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SYSTEMATIC DEVELOPMENT OF SURVEY INSTRUMENTS FOR INDOOR AIR QUALITY STUDIES

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For Presentation at the 78th Annual Meeting of the
Air Pollution Control Association
Detroit, Michigan June 16-21, 1985

Introduction

Continuing advances in instrumentation have made it possible to better characterize personal exposures to pollutants as well as temporal and spatial variations in indoor air quality. Improvements have been made in the portability and sensitivity of monitoring devices for pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), respirable particulates (RSP), formaldehyde (HCHO), and radon.[1,2] New methods for measuring related parameters such as air exchange rates have also been developed.[3]

A similar level of attention needs to be devoted to survey instruments or questionnaires that address related parameters such as characteristics of homes or appliances, appliance use and ventilation practices, and population activity patterns. If properly developed, such instruments can provide substantial information to explain variations in measured indoor pollutant levels or personal exposures. In addition, these instruments can help extend study results by classifying unmonitored populations according to exposure potential.

It is difficult to strike a balance between comprehensive questionnaires that may overburden the respondents and shorter questionnaires that may miss vital information. The purpose of this paper is to describe a framework and methodology for developing and evaluating survey instruments associated with indoor air quality studies. The framework considered in this paper addresses the following questions:

- What factors need to be addressed?
- How can the factors be classified to assist in the systematic development of survey instruments?
- If the information required from each study participant is substantial, how can this information be obtained in a stepwise fashion without burdening the participant?
- How can the efficacy of questions and survey instruments be judged?

The actual formulation of specific questionnaire items is not addressed but sample applications of the framework, drawn from two of our recent studies, are presented.

Framework for Specifying General Factors of Importance

The quality of indoor air is influenced by indoor generation of pollutants, the rate of air exchange between indoor and outdoor air, outdoor pollutant concentrations, pollutant decay or removal indoors, and mixing and recirculation of indoor air. Changes over time in the indoor concentrations of a pollutant can be expressed mathematically in terms of a mass-balance equation:

$$\frac{dC_{in}}{dt} = (1-F_B)\nu C_{out} + \frac{S}{cV} - m\nu C_{in} - \frac{\lambda}{cV} - \frac{qFC_{in}}{cV}$$

where

C_{in} is the indoor concentration of the pollutant

F_B is the filtration or penetration factor for the building envelope

m is the mixing factor or the ratio of the actual residence time for a pollutant over the residence time under well-mixed conditions

ν is the rate of air exchange with the outdoors; ν is composed of air exchange due to infiltration, natural ventilation, and mechanical ventilation

C_{out} is the outdoor concentration of the pollutant

S is the indoor generation rate for that pollutant

V is the indoor volume

c is the coefficient for the indoor volume so that cV is the effective volume that is available for the contaminant to disperse

λ is the rate of chemical or physical decay of the pollutant independent of exfiltration or removal by cleaning devices

q is the flow rate through a cleaning device, if it exists

F is the fraction removed by the cleaning device.

The above equation has been solved for different pollutants and for different conditions.[4]

Each parameter of the mass balance equation can be dependent on a variety of other factors. For example, the rate of air exchange is influenced by the infiltration of outdoor air, by natural ventilation practices, such as opening windows, and by mechanical ventilation, such as with an exhaust fan. Thus, factors such as structural characteristics, weather, appliances in the home, and occupant activities have a role in determining the prevailing air exchange rate at any point in time which in turn influences indoor air quality. Similarly, these and other factors, such as the type of furnishings and type of indoor sources, affect indoor air quality through other mass balance parameters. The specific factors of importance and the manner in which they exert an influence can vary from pollutant to pollutant, but the mass balance equation serves as a basic point of reference for considering these factors. In the process of developing questionnaires to characterize these factors, a researcher often considers this general framework, whether knowingly or not.

In the case of personal-exposure monitoring, additional considerations need to be included because an individual may be located in a number of different environments during the course of his/her daily activities. Such environments could be indoors, which could be in a very complex structure, outdoors, or in a vehicle. In this case, both the pattern of human activities and the characteristics of each environment need to be considered.

Classification of Factors

One important type of classification is determining whether the factors are static or dynamic. Static factors are those characteristics that typically do not change over time or that change infrequently, such as the structural properties of a building or the types of appliances that it contains. In contrast, dynamic factors, such as occupant habits or practices, typically vary over time. The static and dynamic distinction is important in the development of questionnaires because these two classes of factors require different methods of characterization.

Information Collection Strategies

In any monitoring effort, opportunities to characterize factors typically arise at three stages:

- Premonitoring--the period during which participants of a monitoring study are solicited and enrolled
- Monitoring--the period during which air quality measurements are taken
- Postmonitoring--the period that immediately follows the completion of air quality measurements.

Defining the three stages is important because it affects (1) whether characterization of static factors requires participant assistance or only the observations of a field technician, (2) whether general practices or specific practices over a defined timeframe need to be characterized, and (3) whether information concerning practices can be determined prospectively or retrospectively.

These methods of distinguishing information to be collected are considered in Table I. A number of important points are raised in the table:

- Some characterization of static factors can be obtained from participants in advance of monitoring through personal or telephone interviews or by self-administered questionnaires, but participants can be relieved of some of this burden if technicians observe certain characteristics and obtain supplemental information from participants either during or after the monitoring.

