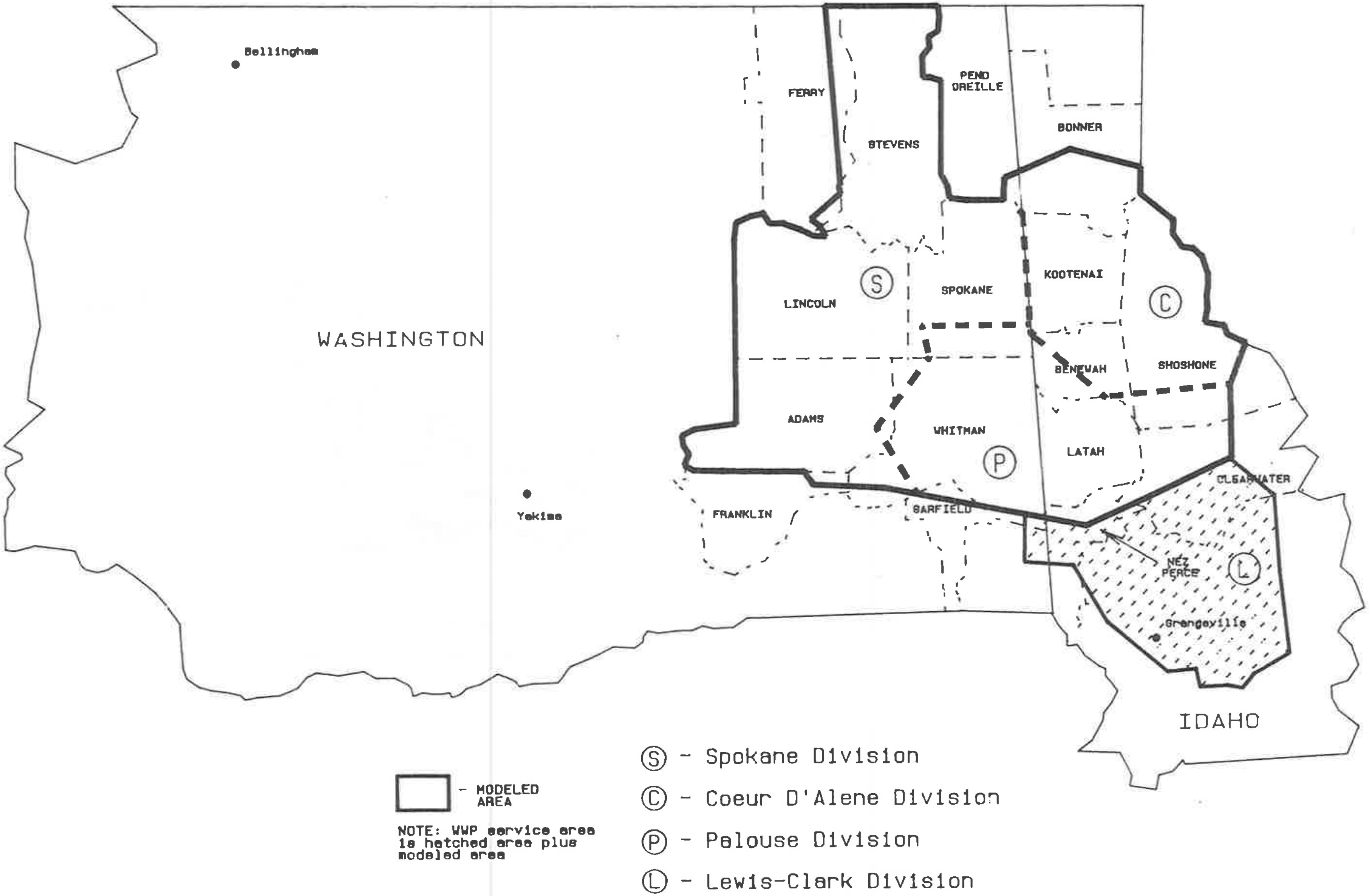


Figure A-2. Washington Water Power Company service territory and area modeled.

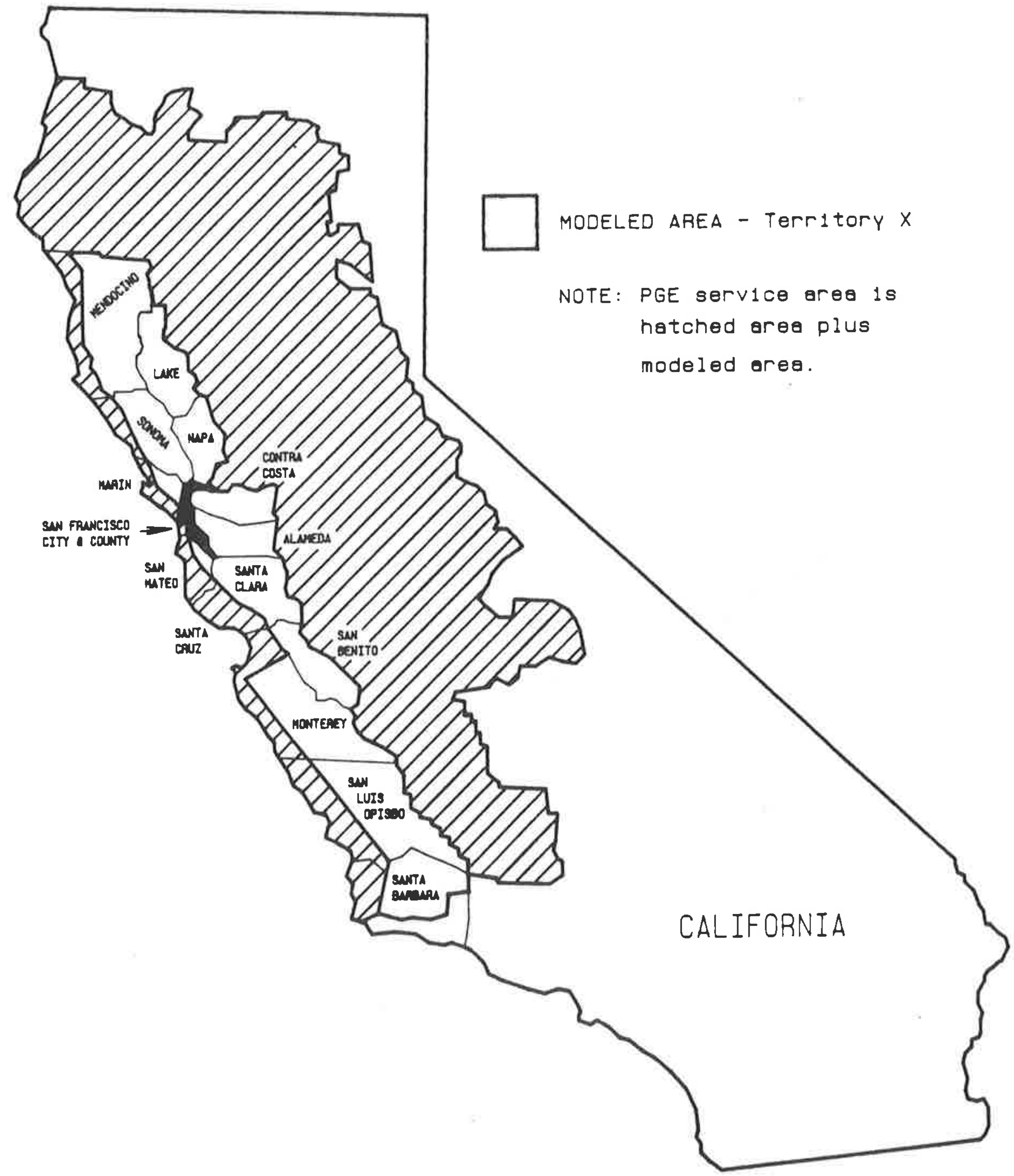
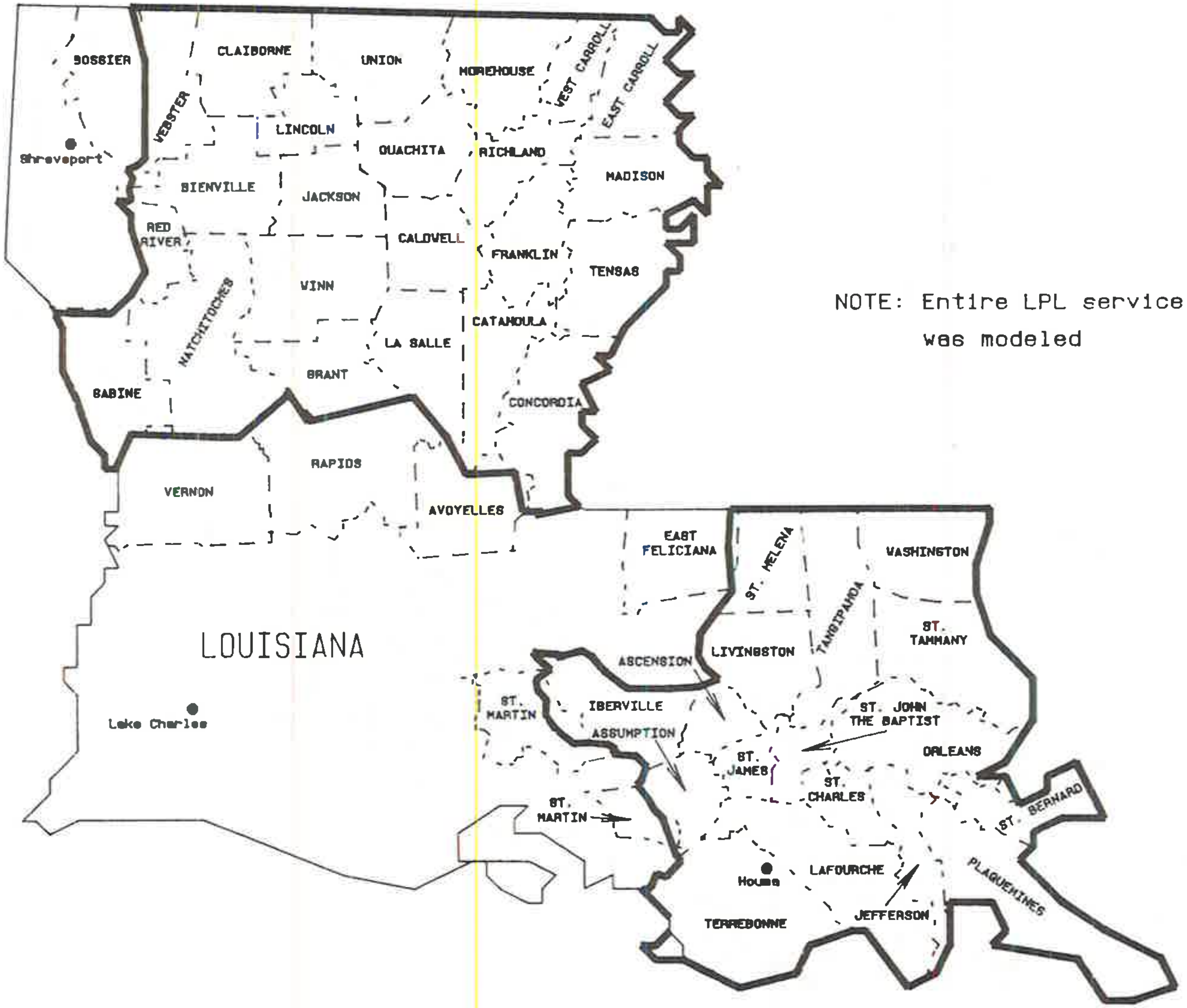


Figure A-3. Pacific Gas and Electric Company service territory and area modeled.



NOTE: Entire LPL service area was modeled

Figure A-4. Louisiana Power and Light Company service territory.

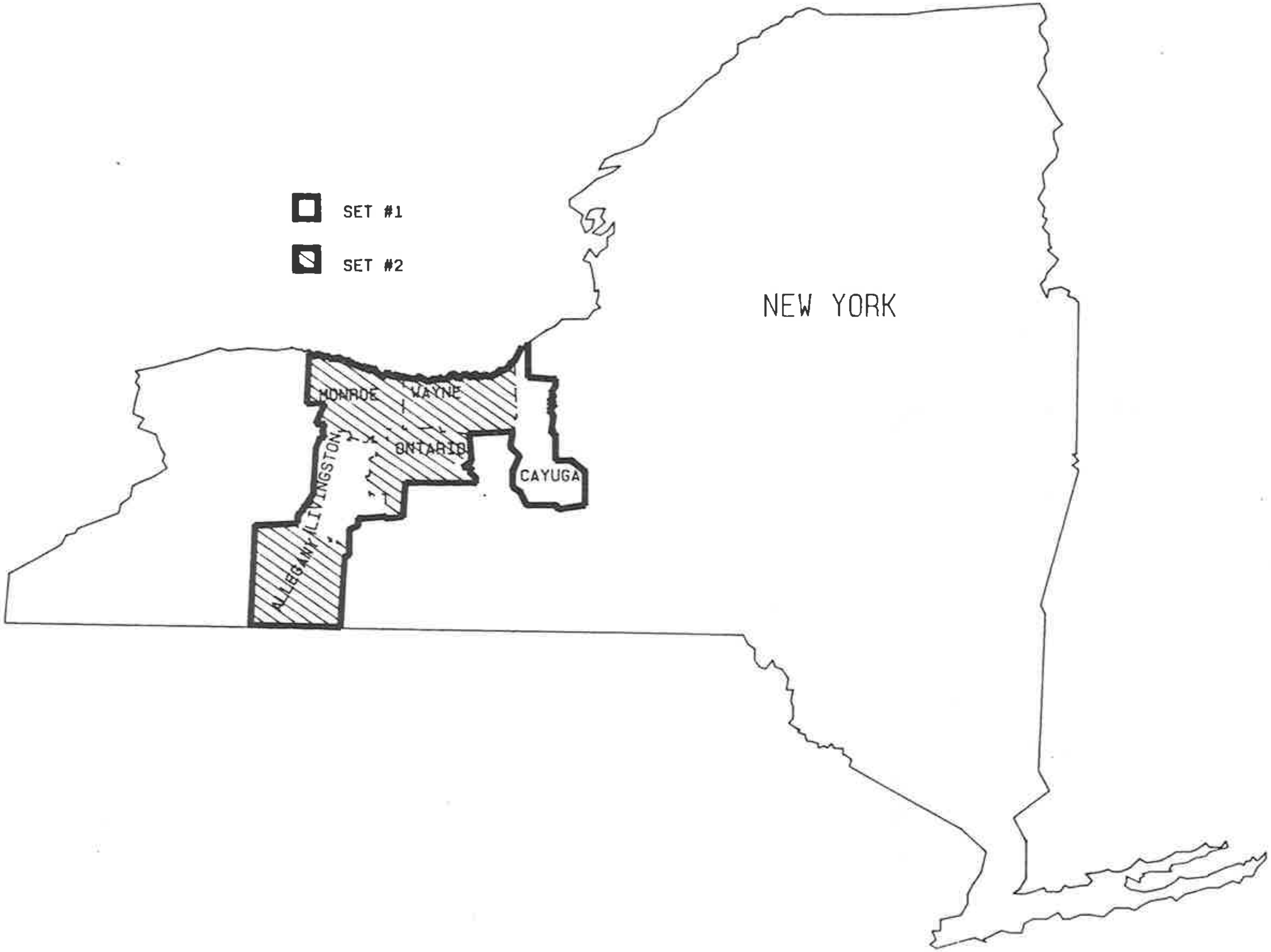


Figure A-5. Counties used in RGE census comparison.

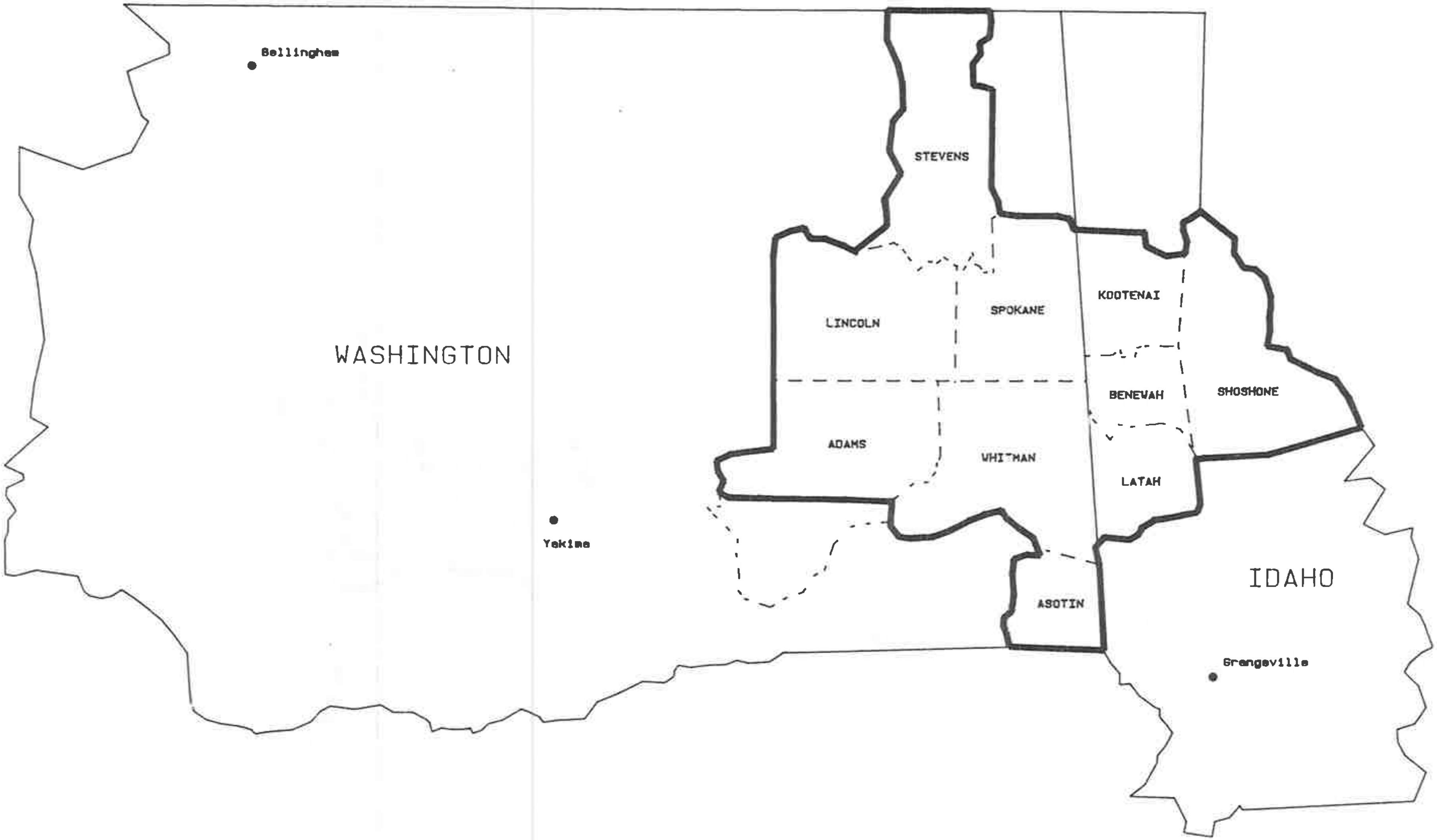


Figure A-6. Counties used in WWP census comparison. The Washington part includes Stevens, Lincoln, Spokane, Adams, Whitman, and Asotin counties. The Idaho part includes Kootenai, Benewah, Latah, and Shoshone counties.

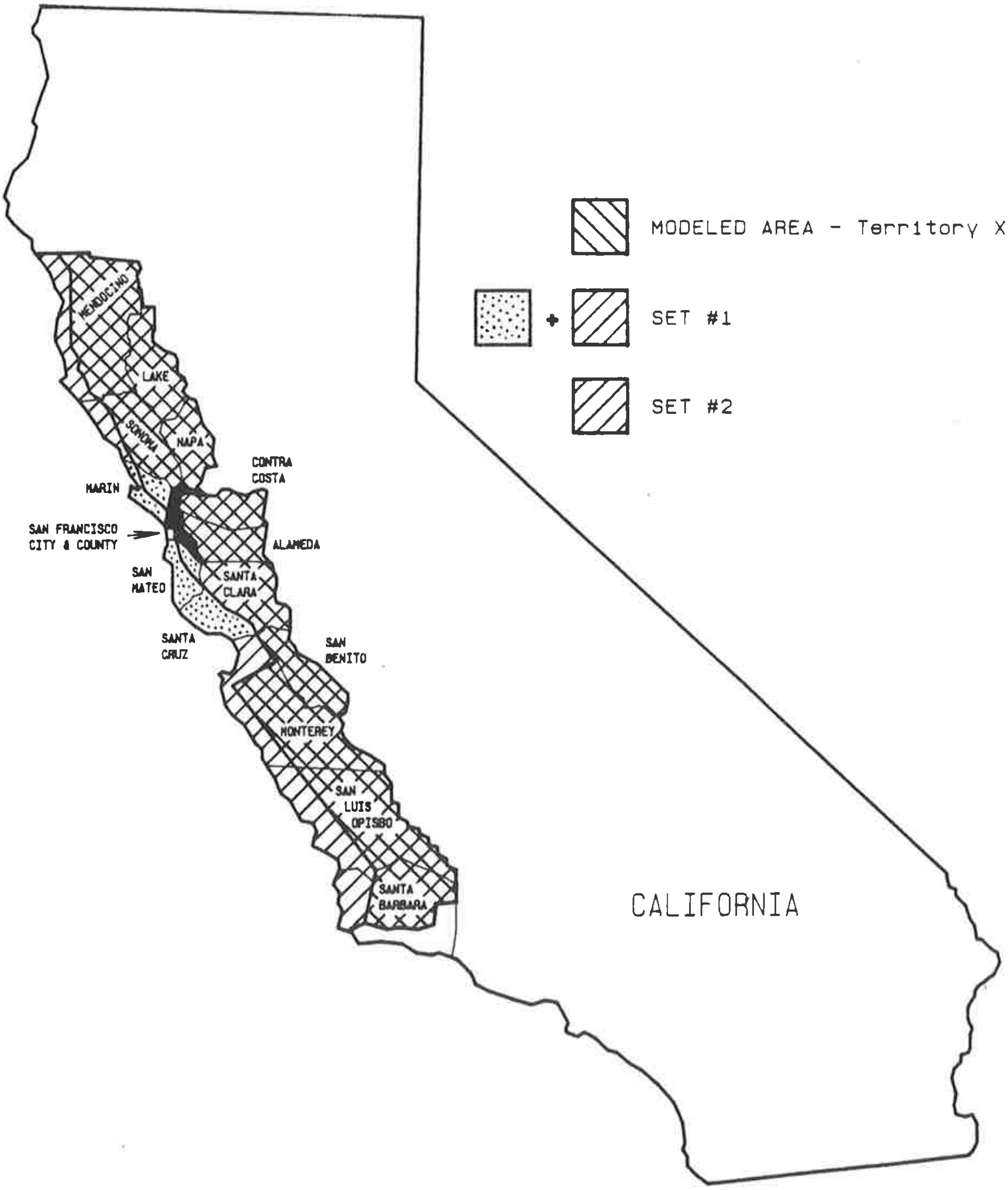


Figure A-7. Counties used in PGE census comparison.

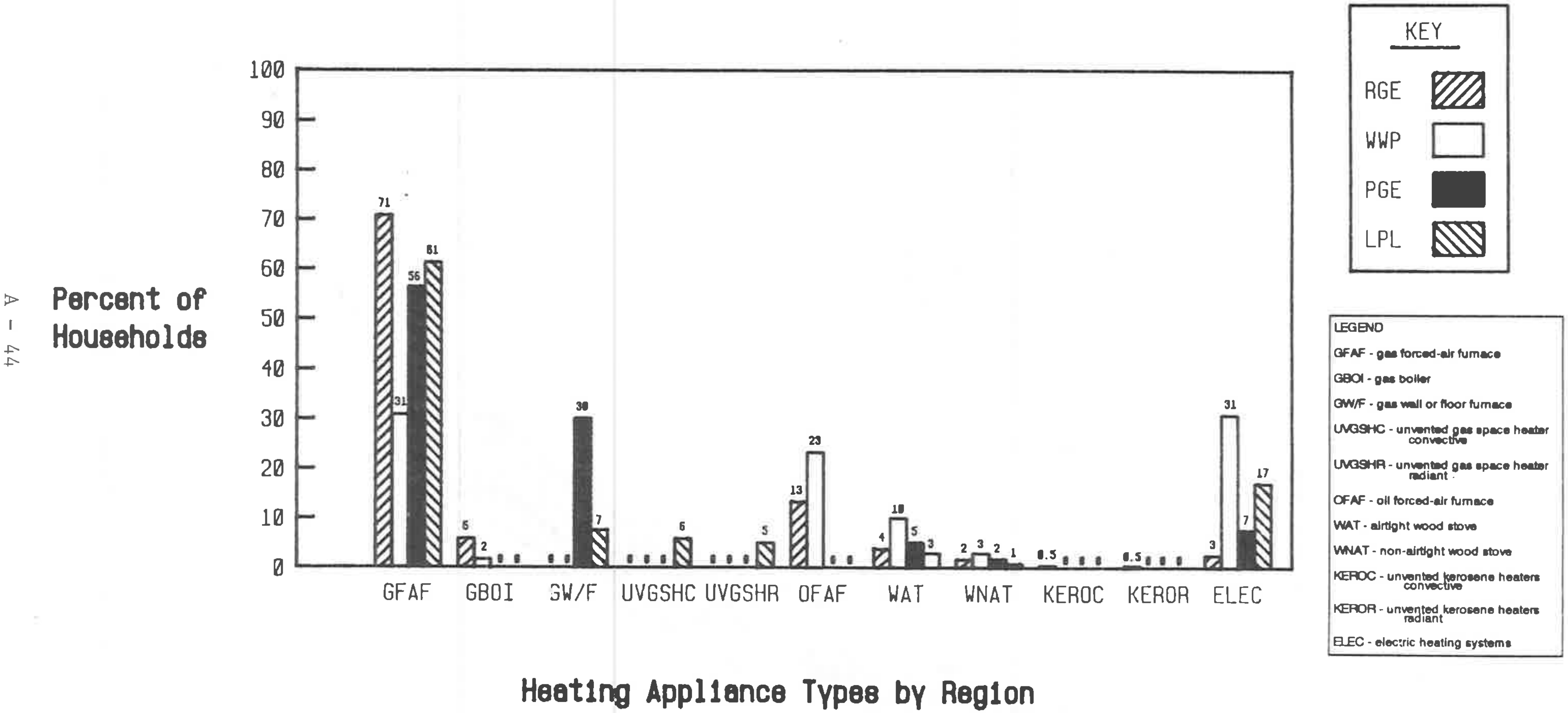


Figure A-8. Regional primary space-heating-appliance distributions.

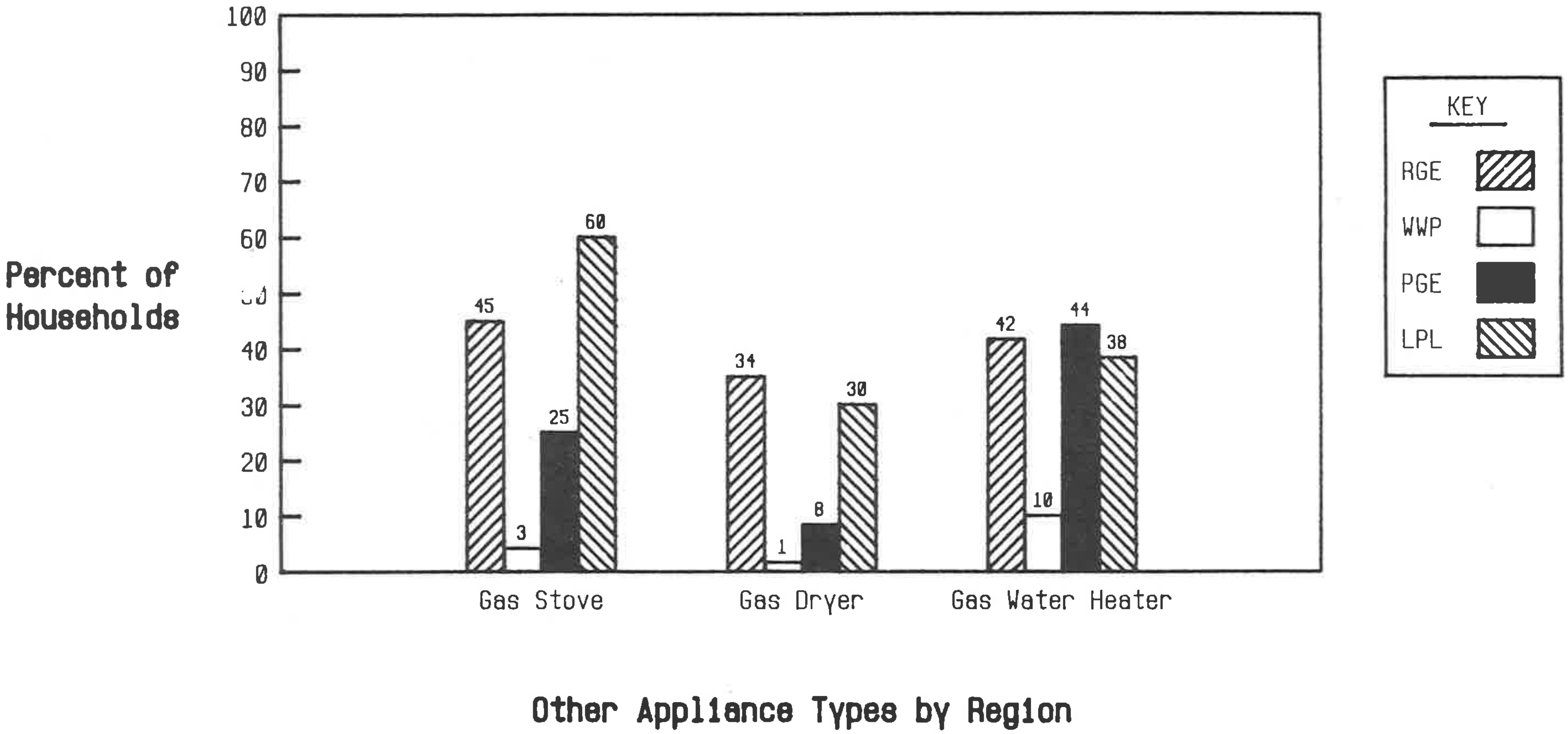


Figure A-9. Regional non-space-heating-appliance distributions.

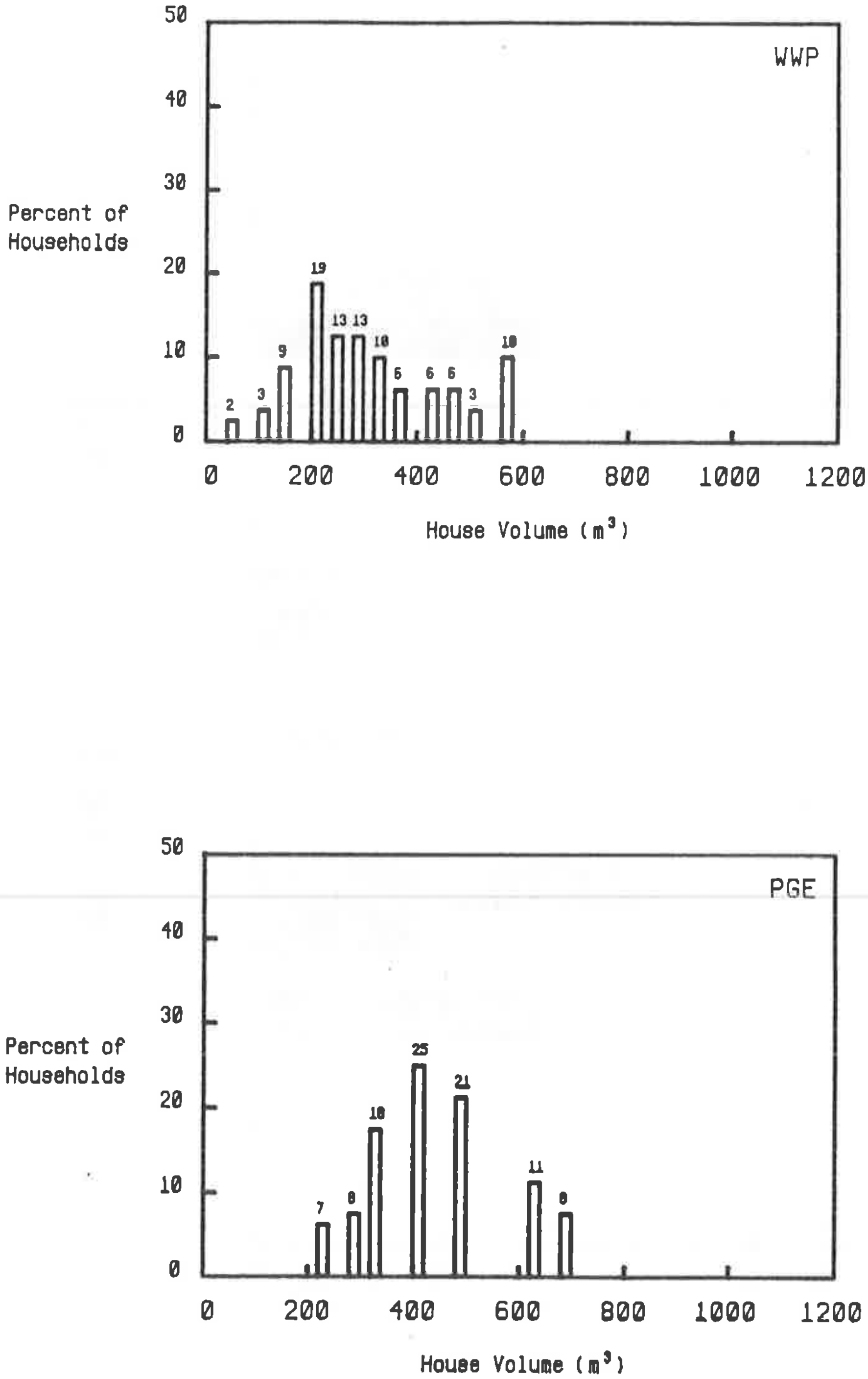
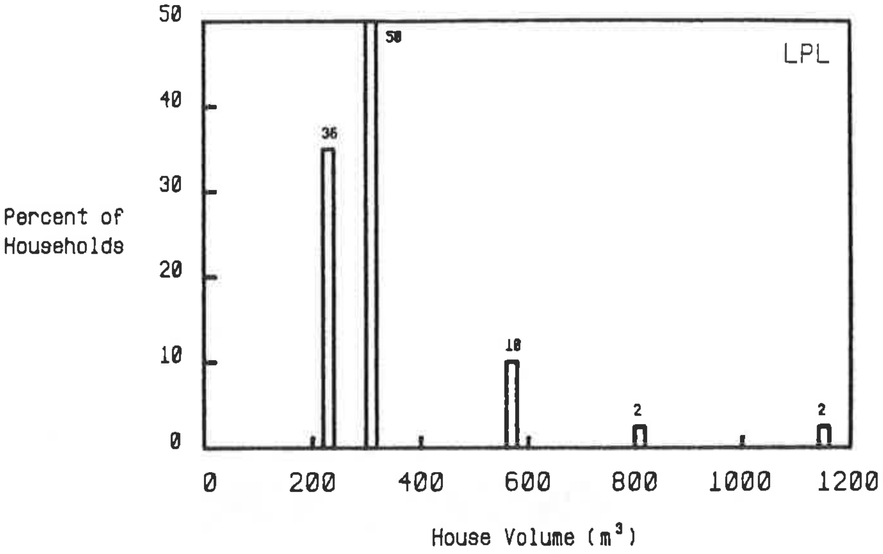


Figure A-10. House-volume distributions for WWP and PGE.



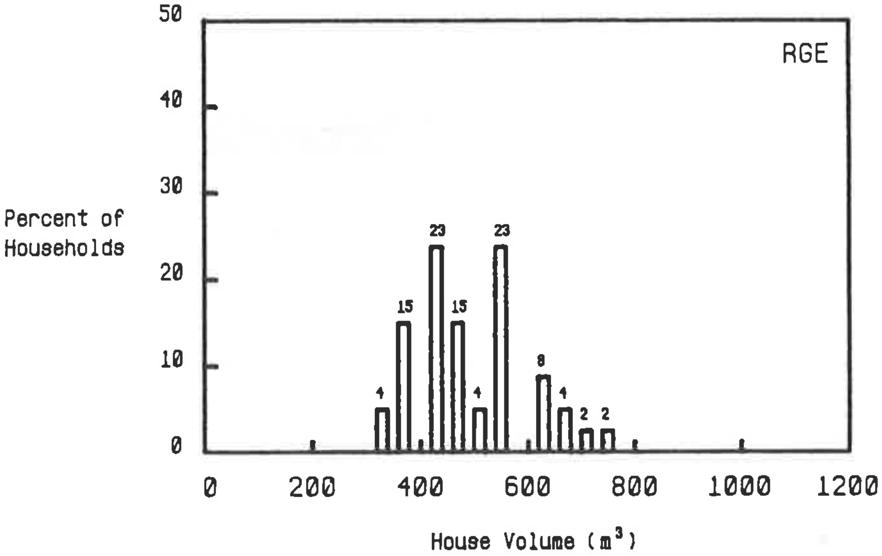


Figure A-11. House-volume distributions for LPL and RGE.

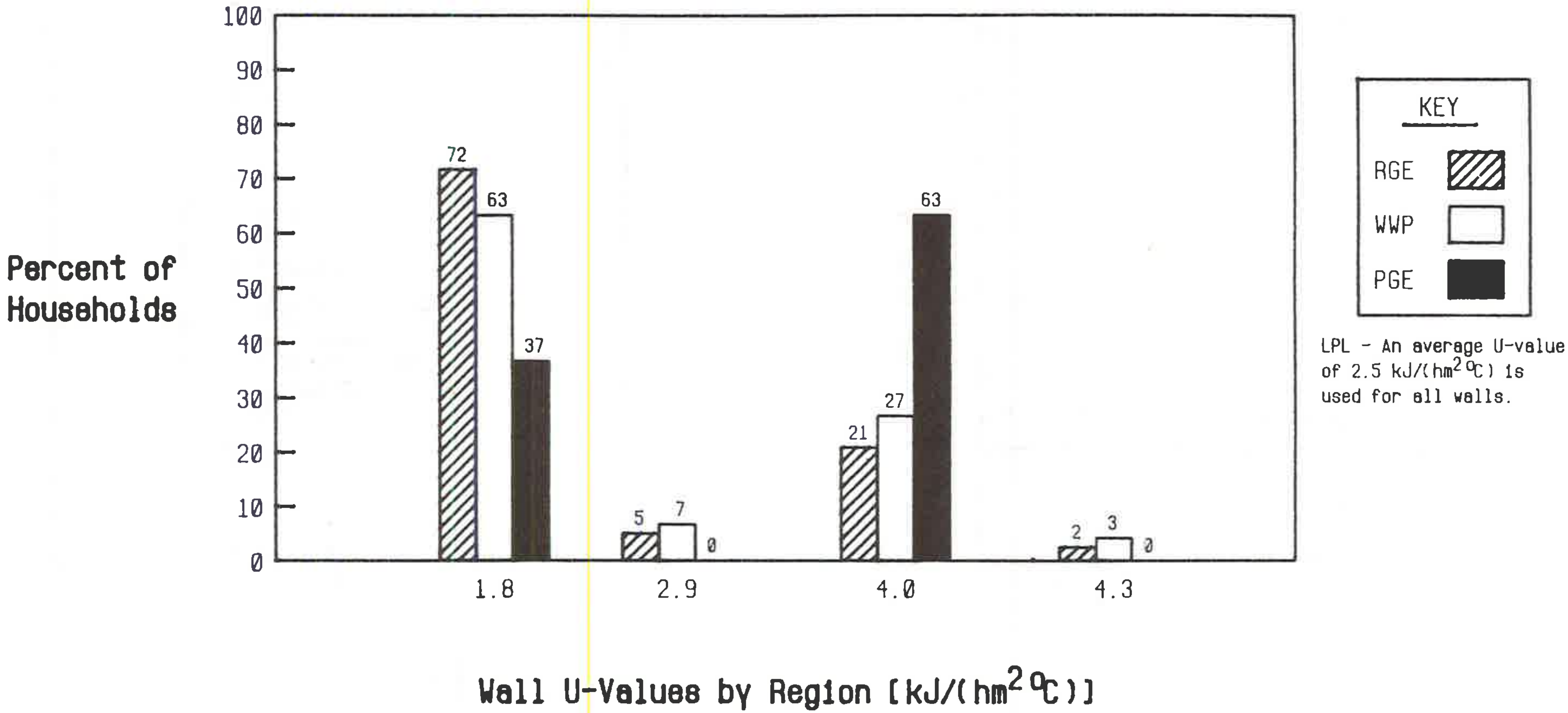
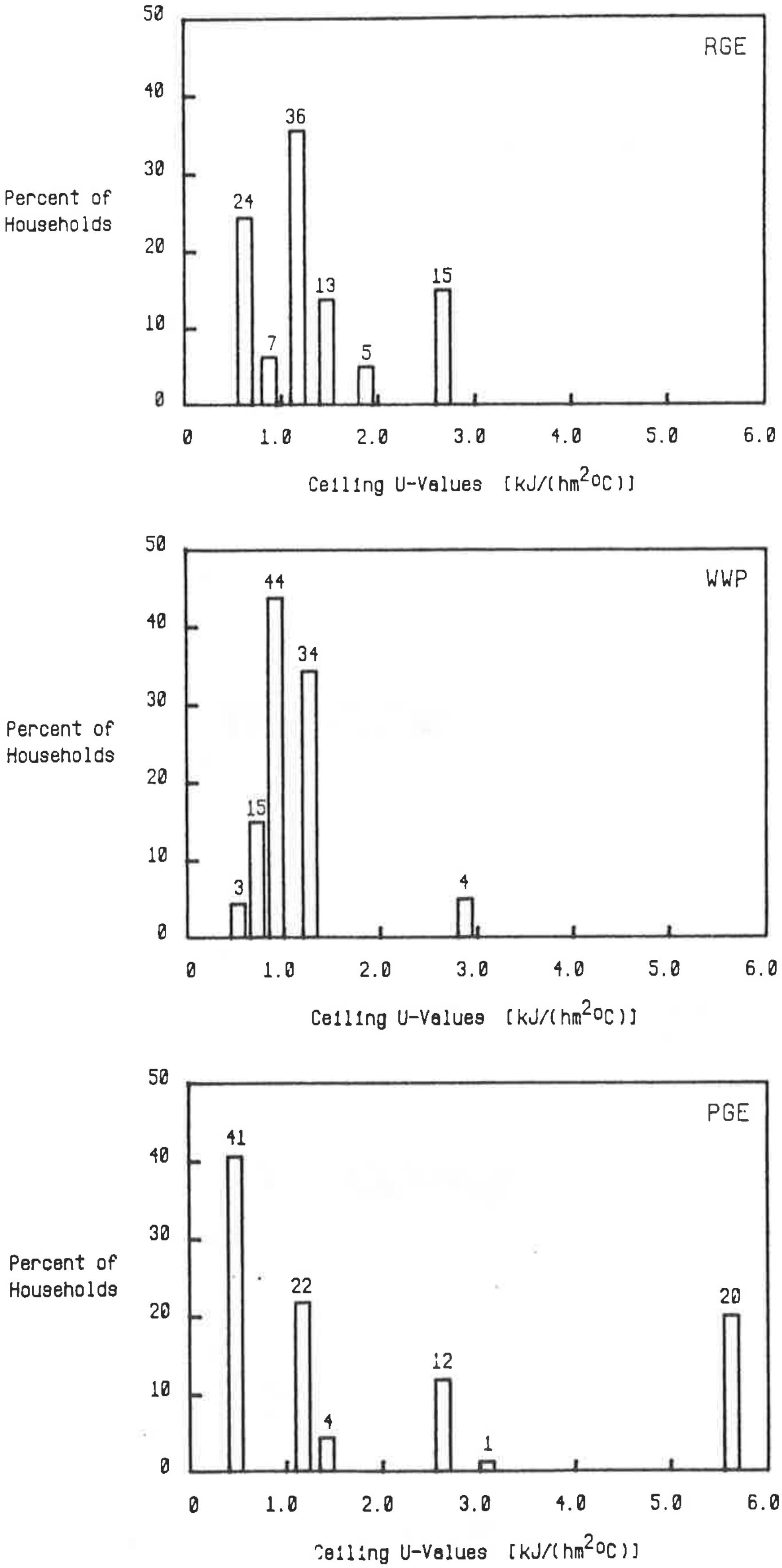


Figure A-12. Regional wall U-value distributions. An average U-value of 2.5 kJ/hm²°C is used for all walls in the LPL region.



LPL - An average U-value of 1.5 kJ/(hm^2°C) is used for all ceilings

Figure A-13. Regional ceiling U-value distributions. An average U-value of 1.5 kJ/hm^2°C is used for all ceilings in the LPL region.

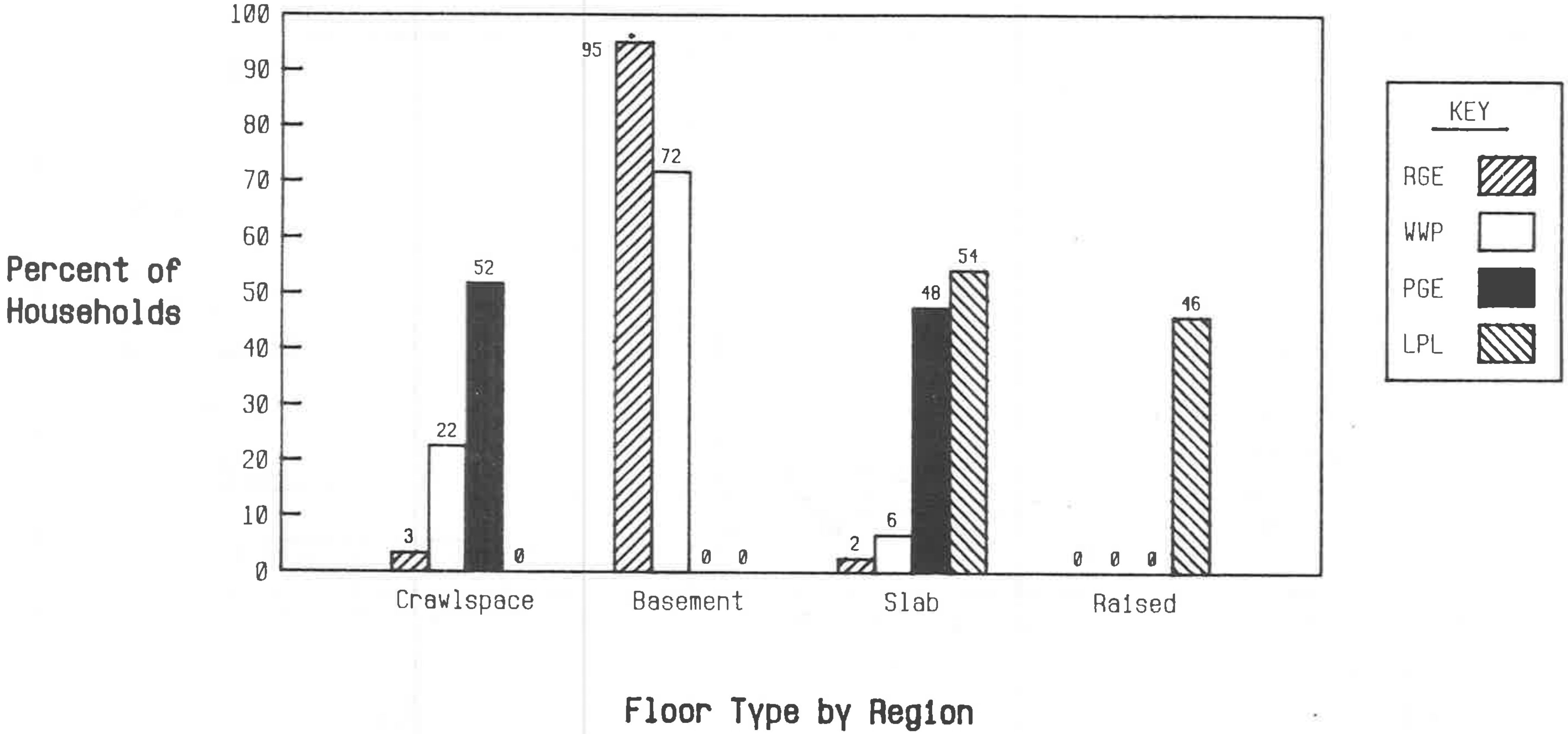
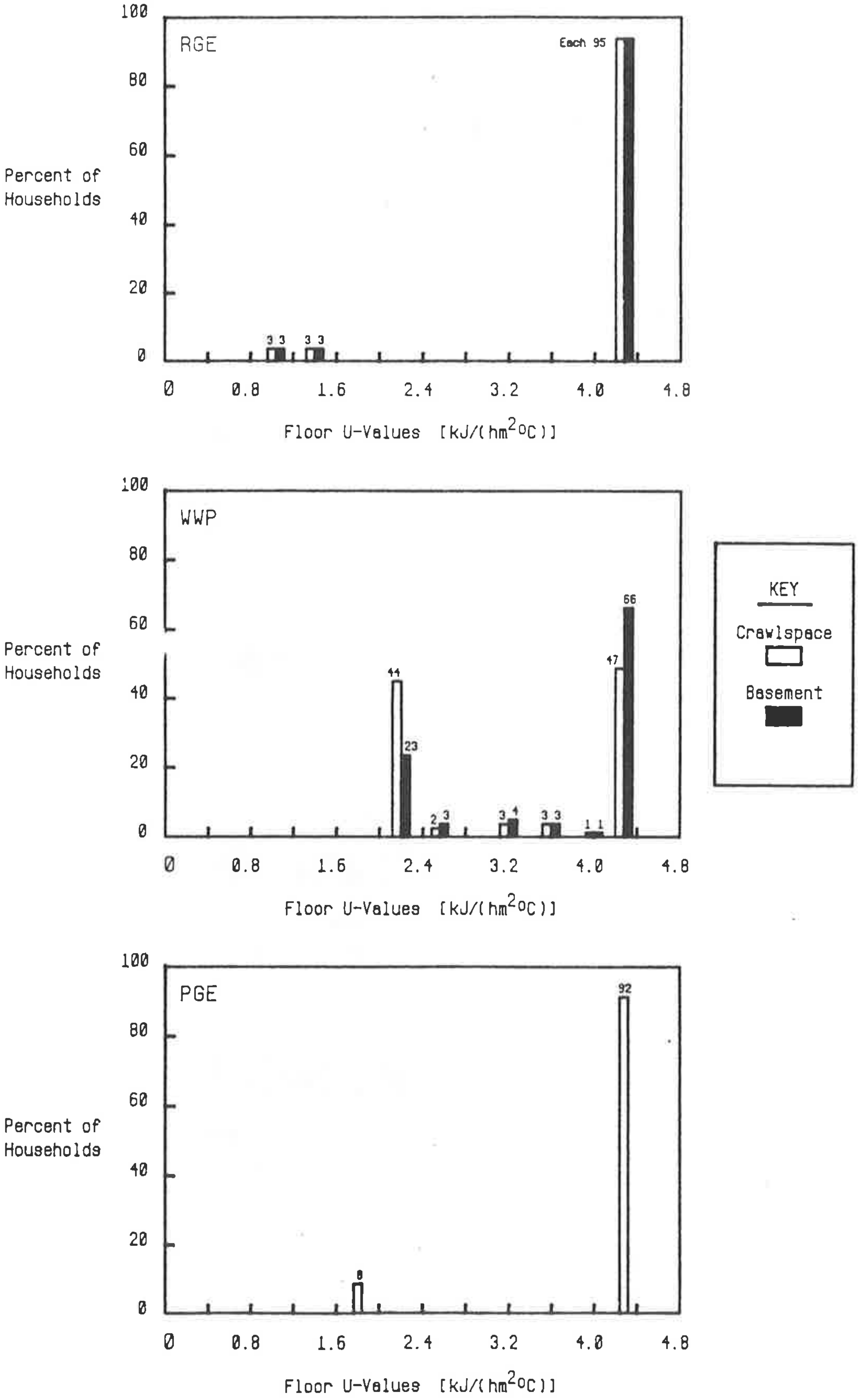


Figure A-14. Regional floor-type distributions.



LPL - An average U-value of 3.6 kJ/(hm²°C) is used for all raised-frame floors.

Figure A-15. Regional floor U-value distributions. An average value of 3.6 kJ/hm²°C is used for all raised-frame floors in the LPL region.

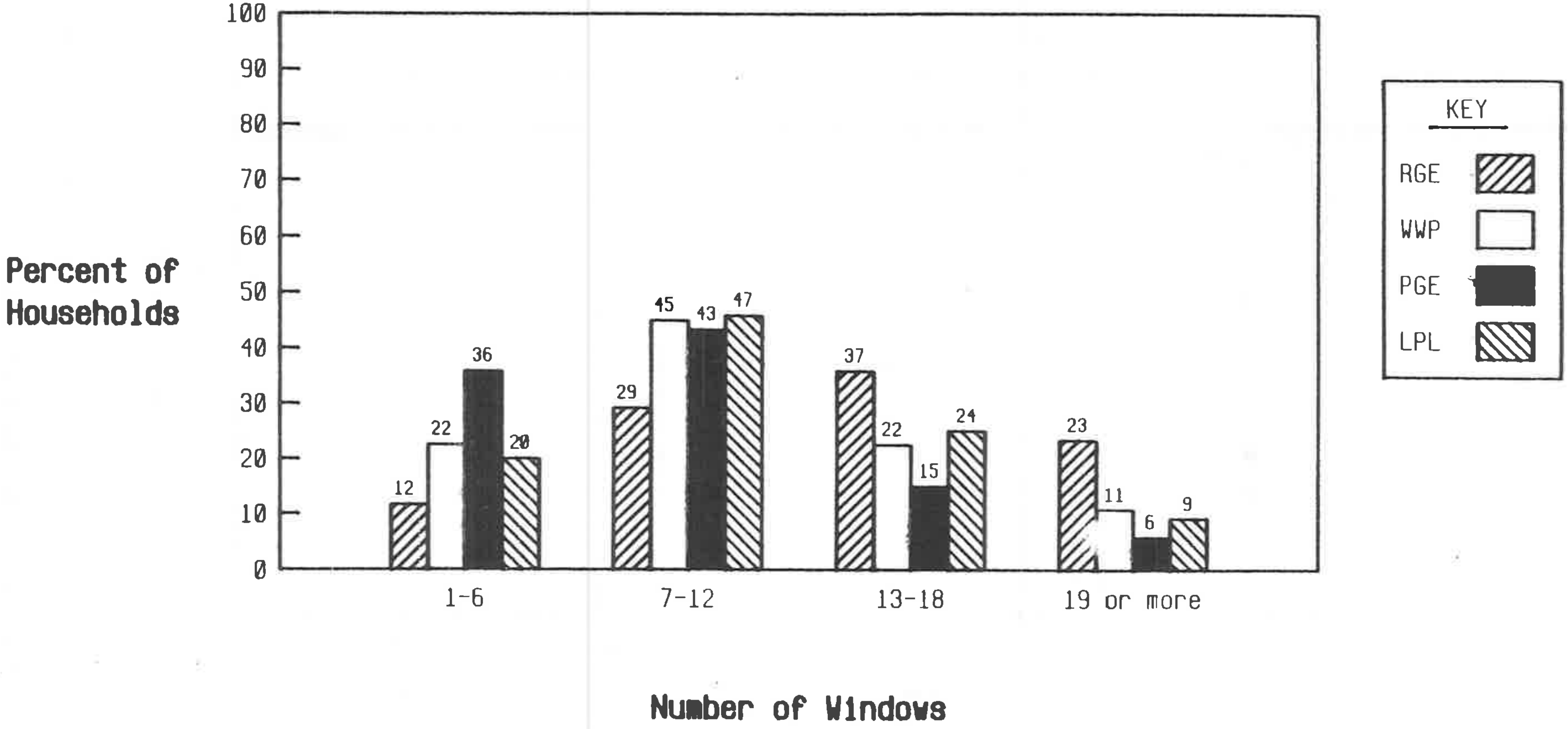


Figure A-16. Regional distributions of number of windows for WWP, PGE, LPL, and RGE.

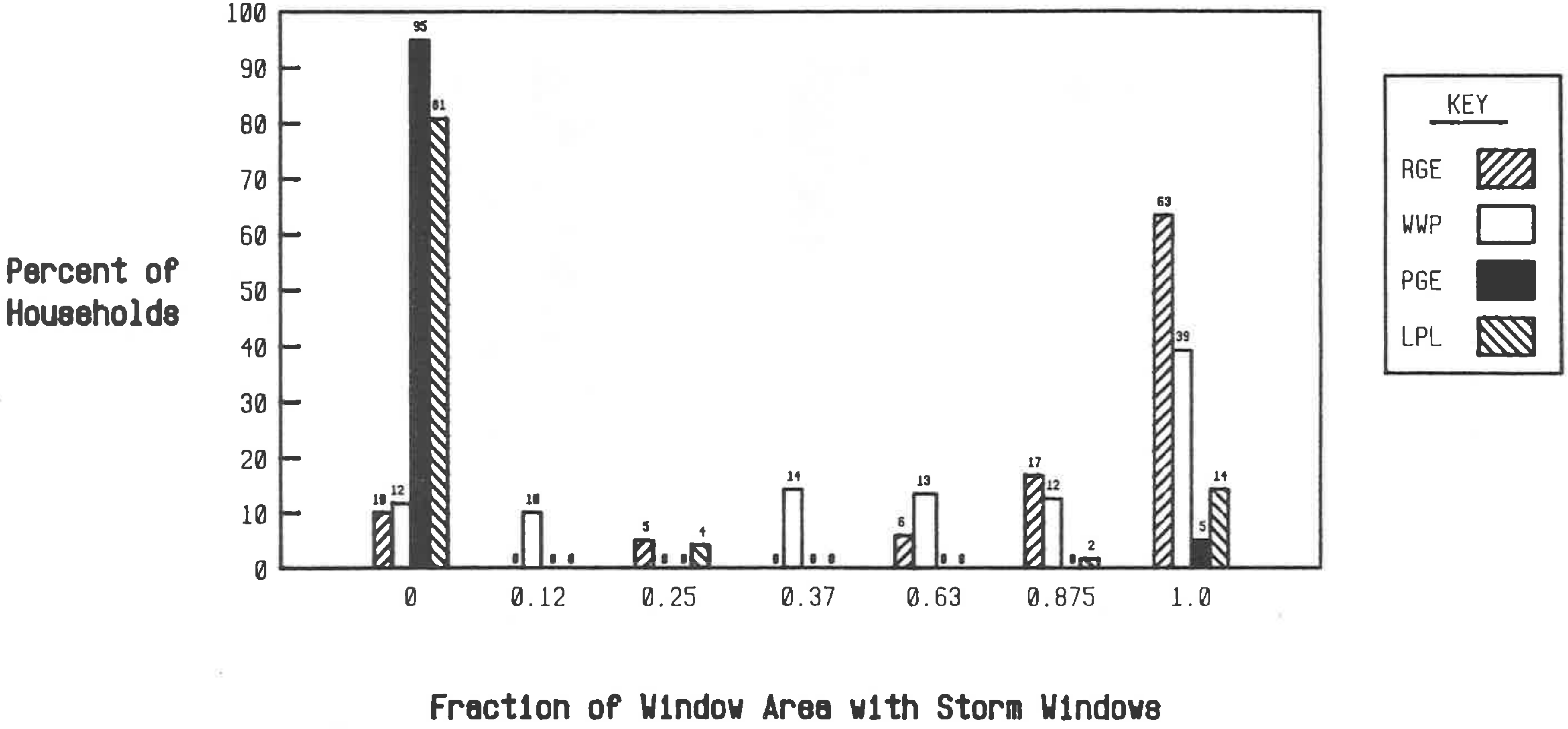


Figure A-17. Regional distributions of the fraction of window area with storm windows.

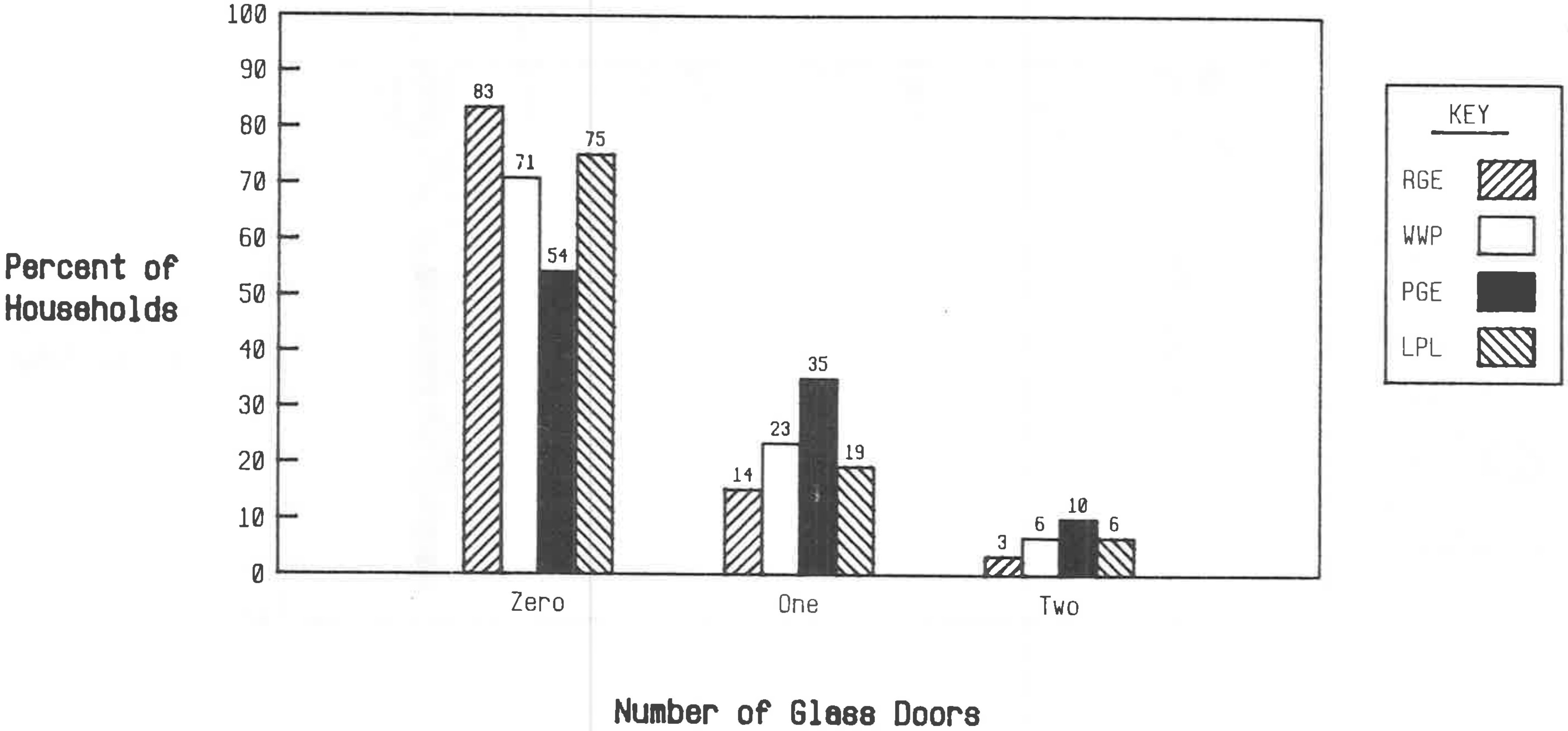


Figure A-18. Regional distributions of the number of sliding glass doors.

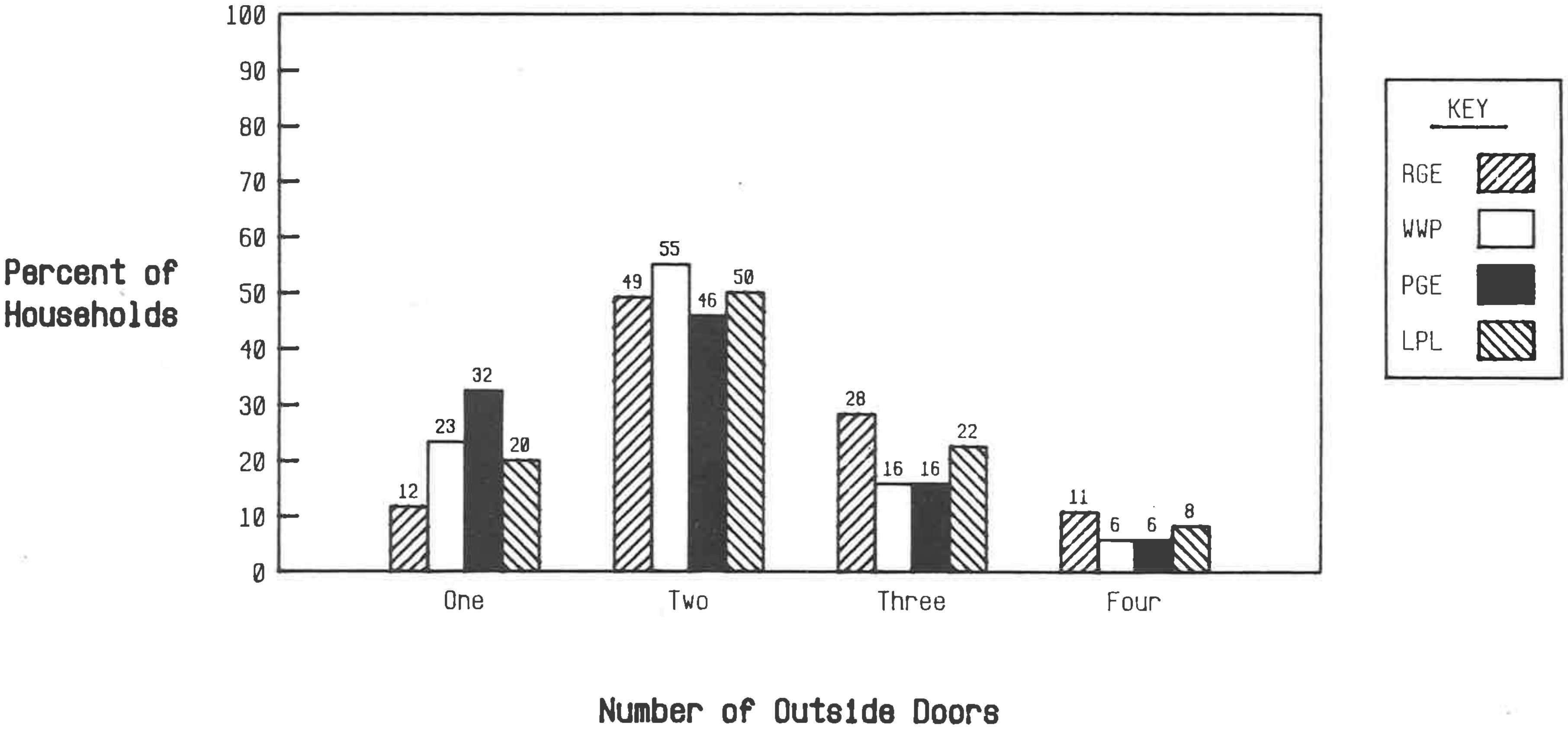


Figure A-19. Regional distributions of the number of outside doors for RGE, WWP, PGE, and LPL.

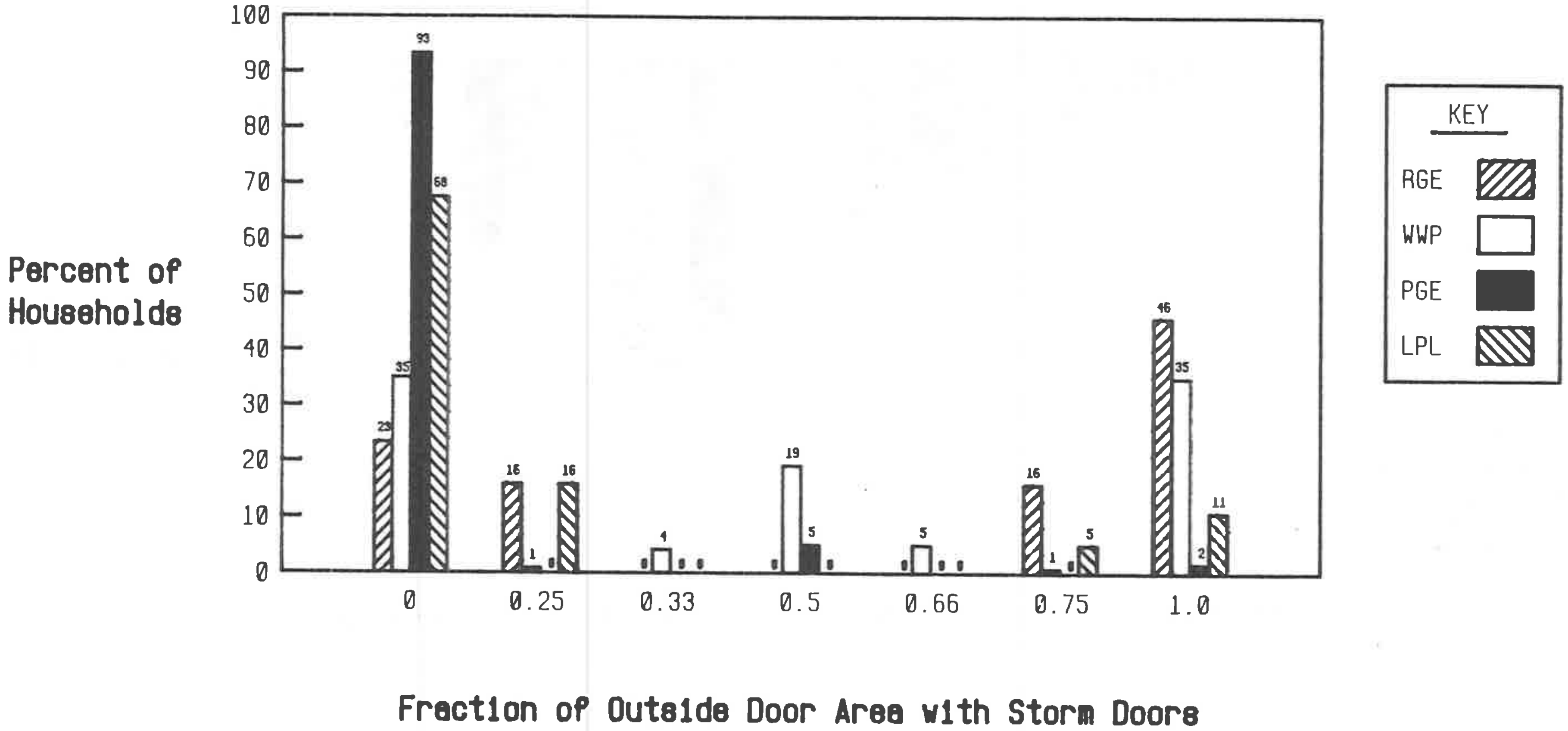


Figure A-20. Regional distributions of the fraction of outside door area with storm doors.

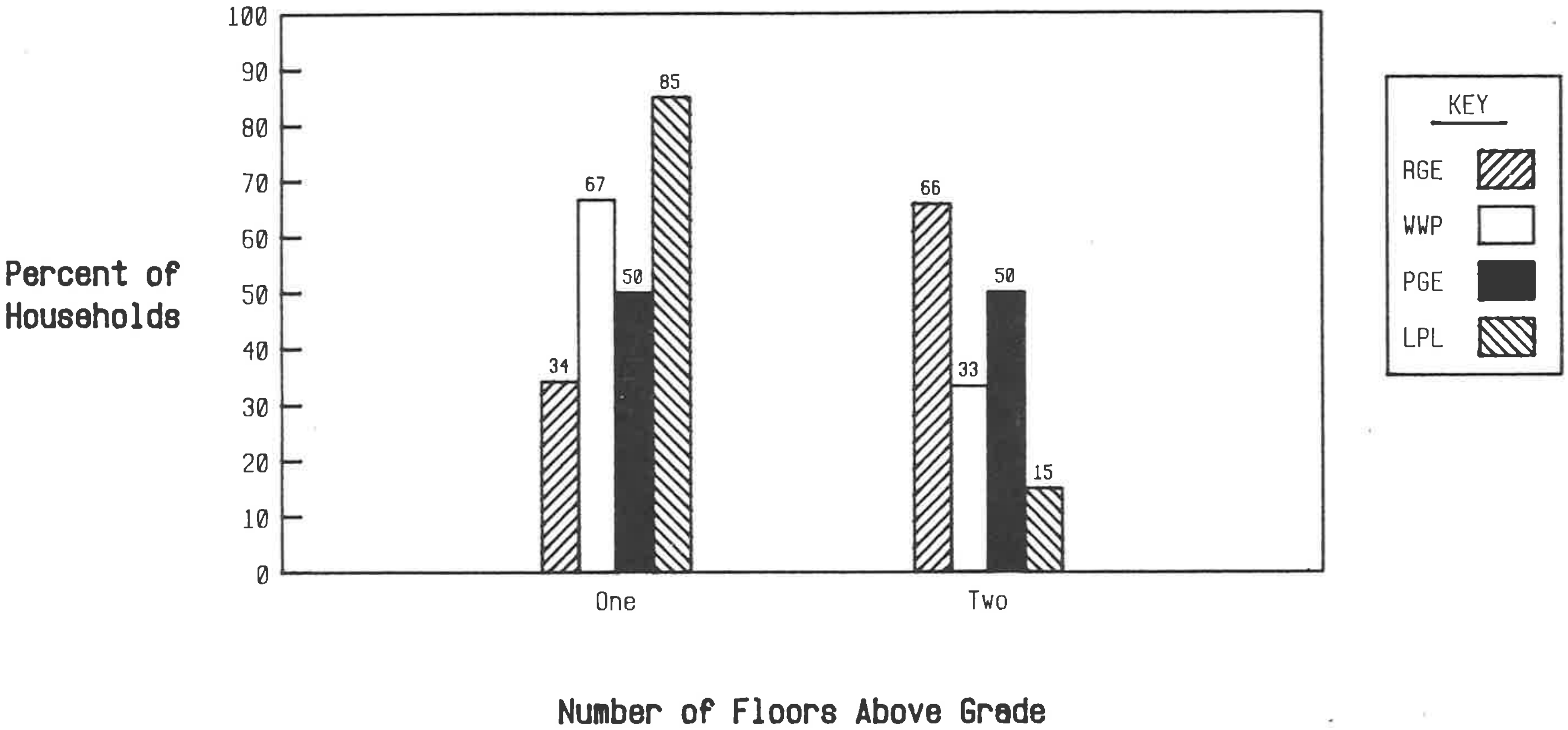


Figure A-21. Regional distributions of the number of floors above grade.

APPENDIX B: NINE HOUSE STUDY

1 Introduction

One key purpose of this macromodel is to provide a tool to assist in the assessment of human exposures to indoor-generated combustion pollutants without having to monitor every person who might be exposed.

A successful modeling effort must have sufficient and correct input data. Although the macromodel does take advantage of existing laboratory and field research for its input data, information gaps still exist. In some cases, existing data must be verified to ensure their validity.

A nine-house study was conducted to test methods designed to efficiently obtain the data needed to fill the gaps in the model's input data. The primary focus of this study was to test a methodology designed to collect source-usage data.

Heating-appliance source usage is influenced by many factors including outdoor temperature, indoor temperature, heater types and efficiencies, house volume, insulation level, ventilation characteristics, solar gain, and heat from other sources (see Chapter II). Building temperatures can be automatically controlled using thermostated heaters or manually, as in the case of wood stoves and kerosene heaters. The aforementioned factors must all be taken into consideration when designing a study to measure appliance usage.

Secondary goals of the nine-house study were to test the validity of the source-usage model for space-heating appliances (see Eq. 5 in Chapter II) and to measure indoor-pollutant concentrations and, if possible, calculate indoor-pollutant source strengths for CO and NO_2.

2 House Selection

Subject households were nonrandomly recruited from employees at the Lawrence Berkeley Laboratory. A total of nine homes were chosen for one-week monitoring periods during the months of January through March, 1987. The houses were chosen on the basis of the type of heating appliance they had; a mix of houses equipped with forced-air furnaces, floor furnaces, wall furnaces, woodburning stoves, and kerosene heaters were recruited for the study. Table B-1 shows the characteristics of the selected houses. All of the furnaces, with the exception of one wall furnace in House 5, were installed when the houses were built, and use natural gas for fuel. The two woodstoves were both airtight and less than four years old--one was a catalytic model. The fireplace was free-standing and constructed with sheet metal. One woodstove used dry hardwood (House 1), whereas the houses with the fireplace

(House 4) and the other woodstove (House 6) used construction wood scraps. The kerosene heaters in House 4 (one convective, one radiant) were both less than five years old. They were fueled with 1-K, low-sulfur kerosene (ASTM, 1978).

All of the houses were located within 25 miles of Berkeley, California, where the winter weather is moderate. During the weeks of testing, the outdoor temperature seldom stayed below freezing. All houses were wood frame construction. Their ages ranged from one to approximately one-hundred years. The amount of insulation in the houses differed considerably. House 7 was completely uninsulated, and Houses 2 and 8 were fully insulated. None of the houses were constructed to be extremely airtight, and none appeared to be overly leaky.

Table B-1 shows that six of the houses had natural-gas cooking appliances, and five of the houses had at least one other vented gas appliance in the living space.

3 Data Collection

Data for this project were collected by three methods. First, details on the construction of the house were collected by visiting technicians. Second, some information was collected via homeowner-comnpleted diaries. And third, some information was collected by electronic monitoring equipment and air pollutant samplers. Two houses were investigated each week for a one-week period. On a pre-scheduled setup day, project staff met with a member of the household. The diary sheets were explained to the household member, and a detailed building-structure, appliance-type, and energy-use questionnaire was completed by a visiting technician. The technicians then set up the instrumentation and drew a very detailed set of house plans including all house dimensions; window and door areas; location, type, and amount of insulation; and relevant information on the heating system.

The diary sheets were left for the occupants to fill out as they went about their daily activities. Separate diary sheets were used to log information on heating-appliance use, smoking, gas cooking, gas-dryer use, and other events affecting IAQ. If a house had more than one heating appliance, a diary sheet was left for each one. The heating-appliance diary allowed the subject to log the thermostat settings, if applicable. Time of day and duration of use were requested on the heating-appliance, gas-cooking, and gas-dryer diaries. The number of cigarettes smoked per day was requested on the smoking diary. A separate diary was used to collect information on ventilation such as how long doors and windows were left open and how long bathroom and kitchen ventilation fans were operated, as well as any other activities that the subjects might consider important to their indoor air.

An attempt to minimize the intrusion of the subjects' life styles was made by making the diary sheets easy to complete. The sheets were attached to clipboards equipped with pencils, and it was suggested that they be placed near the activity to be logged (e.g., the gas-cooking log near the gas cooking stove).

Table B-2 lists the instrumentation used in this study. A real-time data-logging system was employed to monitor indoor and outdoor temperatures and the usage of heating appliance(s), domestic hot water (DHW) burner, gas dryer, and ventilation fan(s). Data were recorded as an hourly average of measurements collected every 15 seconds. The week's worth of hourly measurements were downloaded to a personal computer for data reduction at the end of the testing period.

Air temperatures were monitored at one outdoor and several indoor locations. The heating-appliance and DHW-burner usage rates were measured by monitoring the temperature at the burner or in the flue. The amount of time that furnace blowers, ventilation fans, and gas dryers were in use was monitored using either power-status transducers or clamp-on current transducers. The amount of fuel used in houses that were heated by wood or kerosene was obtained gravimetrically.

Parallel, one-week-integrated, whole-house infiltration measurements were obtained using two different continuous injection methods. The first method was the perfluorocarbon tracer (PFT) method developed by Dietz and Cote (1982). Two sets of replicate pairs of PFT collector tubes and three or four PFT sources (all emitting the same tracer) were deployed in each house. The second method employed a system that continuously injected sulfur hexafluoride (SF_6) as a tracer, and indoor air samples were continuously collected in multilayer air-sampling bags for one week. The theoretical basis for the SF_6 technique is identical to that of the PFT technique, the only difference being that the sources and air samples of the second technique are actively injected and sampled using peristaltic pumps. The SF_6 concentrations in these one-week average air samples were later analyzed by gas chromatography (Fisk *et al.* 1985). Each tracer-source injection unit or air-sampling unit was built into a molded plastic suitcase. The suitcases contain space for a bag of pure SF_6 or an evacuated sample bag, a peristaltic pump for either injecting or sampling, and an elapsed-time meter. The injection suitcases also contained small, quiet fans that promoted mixing of the tracer with room air. One injection suitcase and two sampling suitcases were used in each home. The average SF_6 concentrations generated in the houses are typically in the range of 20 to 200 ppb. Indoor-air samples were analyzed for SF_6, CO, and CO_2. Outdoor-air samples were analyzed for CO and CO_2. One-week indoor and outdoor NO_2 concentrations were obtained using from three to six Palmes Tubes at each house (Palmes, *et al.* 1976).

4 Data Analysis

Table B-3 shows parameters calculated from the detailed house plans and house-characteristics questionnaire. These calculations were made with the help of a computer program designed for residential building energy analysis called the Computerized Instrumental Residential Audit (CIRA) (Sonderegger *et al.*, 1982; BHKRA, 1984).

Usage data for parameters monitored by the real-time data-collection system are shown in Table B-4. The average energy supplied is given in kJ/h and is the average heat output over the entire week. Usage results for the DHW burner, gas dryer, and local ventilation are also given, but on a time basis. The heat-source output was calculated differently depending on the source type. For gas furnaces, if a heater output specification was given on the appliance, this was the output used. If only a heater input was given, an efficiency of 70% was assumed. For the unvented heaters, the rated output was used. For wood stoves, the heat supplied to the house was calculated using the total mass of wood consumed during the week, a value of 16,000 kJ/kg for the heat content of wood (Shelton, 1983), the wood stove efficiency, and the total time the wood stove was on. The efficiencies used for individual wood stoves were estimated to be 65% for the catalytic airtight stove, 50% for the non-catalytic airtight stove, and 25% for the fireplace based on their construction and material characteristics (Shelton, 1985).

5 Results and Discussion

5.1 Comparison of air exchange rate measurement techniques

Table B-5 summarizes the air-exchange-rate results for the two integrating techniques used in this study: the PFT passive technique and the SF_6 active integrating technique. The PFT technique consistently gave lower air-exchange rates than did the SF_6 technique. However, the results of all but two houses were within 20% and the two houses with deviations greater than 20% had relatively high air-exchange rates, which can lead to incomplete air mixing within the houses. Since there was no reason to suspect one technique was more accurate than the other, the two air-exchange-rate estimates were averaged for subsequent analyses.

5.2 Homeowner Diary Effectiveness

Several appliance-use patterns were electronically sensed by the in-house data-logging system and were also normally recorded by the homeowner in their appliance-use diary(ies). Table B-6 summarizes these comparisons. Overall, the results indicate that diaries are not always reliable; however, there were reasonably good correlations with space-heating-appliance usage. The main discrepancies for space-heating-appliance usage occurred in wood-stove use. In both cases, the homeowner underestimated the wood-stove use duration. This may be because the homeowners assumed the coals were out and recorded the wood stove as "off," whereas the temperature of the stove may have still been elevated and recorded as "on" by the data logger.

5.3 Energy Consumption

The primary goals of this study were to test a methodology for collecting information on source usage and to test the heating-source-usage algorithm used in the macromodel. Table B-7 summarizes the key input data to the macromodel algorithm, the calculated energy-consumption rate, and the implied life-style factor (see Chapter II). The geometric means (GM) of the calculated energy-consumption rate and the actual energy-consumption rate across all houses were not significantly different at the 95% confidence level. The GM of the implied life-style factor is 0.64, which, possibly fortuitously, agrees very well with the estimate that, on average, people spend 65-70% of their time at their residence (see Chapter I). Because of the relatively mild outdoor temperature, the effect of solar-gain estimates had a very large impact on the calculated (i.e., modeled) energy-consumption rate. In fact, a 12% increase in the estimate of solar gain would cause a 35% decrease in the GM of the calculated energy-consumption rate, from 6270 kJ/h to 4050 kJ, thereby obtaining almost exact agreement between calculated versus actual energy consumption.

The free heat associated with internal sources was assumed to be 3000 kJ/h for these analyses and the macromodel; however, CIRA (Sonderegger *et al.*, 1982; BHKRA, 1984) can estimate the free heat from internal sources using the number of occupants and the number and type of selected appliances. The results from CIRA showed the GM of internal free heat across the nine houses was 3200 kJ/h (geometric 95% confidence interval was 1.2), which is very close to the assumed value.

An alternative way to analyze the data is to look at the daily variations of energy supplied to the house and the daily variations in outdoor temperature. Figures B-1, B-2, and B-3 summarize the daily energy-consumption rate (times appliance efficiency) versus the outdoor temperature. Linear regressions were run on the data set from each house. Table B-8 summarizes r-squares, intercepts, slopes, and 95% confidence intervals for Houses 2, 3, 5, and 9--the only houses that had slopes significantly different from zero. The slope of the regression line corresponds to the $b(UA + qVa)$ term in the macromodel [see Eq. (5) in Chapter II]. The values of $b(UA + qVa)$ for all four houses are within the 95% confidence interval of the slope. Houses 2, 3, 5, and 9 were also the only houses with y-intercepts significantly different from zero and the only houses with r-squares over 0.6. The y-intercept is an estimate of the negative of the total free heat supplied to the house. For Houses 2 and 3, the negative of the estimates for total free heat used in Table

B-7 were within the 95% confidence interval for the y-intercept, but Houses 5 and 9 were just outside the interval. This is not surprising, since the estimates for total free heat are not based on actual measurements.

Overall, the model appears to adequately characterize the space-heating energy supplied to the aggregate of houses. The weaknesses of the model are the large uncertainties associated with house "free" heat and the inability of the model to predict "b," the life-style factor, *a priori*. The model as a whole, cannot be considered "validated" because of the small sample size and the moderate outdoor temperatures; however, the results obtained in this field study are consistent with the model.

5.4 Indoor Air-Pollution Levels

Table B-9 summarizes the indoor and outdoor one-week average air-pollution levels measured in the nine houses. Houses 1, 3, 4, and 5 had elevated indoor CO levels compared with outdoor levels. All of these homes had multiple sources or potential sources of CO; therefore, it was not possible to identify which source(s) was (were) responsible for the elevated CO.

Compared with probable maximum indoor NO_2 levels, Houses 2, 3, 4, 5, 7, 8, and 9 all had elevated NO_2 levels. Of those, Houses 3, 5, 7, and 9 had gas ranges, which could have accounted for the elevated levels. House 4's kerosene heaters probably accounted for the elevated indoor NO_2 level, although the house also contains a wall furnace. Using a reactivity rate of 0.77 h^{-1}, the GM used in the macromodel, and the data on Tables B-4 and B-9, the kerosene-heater NO_2 emission rate was estimated to be 7.9 μg/kJ, which is between the emission-rate values for radiant and convective kerosene heaters (see Chapter III or Appendix A). This agrees with the fact that House 4 used one radiant and one convective heater. The only NO_2 sources in Houses 2 and 8 were forced-air furnaces. Calculations of the source emission rates, again using an NO_2 reactivity of 0.77 h^{-1}, were 1.3 μg/kJ for House 2, and 0.71 μg/kJ for House 8. These imply vent factors of approximately 0.2 and 0.1 for the forced-air furnaces in Houses 2 and 8, respectively. The hypothesis that House 2's furnace did not fully vent was confirmed by a NO_2 passive-monitor reading of 0.042 ppm in the furnace closet and subsequent real-time monitoring.

As expected, all houses had CO_2 levels above those of outdoors. With the exception of House 4, the elevated CO_2 levels were probably primarily due to the house occupants. The relatively high indoor CO_2 level in House 4 was probably due to the usage of the kerosene heaters as well as from the occupants themselves.

6 Summary

The nine-house field-study results were consistent with the macromodel theory. The weaknesses in this approach include the poor characterization of the free heat and lifestyle components of the energy-use theory. The approach of using one-week average concentrations to determine pollutant source strengths and vent factors only worked in houses with one potential source. The lack of an easy method to measure NO_2 reactivity rates reduced the accuracy of the source-strength and vent-factor estimates. Future, large-scale field studies will need to include a real-time monitoring component in, at least, a subset of the houses to match implied source strengths with actual sources and to determine the NO_2 reactivity rate distributions.

7 References for Appendix B

ASTM (1978) Standard specification for kerosene. ASTM-D 3699-78 American Society for Testing and Materials, Philadelphia, PA.

BHKRA (1984) *EEDO: Energy Economics of Design Options*, Burt Hill Koser Rittleman Associates, Butler, PA.

Dietz, R.N. and Cote, E.A. (1982) Air infiltration measurements in a home using a convenient perfluorocarbon tracer technique. *Environ. Intern.* **8**:419-433.

Fisk, W.J. Binenboym, J., Koboli, H., Grimsrud, D.T., Robb, A.W., and Weber, B.J. (1985) "A Multi-Tracer System for Measuring Ventilation Rates and Ventilation Efficiencies in Large Mechanically-Ventilated Buildings," Proceedings of the AIC Conference, Het Meerdal, Netherlands, September 16-19, Air Infiltration Centre, Berkshire, Great Britain; also LBL-20209, Lawrence Berkeley Laboratory, Berkeley, CA.

Palmes, E.D., Gunnison, A.F., DiMattio, J. and Tomczyk, C. (1976) Personal sampler for nitrogen dioxide. *Am. Ind. Hyg. Assoc. J.* **37**:570-577.

Sonderegger, R.C., Garnier, J.Y., and Dixon, J.D. (1982) *Computerized Instrumented Residential Audit:* CIRA, Pub. #425, Lawrence Berkeley Laboratory, Berkeley, CA.

Shelton, J. (1983) *Jay Sheltons Solid Fuels Encyclopedia*, Garden Way Publishing, Charlotte, VT.

Shelton, J. (1985) *Wood Stoves - A Progress Report*, Shelton Research, Santa Fe, NM.

Table B-1. Combustion-pollutant field-study house characteristics.

House	Location[a]	No. of Occupants	Heat[b] Source	Heater Control	Heating[c] Capacity	Cooking[d] Stove	Domestic[e] Hot Water	Gas Dryer	Year Built	Building[f] Type	Insulated	No. of Storeys	Mech.[g] Vent.
					(kJ/h)								
1	Berkeley	4	cW	Manual	18,800	G	In	In	1890s	2x4	Partially	2	N
2	Concord	2	FAF	Thermost.	92,300	E	Out	None	1960s	2x4	Fully	1	RH
3	Albany	1	2*FF	Thermost.	42,000	G	Out	None	1926	2x4	Partially	1.5	N
4	Concord	3	2*K,WF,FP	Manual	76,200	E	In	Out	1954	2x4	Partially	2	KCF,BF
5	Albany	4	2*WF	Thermost.	59,500	G	Out	In	1936	2x4	Partially	1	BF
6	Berkeley	2	W	Manual	17,300	G	Out	Out	1986	2x4	Partially	2	N
7	Berkeley	4	FF	Thermost.	19,200	G	In	In	1910	2x4	None	1	N
8	Orinda	2	FAF	Thermost.	105,000	E	Out	None	1933	Double	Fully	1	RH,BF
9	Berkeley	5	FF	Thermost.	34,000	G	In	Out	1920s	2x4	Partially	2	N

[a]All houses located in California.

[b]Heating source type code: W = airtight wood stove (c = catalytic), FAF = forced-air furnace, FF = floor furnace, K = kerosene, WF = wall furnace, FP = fireplace; * is a multiplier (e.g., 2*FF = two floor furnaces).

[c]Total heat output of all heating sources (if all were on). Based on rated output or rated input and estimated efficiencies for natural-gas furnaces and kerosene heaters and incorporating fuel usage, efficiency, and wood heat content for woodstoves.

[d]Cooking stove type: G = all natural gas, E = all electirc.

[e]All are natural gas: In = inside living space, Out = garage or outside.

[f]All houses but #8 are 2x4 frame. House 8 has a 36-cm double wall type construction.

[g]Mechanical Ventilation: N = none, RH = kitchen range hood, KCF = kitchen ceiling fan, BF = bathroom fan.

Table B-2. Field-study test-house measurement parameters.

PARAMETER	METHOD	NUMBER OF SENSORS	AVERAGING PERIOD
Indoor temperature	Calibrated AD590 sensor	2 to 5	One hour
Outdoor temperature	Calibrated AD590 sensor	1	One hour
Heat source on time	Thermocouple type T	1/source	Min. of use/h
Ventilation or furnace fan on	Power status or current sensor	1/fan	Min. of use/h
Domestic hot water (DHW) use	Temperature of DHW pipes with type-T thermocouples	2	Min. of use/h
Domestic hot water burner on	Temperature of DHW flue Type-T thermocouple	1	Min. on/h
Infiltration method 1	Continuous tracer method Sulfur hexaflouride injection source and samplers	1 source 2 samplers	One week
Infiltration method 2	Continuous tracer method Perfluorocarbon source and passive detectors (Dietz) Max-min thermometers with sources	2 to 4 sources 2 pairs of samplers	One week
Volume and area	Physical measurements Tape measure		
Firewood use	Preweighed firewood		One week
Carbon Monoxide and Carbon Dioxide	Integrating bag samplers IR analyzers at lab	1 to 2 inside 1 outside	One week
Nitrogen Dioxide	NO_2 passive monitors (Palmes tubes)	2 to 4 inside 1 outside	One week

Table B-3. Measured and calculated building energy parameters.

House Number	Exposed[a] Surface Area (m^2)	House[a] Volume (m^3)	U[b] ($kJ/hm^2{}^\circ C$)	Net[b] Solar Gain (kJ/h)
1	399	513	4.39	8670
2	371	292	2.35	1790
3	294	207	4.98	2760
4	368	314	5.56	2420
5	342	232	3.42	2890
6	203	221	3.17	5330
7	415	371	6.38	8670
8	627	539	2.82	8670
9	364	427	5.18	9710

[a]Calculated from house measurements.

[b]Calculated from house plan-data and CIRA (Sonderegger et al., 1982; BHKRA, 1984).

Table B-4. Field study measured appliance usage.

House Number	Heating Source Type[a]	Estimated Heat Output (kJ/h)	Heater Use (h/week)[b]	Average Energy Supplied (kJ/h)[c]	Domestic Hot-Water Burner (h/week)	Gas-Dryer Use (h/week)	Kitchen Ventilation Fan Use (h/week)	Bathroom Ventilation Fan Use (h/week)
1	W	18,800	71.7	8,024	23.7	15.1	NA	NA
2	FAF	92,300	16.6	9,120	20.5	NA	26.1	NA
3	FF	21,000	7.7	959	19.5	NA	NA	NA
	FF	21,000	18.0	2,250				
4	CKH	9,620	38.7	2,216	12.4	NA	1.3	1.0
	RKH	11,700	31.7	2,208				
	WF	22,300	17.9	2,376				
	FP	32,900	8.7	1,704				
5	WF	26,800	0.6	96	18.0	5.2	NA	0.2
	WF	29,700	6.6	1,167				
6	W	17,300	6.1	628	16.1	8.9	NA	NA
7	FF	19,200	11.9	1,360	29.7	5.4	NA	NA
8	FAF	105,000	26.6	16,625	2.7	NA	0.1	4.0
9	FF	34,000	36.8	7,448	23.8	NA	NA	NA

[a]Heating Source Type: W = wood stove, FAF = forced-air furnace, FF = floor furnace, CKH = convective kerosene heater, RKH = radiant kerosene heater, WF = wall furnace, FP = fireplace.

[b]Total heater use for the week's test.

[c]Average energy supplied = heater output * total heater use /168 (h/week).

Table B-5. Comparison of active SF_6 and passive PFT air exchange rate results.

House Number	SF_6 Derived Air-Exchange Rate (h^{-1})	PFT-Derived Air-Exchange Rate (h^{-1})	Average PFT/SF_6 Air-Exchange Rate (h^{-1})	Deviation Between SF_6 PFT Technique (%)
1	0.73	n.m.[a]	0.73	n.a.[b]
2	1.36	1.07	1.21	24.5
3	0.43	0.35	0.39	19.4
4-1[c]	0.50	0.48	0.49	3.7
4-2	0.63	0.61	0.62	2.7
5	0.84	0.71	0.78	16.9
6	1.13	1.00	1.07	11.8
7	0.85	0.76	0.80	11.7
8	0.47	0.41	0.44	12.7
9	1.23	0.84	1.04	37.5

Average				15.7

[a]Not measured.

[b]Not applicable.

[c]Data from House 4 (week 1) were not used elsewhere.

Table B-6. Comparison of diary and datalogger usage information.

House Number	Heater[a] Type	Heat Source (min) Diary	Heat Source (min) Datalogger	Gas Dryer (min) Diary	Gas Dryer (min) Datalogger	Kitchen Ventilation (min) Diary	Kitchen Ventilation (min) Datalogger	Bathroom Ventilation (min) Diary	Bathroom Ventilation (min) Datalogger
1	W	3030	4400	876	905				
2						290+[b]	1568		
3	FF	1129	1169						
4	RKH	1785	1882	5	78	20	59		
	CKH	2380	2335						
	WF	1185	1083						
5				330	311			10	10
6	W	265	408	108+[b]	532				
7				211	325				
8						8	7	176	239
9									

[a]Heater type code: W = wood stove, FF = floor furnace, RKH = radiant kerosene heater, CKH = convective kerosene heater, WF = wall furnace.

[b]A "+" indicates that some events were not fully documented in the diary.

Table B-7. Summary of calculated and actual energy consumption.

House Number	Solar[a] Gain (kJ/h)	Total[b] Free Heat (kJ/h)	UA[a] (kJ/h°C)	qVA (kJ/h°C)	Inside/Outside Temperature Difference(°C)	Calculated Energy Consumpt. times Efficiency (kJ/h)	Actual Energy Consumpt. times Efficiency (kJ/h)	Implied[c] Life-style "b" Factor (unitless)
1	8700	11700	1750	455	8.3	6630	8020	1.21
2	1800	4800	870	428	10.4	8710	9120	1.05
3	2800	5800	1460	98	7.6	6100	3210	0.53
4	2400	5400	2050	236	9.1	15350	8500	0.55
5	2900	5900	1170	218	9.6	7430	1260	0.17
6	5300	8300	640	286	9.7	670	630	0.94
7	8700	11700	2650	360	5.6	5190	1360	0.26
8	8700	11700	1640	289	11.1	9790	16630	1.70
9	9700	12700	1880	535	9.8	11000	7450	0.68
GM	4720	8090	1450	292	8.9	6270	4010	0.64
G95%CI[d]	1.7	1.4	1.4	1.5	1.2	2.0	2.4	1.8

[a]Calculated using CIRA (Sonderegger, et al., 1982; BHKRA, 1984).

[b]Assuming 3000 kJ/h from internal sources.

[c]Calculated using Eq. 5 in Chapter II.

[d]Geometric 95% confidence interval.

Table B-8. Summary data from individual house regressions with slopes significantly different from zero.[a]

House Number	r-Square	y-Int. (kJ/h)	y-Int. 95% Conf. Interval (kJ/h)	Negative[b] Total Free Heat (kJ/h)	Slope (kJ/h^{o}C)	Slope 95% Conf. Interval (kJ/h^{o}C)	b(UA + qVa)[b] (kJ/h^{o}C)
2	0.81	-6210	-9190 to -3220	-4800	1460	660 to 2270	1360
3	0.63	-3810	-7110 to -500	-5800	940	120 to 1760	830
5	0.69	-3800	-5250 to -2350	-5900	520	120 to 920	240
9	0.69	-19500	-23900 to -15000	-12700	2830	660 to 5000	1550

[a]The y-axis was daily average heat supplied to house, and x-axis was indoor temperature difference.

[b]See Table B-7.

Table B-9. Field-study week-average pollutant concentrations.

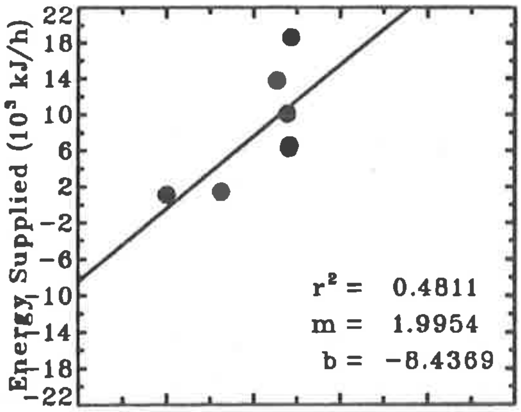
House Number	CO (ppm)[a] Indoor	CO (ppm)[a] Outside	NO_2 (ppm)[b] Indoor	NO_2 (ppm)[b] Outside	Max. Indoor Background NO_2 (ppm)[c]	CO_2 (ppm)[a] Indoor	CO_2 (ppm)[a] Outside
1	1.9	1.4	0.027	0.034	0.027	495	400
2[d]	1.4	1.5	0.026	0.025	0.021	608	395
3	2.8	1.4	0.040	0.036	0.024	760	405
4	1.8	0.9	0.049	0.017	0.013	1265	309
5	1.4	1.0	0.031	0.026	0.021	853	415
6	1.5	1.4	0.023	0.026	0.022	540	385
7	1.1	1.0	0.039	0.027	0.022	660	395
8	0.5	0.6	0.015	0.015	0.010	703	390
9	0.8	0.7	0.036	0.017	0.014	603	380

[a] One-week integrated samples collected in air-sample bags and analyzed with infrared analysis.

[b] Samples collected with Palmes tubes (Palmes et al., 1976).

[c] Theoretical maximum indoor NO_2 concentration if no NO_2 source existed in the house calculated using an NO_2 reactivity rate of 0.2 h^{-1} over two GSDs from the GM used in the macromodel.

[d] The one-week integrated NO_2 concentration measured in the furnace closet of this house was 0.042 ppm.



HOUSE 01

HOUSE VOLUME: 515 m^3

INNER SURFACE AREA: 399 m^2

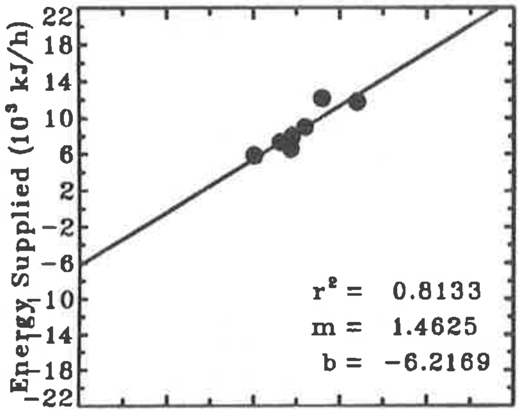
OVERALL U-VALUE: 4.3 kJ/hm^{2}degC

MEAN AIR-EXCHANGE RATE: 0.7 h^{-1}

ESTIMATED NET SOLAR GAIN: 8.6 MJ/h

SOURCE TYPE: Wood Stove

TEMPERATURE CONTROL: Manual



HOUSE 02

HOUSE VOLUME: 291 m^3

INNER SURFACE AREA: 371 m^2

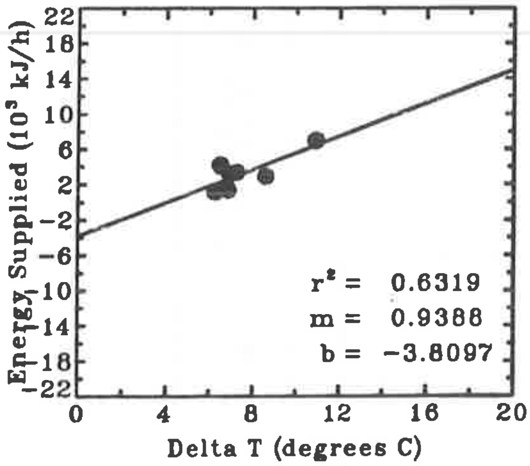
OVERALL U-VALUE: 2.3 kJ/hm^{2}degC

MEAN AIR-EXCHANGE RATE: 1.2 h^{-1}

ESTIMATED NET SOLAR GAIN: 1.8 MJ/h

SOURCE TYPE: FAF

TEMPERATURE CONTROL: Thermostat



HOUSE 03

HOUSE VOLUME: 207 m^3

INNER SURFACE AREA: 294 m^2

OVERALL U-VALUE: 4.9 kJ/hm^{2}degC

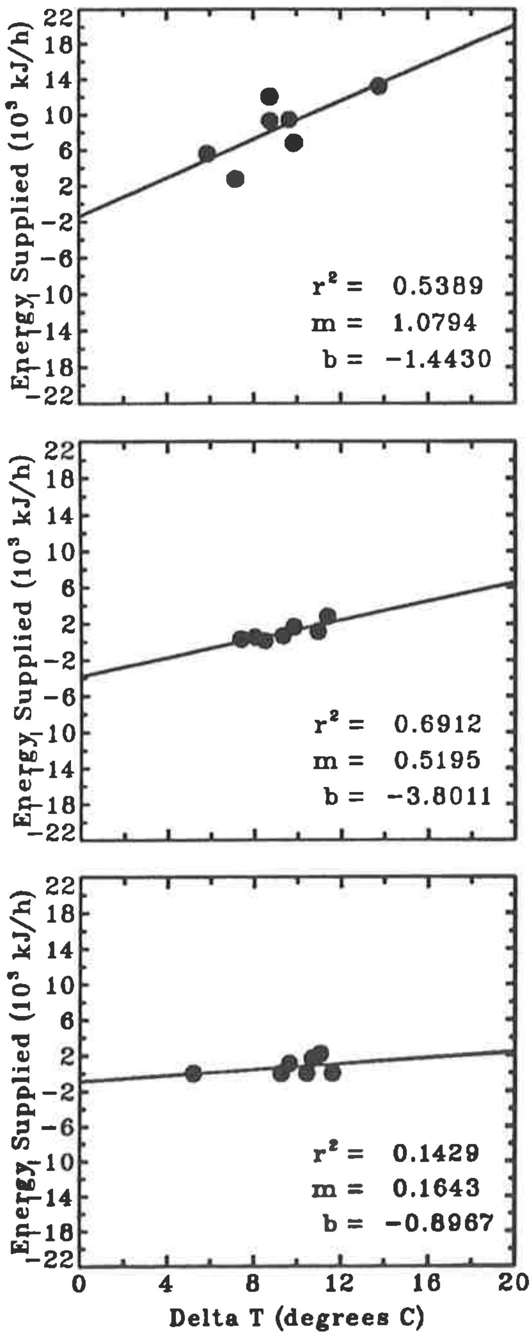
MEAN AIR-EXCHANGE RATE: 0.3 h^{-1}

ESTIMATED NET SOLAR GAIN: 2.8 MJ/h

SOURCE TYPE: Floor Furnace

TEMPERATURE CONTROL: Thermostat

Figure B-1. Field-study energy-use data. Average daily indoor minus outdoor temperature difference vs. average daily heating energy supplied for Houses 1, 2, and 3.



HOUSE 04

HOUSE VOLUME: 314 m^3

INNER SURFACE AREA: 368 m^2

OVERALL U-VALUE: 5.5 kJ/hm^2degC

MEAN AIR-EXCHANGE RATE: 0.6 h^{-1}

ESTIMATED NET SOLAR GAIN: 2.4 MJ/h

SOURCE TYPE: Two Kerosene Heaters

TEMPERATURE CONTROL: Manual

HOUSE 05

HOUSE VOLUME: 232 m^3

INNER SURFACE AREA: 342 m^2

OVERALL U-VALUE: 3.4 kJ/hm^2degC

MEAN AIR-EXCHANGE RATE: 0.7 h^{-1}

ESTIMATED NET SOLAR GAIN: 2.9 MJ/h

SOURCE TYPE: Wall Furnace

TEMPERATURE CONTROL: Thermostat

HOUSE 06

HOUSE VOLUME: 232 m^3

INNER SURFACE AREA: 203 m^2

OVERALL U-VALUE: 3.1 kJ/hm^2degC

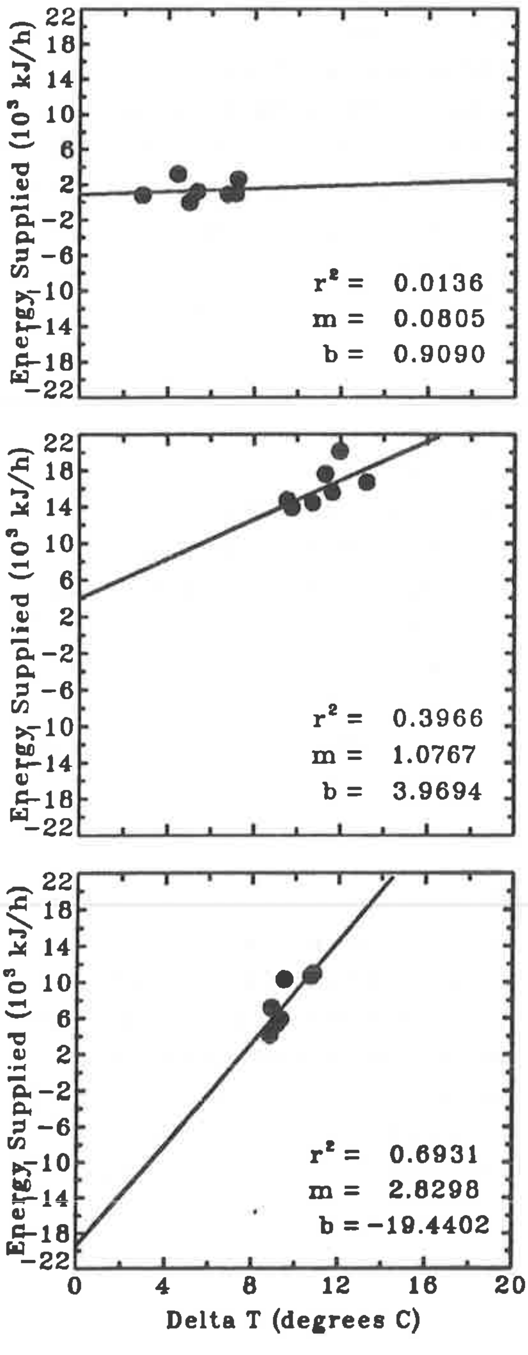
MEAN AIR-EXCHANGE RATE: 1.1 h^{-1}

ESTIMATED NET SOLAR GAIN: 5.4 MJ/h

SOURCE TYPE: Wood Stove

TEMPERATURE CONTROL: Manual

Figure B-2. Field-study energy-use data. Average daily indoor minus outdoor temperature difference vs. average daily heating energy supplied for Houses 4, 5, and 6.



HOUSE 07

HOUSE VOLUME: 371 m^3

INNER SURFACE AREA: 415 m^2

OVERALL U-VALUE: 6.3 kJ/hm^{2}degC

MEAN AIR-EXCHANGE RATE: 0.8 h^{-1}

ESTIMATED NET SOLAR GAIN: 8.7 MJ/h

SOURCE TYPE: Floor Furnace

TEMPERATURE CONTROL: Thermostat

HOUSE 08

HOUSE VOLUME: 581 m^3

INNER SURFACE AREA: 627 m^2

OVERALL U-VALUE: 2.6 kJ/hm^{2}degC

MEAN AIR-EXCHANGE RATE: 0.4 h^{-1}

ESTIMATED NET SOLAR GAIN: 8.7 MJ/h

SOURCE TYPE: FAF

TEMPERATURE CONTROL: Thermostat

HOUSE 09

HOUSE VOLUME: 427 m^3

INNER SURFACE AREA: 364 m^2

OVERALL U-VALUE: 5.1 kJ/hm^{2}degC

MEAN AIR-EXCHANGE RATE: 1.0 h^{-1}

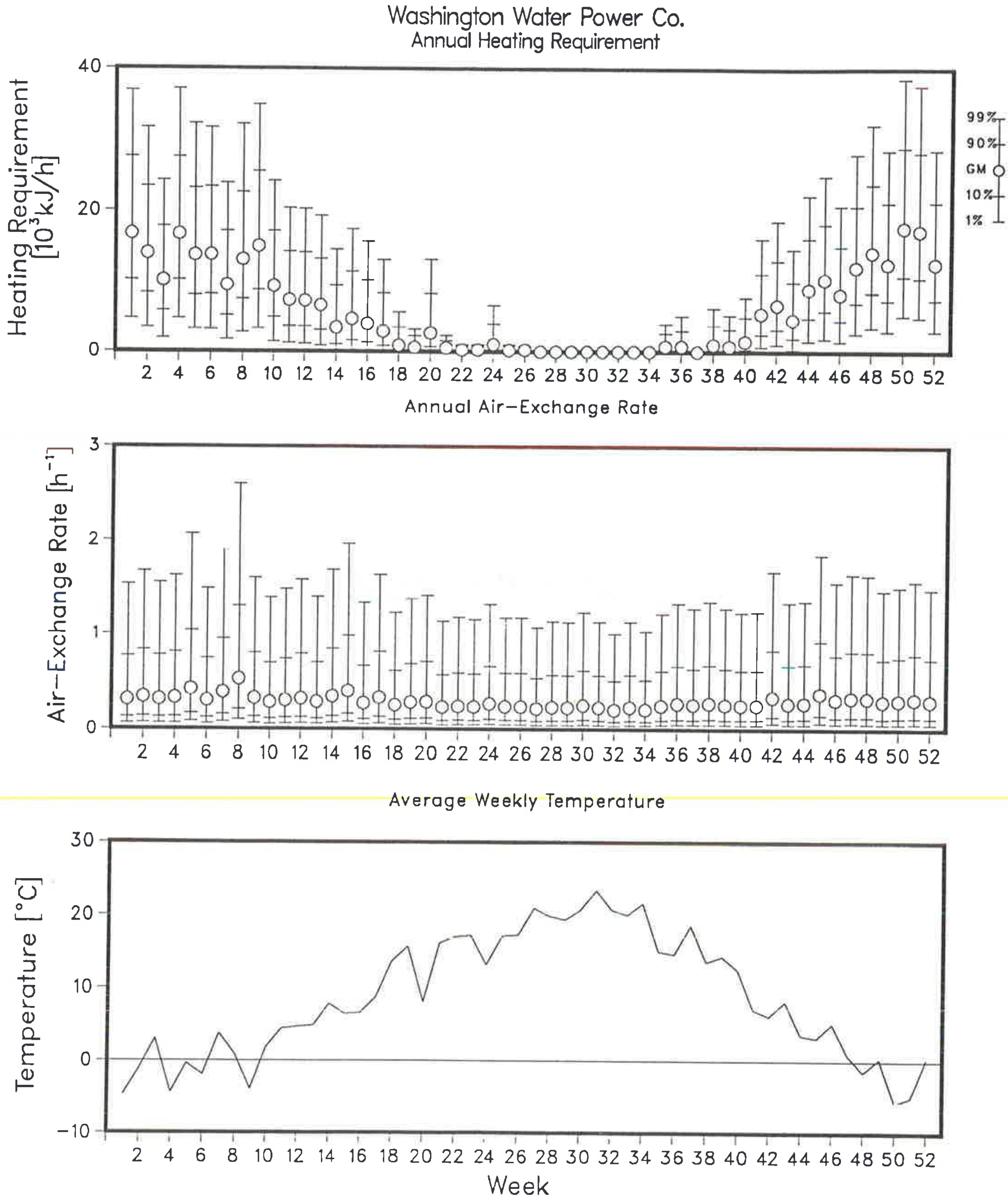
ESTIMATED NET SOLAR GAIN: 9.7 MJ/h

SOURCE TYPE: Floor Furnace

TEMPERATURE CONTROL: Thermostat

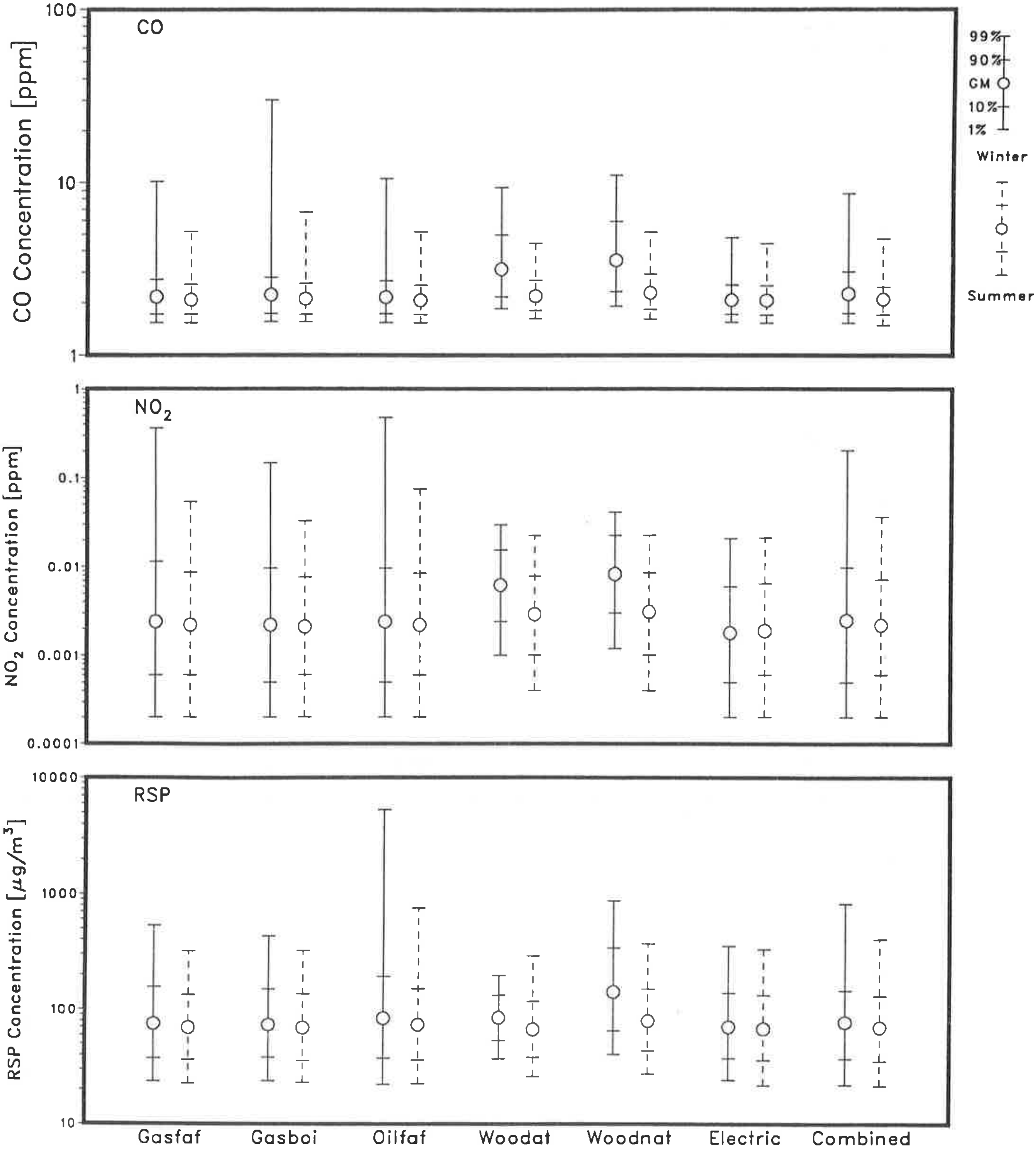
Figure B-3. Field-study energy-use data. Average daily indoor minus outdoor temperature difference vs. average heating energy supplied for Houses 7, 8, and 9.

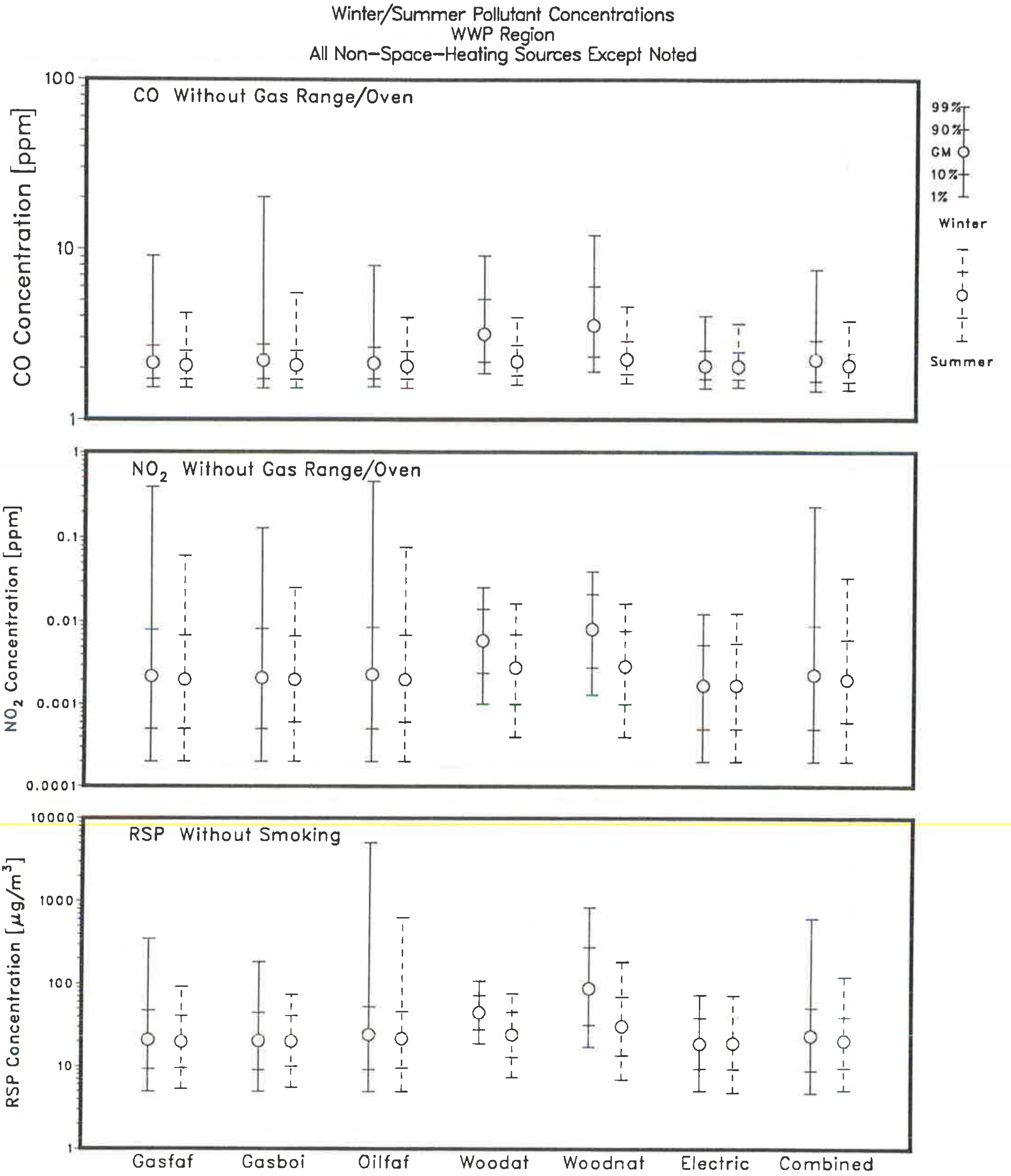
APPENDIX C: SELECTED GRAPHIC OUTPUT OF PRELIMINARY MODEL PREDICTIONS



Washington Water Power Co.
Annual Heating Requirement
Heating Requirement [10³kJ/h]
99%
90%
GM
10%
1%
Annual Air–Exchange Rate
Air–Exchange Rate [h⁻¹]
Average Weekly Temperature
Temperature [°C]
Week

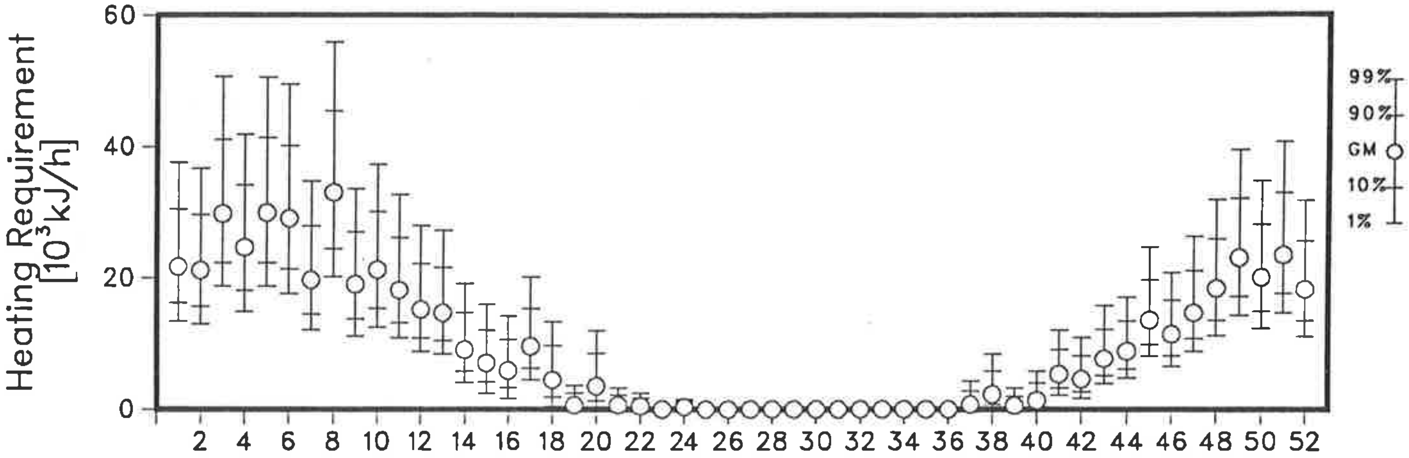
Winter/Summer Pollutant Concentrations
WWP Region
All Non-Space-Heating Sources



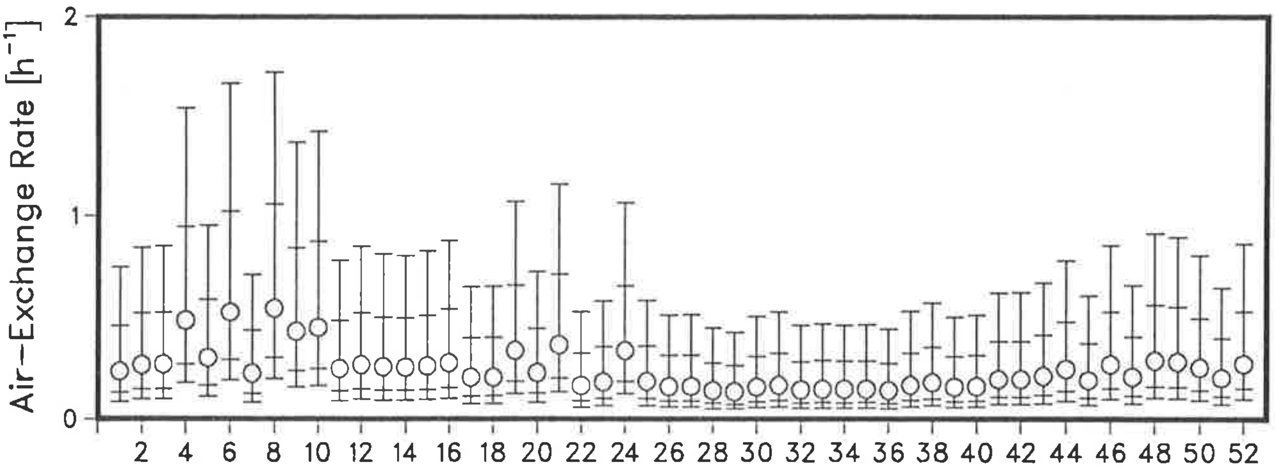

Winter/Summer Pollutant Concentrations
WWP Region
All Non-Space-Heating Sources Except Noted
CO Without Gas Range/Oven
CO Concentration [ppm]
100
10
1
99%
90%
GM
10%
1%
Winter
Summer
NO2 Without Gas Range/Oven
NO2 Concentration [ppm]
1
0.1
0.01
0.001
0.0001
RSP Without Smoking
RSP Concentration [μg/m3]
10000
1000
100
10
1
Gasfaf
Gasboi
Oilfaf
Woodat
Woodnat
Electric
Combined

Rochester Gas and Electric Co.

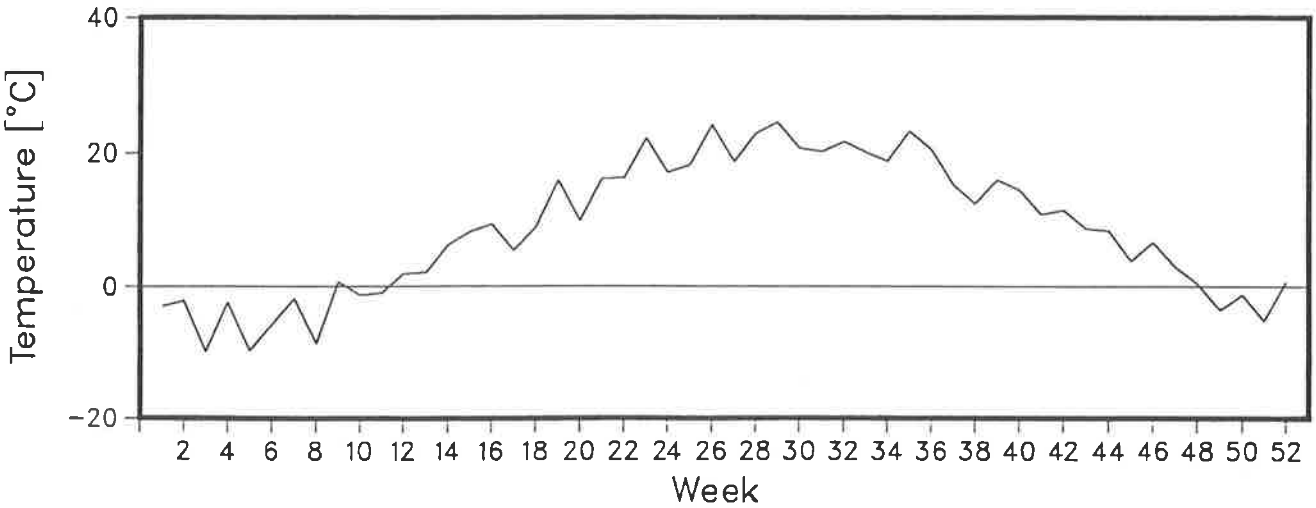
Annual Heating Requirement

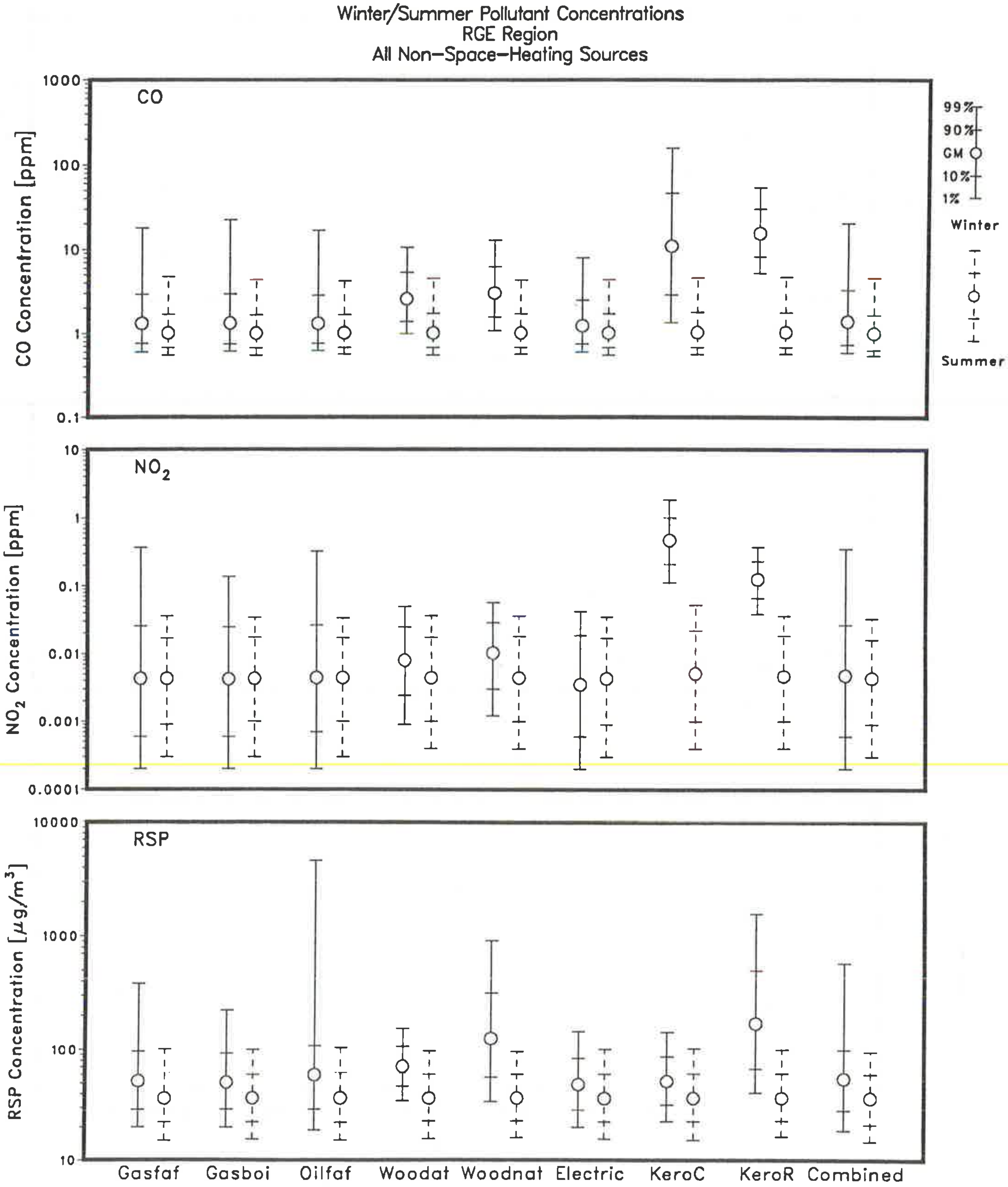


Annual Air–Exchange Rate



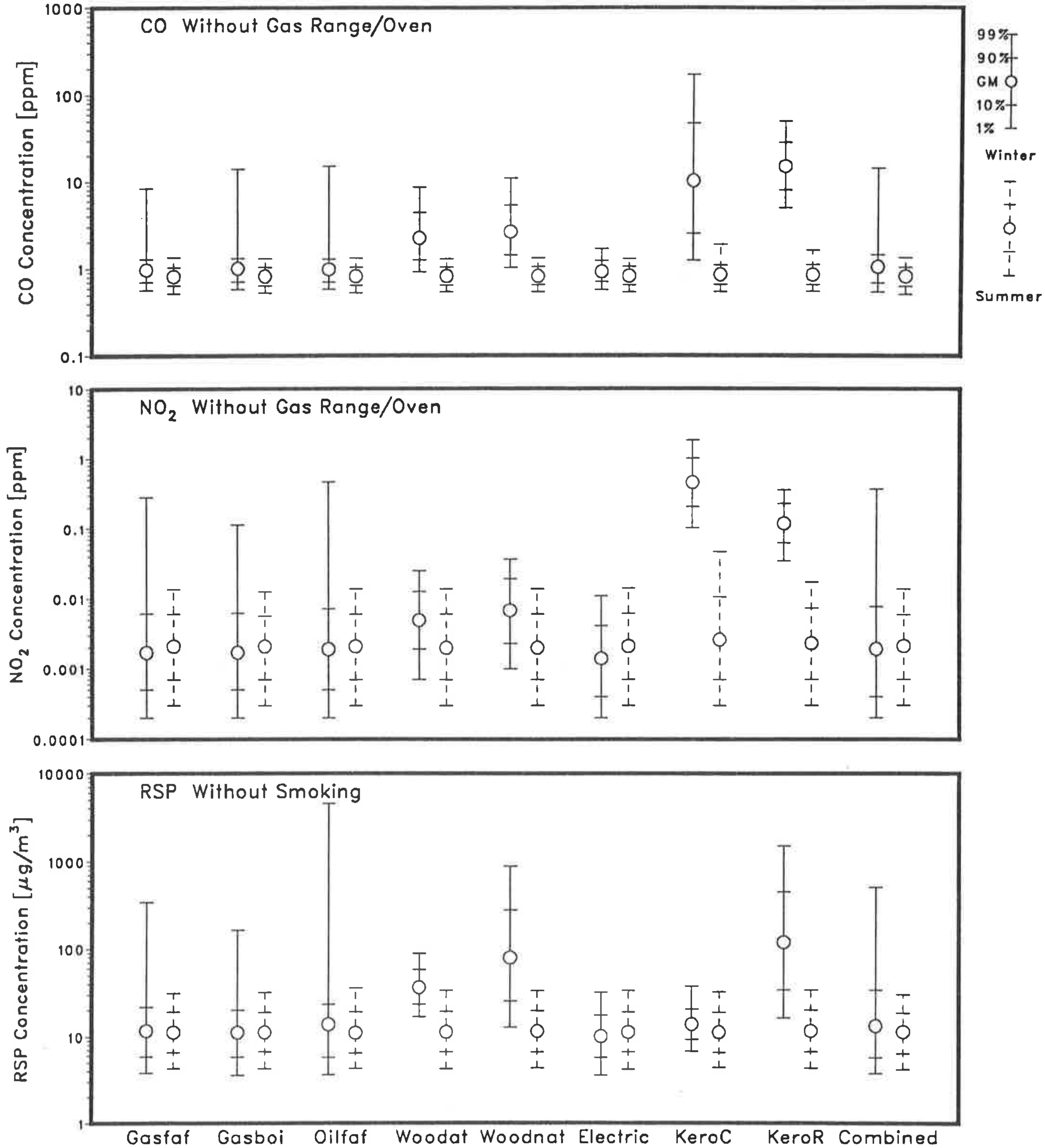
Average Weekly Temperature



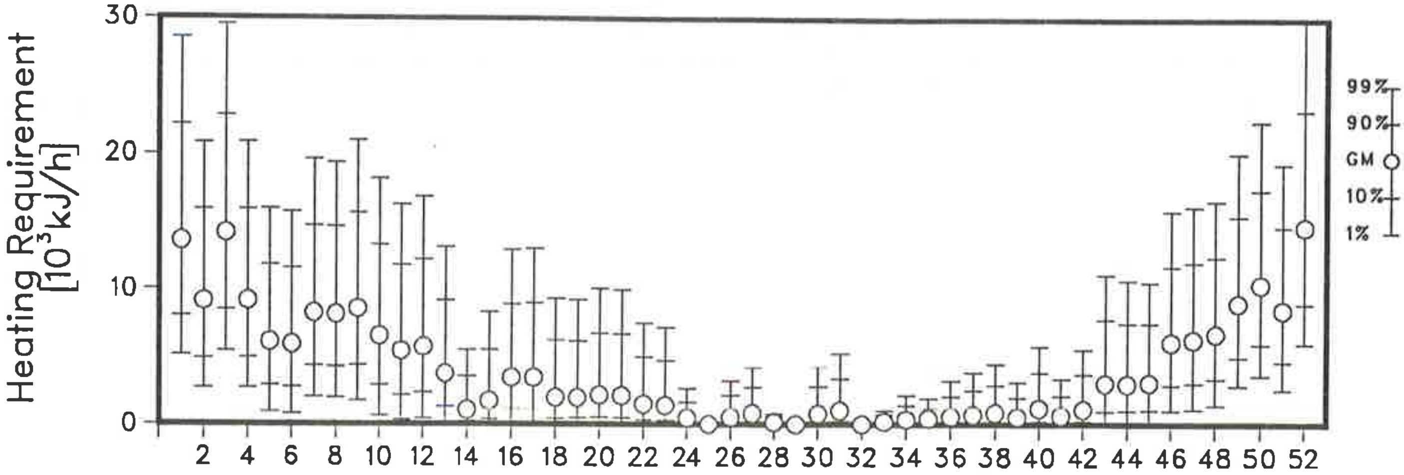


Winter/Summer Pollutant Concentrations
RGE Region
All Non-Space-Heating Sources
CO
CO Concentration [ppm]
1000
100
10
1
0.1
99%
90%
GM
10%
1%
Winter
Summer
NO2
NO2 Concentration [ppm]
10
1
0.1
0.01
0.001
0.0001
RSP
RSP Concentration [μg/m3]
10000
1000
100
10
Gasfaf
Gasboi
Oilfaf
Woodat
Woodnat
Electric
KeroC
KeroR
Combined

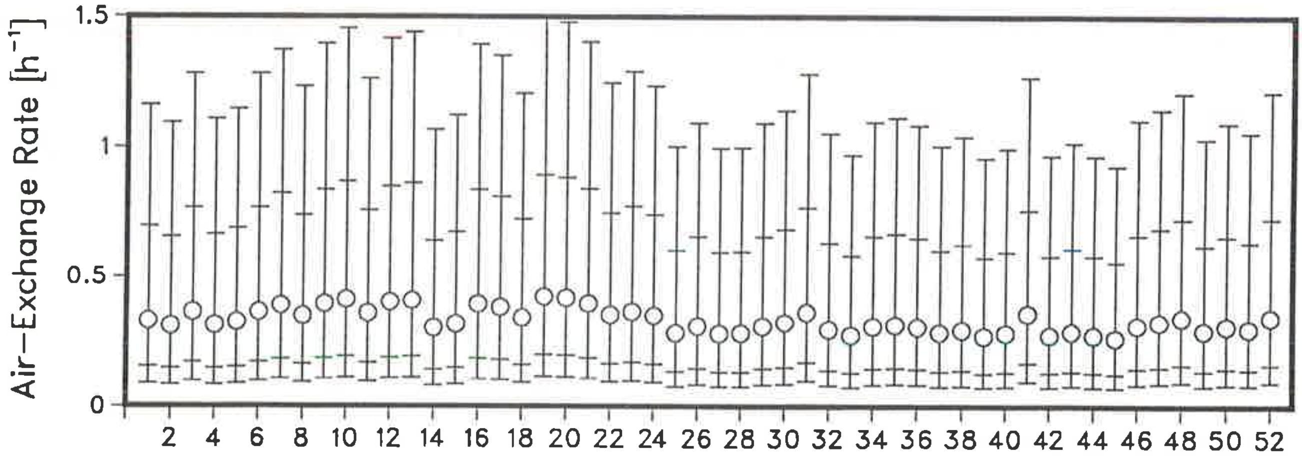
Winter/Summer Pollutant Concentrations
RGE Region
All Non-Space-Heating Sources Except Noted



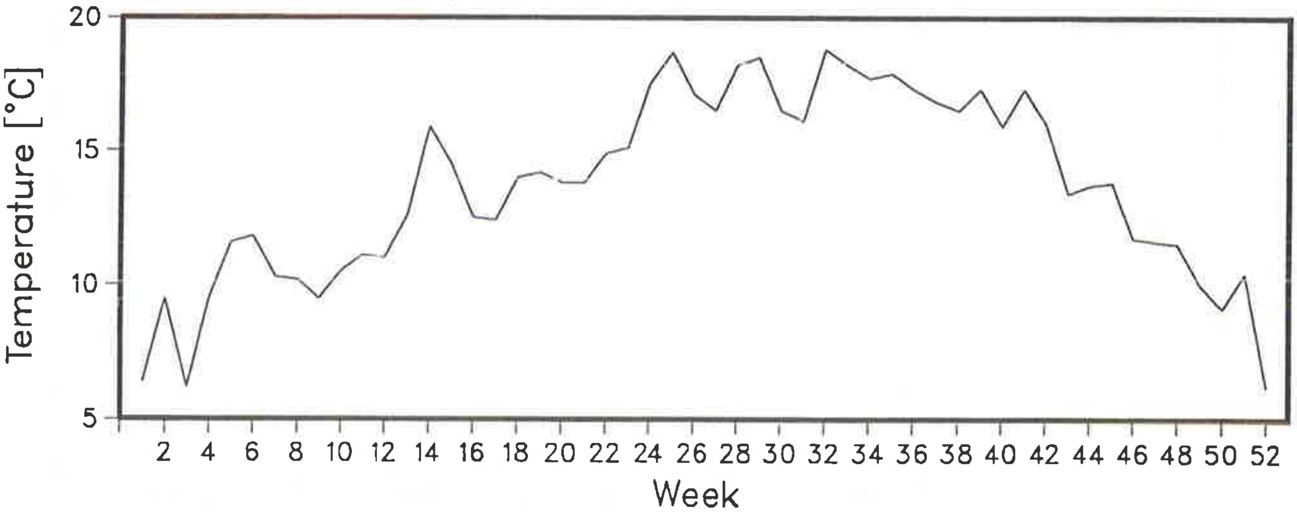
Pacific Gas & Electric Co.
Annual Heating Requirement



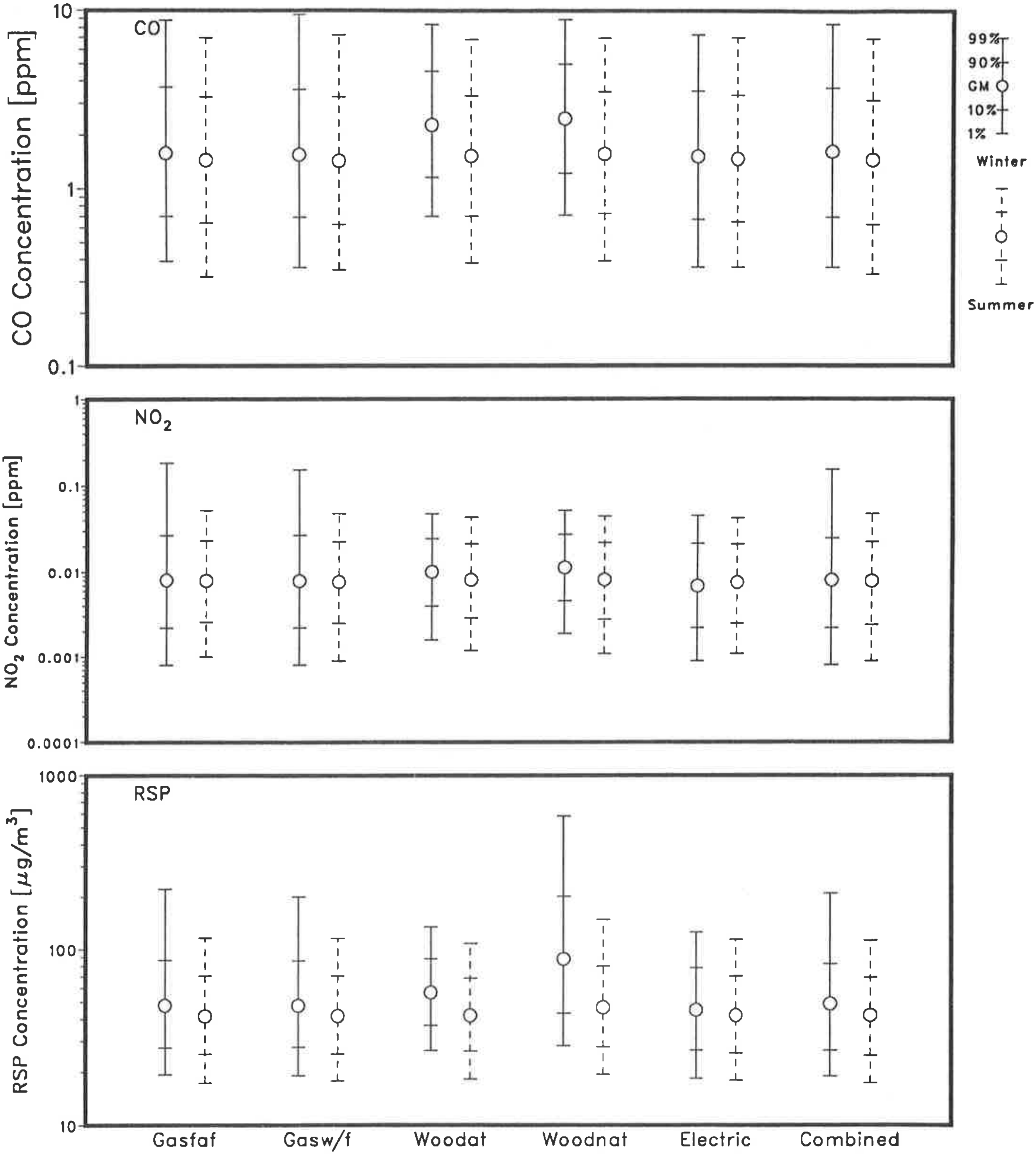
Annual Air–Exchange Rate

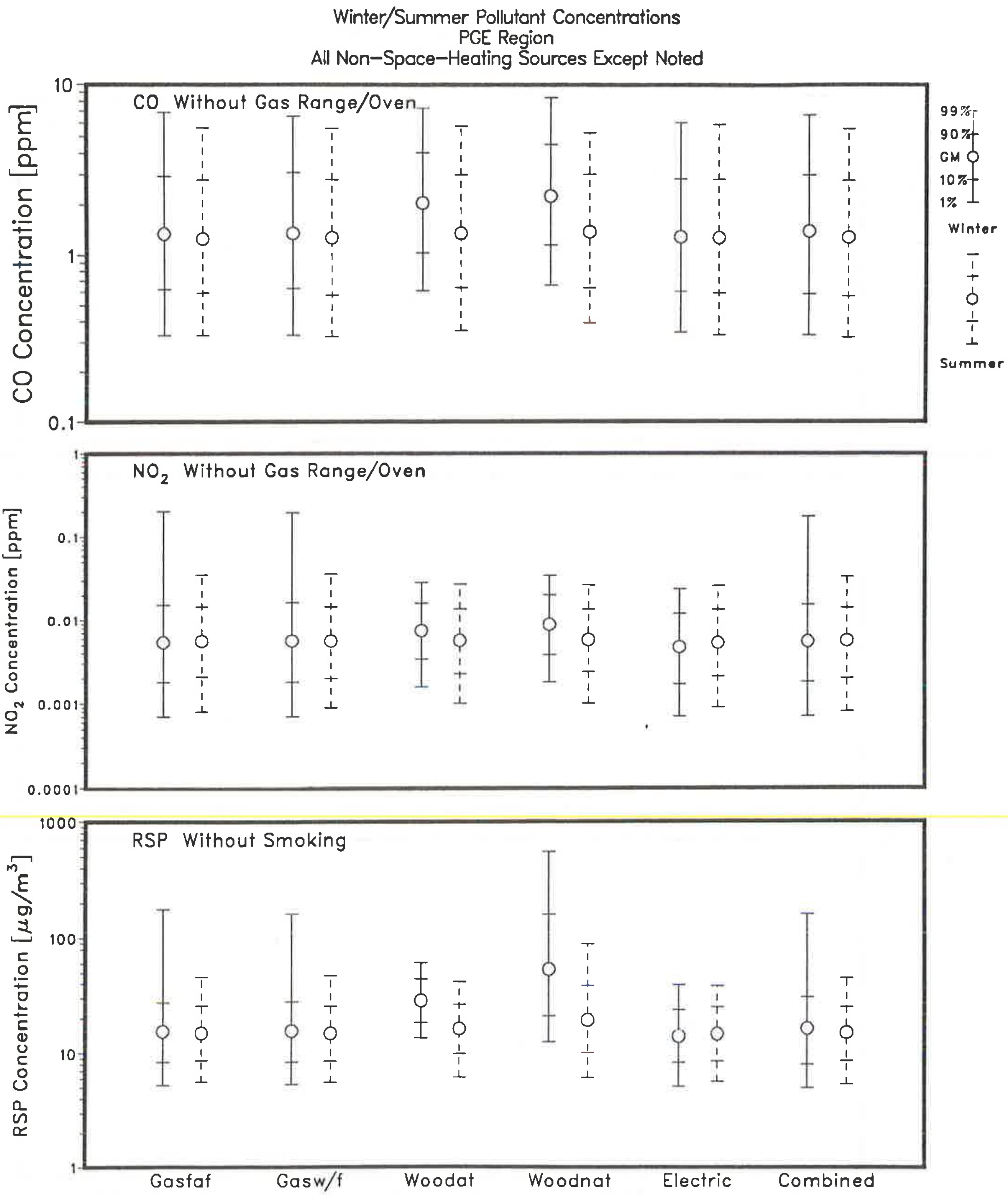


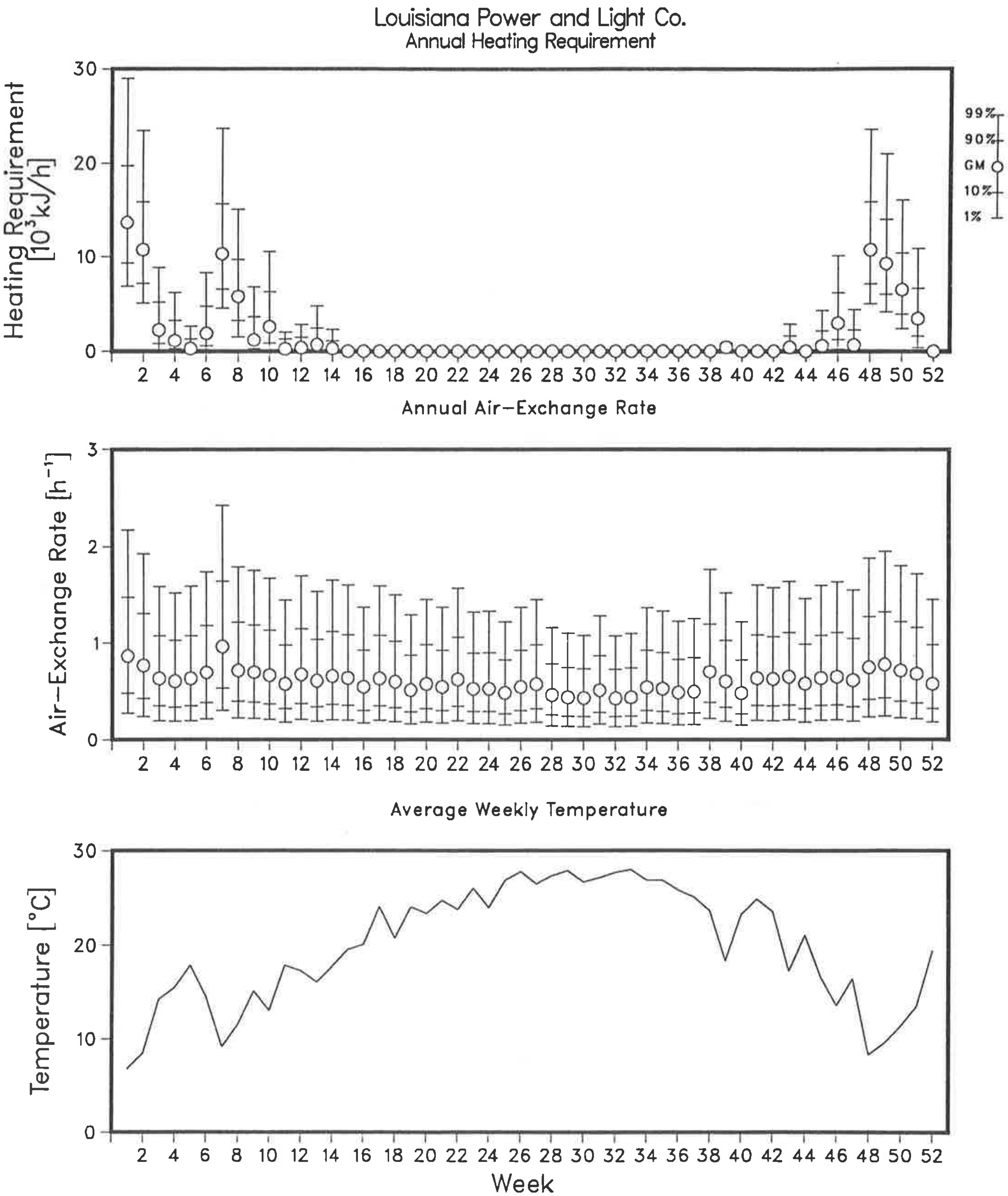
Average Weekly Temperature



Winter/Summer Pollutant Concentrations
P.G. & E. Region
All Non–Space–Heating Sources

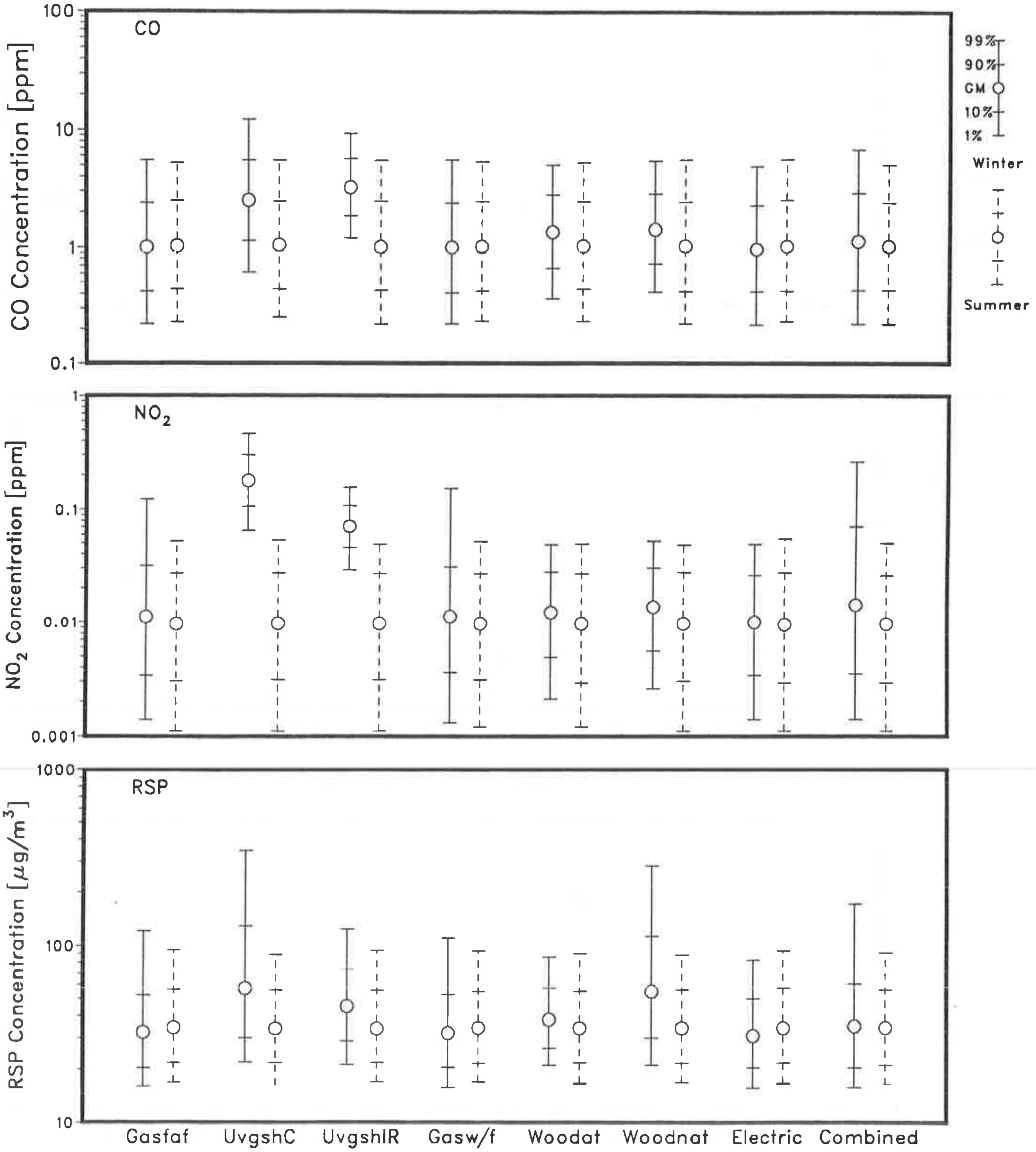



Winter/Summer Pollutant Concentrations
PGE Region
All Non-Space-Heating Sources Except Noted
CO Without Gas Range/Oven
CO Concentration [ppm]
10
1
0.1
99%
90%
GM
10%
1%
Winter
Summer
NO2 Without Gas Range/Oven
NO2 Concentration [ppm]
1
0.1
0.01
0.001
0.0001
RSP Without Smoking
RSP Concentration [μg/m3]
1000
100
10
1
Gasfaf
Gasw/f
Woodat
Woodnat
Electric
Combined



Louisiana Power and Light Co.
Annual Heating Requirement
Heating Requirement [10³kJ/h]
99%
90%
GM
10%
1%
Annual Air-Exchange Rate
Air-Exchange Rate [h⁻¹]
Average Weekly Temperature
Temperature [°C]
Week

Winter/Summer Pollutant Concentrations
LPL Region
All Non-Space-Heating Sources



Winter/Summer Pollutant Concentrations
LPL Region
All Non-Space-Heating Sources Except Noted