- Participants can provide a limited description of general practices in advance of monitoring, but actual practices that can influence monitoring results need to be characterized on a real-time or short-term-recall basis; this information is generally recorded by participants using activity logs; some of the participant's burden for this activity can be relieved if technicians periodically pose supplemental questions during or after monitoring.

- After monitoring has been completed, it is also possible to obtain clarifying or supplemental information from participants concerning static or dynamic factors for which periodic, short-term recall was not a practical approach.

Generally, it would be easier to obtain information on static factors than on dynamic factors at the premonitoring stage. On the other hand, supplemental information obtained at the postmonitoring stage would usually be more valuable for dynamic factors than for static factors.

Evaluation of Efficacy

The efficacy of survey instruments can be assessed from three perspectives:

1. How much of a time burden is placed on the respondents for reporting or recording the desired information?

2. How accurate and complete is the reported and recorded information?

3. How does the information help interpret the monitoring results?

To the extent practical, the respondent burden associated with survey instruments should be minimized. In extreme cases, excessive reporting requirements could result in low participation rates or high attrition rates. Some questions, however desirable, may be beyond some respondents' ability to provide accurate or complete information. To assess accuracy, quality-control or consistency checks can be made in different ways for static versus dynamic factors. For example, for some static factors, the technician's observations during the monitoring period can be compared with the participant's descriptions that were obtained before monitoring. For some dynamic factors, it is possible to use an automated sensing device to complement or check a participant's records of real-time practices. A pilot test will help to point out specific questions or recording devices with which respondents are having difficulty.

The contribution of specific information items to the interpretation of monitoring results can be assessed in a number of ways; one method for which objective criteria can be formulated is regression analysis. This method is generally applicable to cross-sectional monitoring studies because the dependent variable, pollutant concentration, is measured on an interval scale and the independent variables constructed from survey instruments are typically a combination of interval and categorical scales. Various criteria can be used to assess the contribution of a specific variable, such as the extent of increase in explained variance or the level of significance of a regression coefficient.

Sample Applications from Two Studies and Discussion

Two GEOMET studies have been chosen to illustrate some of the principles and methods outlined in this paper. This first is a personal monitoring study that was completed in 1983 and the second is an indoor air quality survey for which monitoring is currently in progress. These studies show (1) some of the differences in approach for personal exposure versus indoor air quality monitoring and (2) application of the principles and methods involved in questionnaire development and evaluation.

CO Exposure Study. During the fall of 1982, GEOMET conducted a pilot study of personal exposures to CO among three population subgroups--housewives, office workers, and construction workers.[5] The general objectives of the study were to compare exposure estimates for the three groups, to determine the contribution of exposures in specific environment types to total exposures, and to assess the feasibility of asking participants to record selected activities and to take readings from CO exposure monitors.

The major factors characterized during this study are listed in Table II according to the same classification scheme used in Table I. During premonitoring, a screening questionnaire was administered when the participant was recruited, which required about 10 minutes to complete. During the monitoring stage, dynamic factors were emphasized. The extent of real-time recording by participants was kept to a minimum so that a compact, straightforward activity card (Figure 1) could be used; about 5 minutes per sampling day were required for participants to record their activities. Supplemental questions were asked by technicians on a 24-hour recall basis when they serviced the exposure monitors. These questions, which took 2-3 minutes per sampling day to ask, focused on combustion activities that could influence indoor exposures and on traffic-density levels that could affect exposures during travel. Answers to the supplemental questions were recorded by checking boxes 1 through 8 in the last column on the activity card (Figure 1).

The contribution of different components of the survey (screening questionnaire, activity card, and supplemental questions) to the interpretation of monitoring results was assessed using stepwise regression methods available with SPSS/PC.[6] Only variables that increased the adjusted R^2 value for the regression equation and that were not excessively correlated with variables selected on previous steps were chosen by the stepwise method.

The first component of personal exposures examined in this way was exposure during travel, based on a total of 544 trips taken by study participants. Four variables from the screening questionnaire explained 9 percent of the variance ($R^2 = 0.09$) in traveling exposure. When variables from the activity card were added to the set of candidate predictors, 13 percent of the variance was explained. Two variables from the activity card were selected and the four original screening variables were also retained. With the addition of variables based on supplemental questions, 16 percent of the variance was explained. Three variables based on supplemental questions were chosen along with the four screening variables and two activity-card variables selected at the second stage of analysis. Thus, each stage of information collection contributed to the interpretation even though the total explained variance was low. Further details from respondents such as specific routes of travel might have helped to further explain variations in traveling exposures, but this type of information was considered excessive in view of the pilot nature of the study.

Another component of personal exposures that was examined was residential exposure, based on 439 occasions during which subjects were in their residences. Seven variables from the screening questionnaire explained 16 percent of the variance in residential exposure. Only two candidate predictors could be developed from the activity card; at the second stage of analysis, both of these variables and the seven previous variables were selected and 19 percent of the variance was explained. With the addition of variables based on supplemental questions, the explained variance was increased to 31 percent. A total of 12 variables were retained as predictors, three of which were based on supplemental questions. Moreover, all three supplemental variables were among the five most important predictors of residential exposures, based on t-statistics reflecting the ratio of each regression coefficient to its standard error.

Thus, the supplemental questions made a larger contribution to the interpretation of residential than traveling exposure. These supplemental questions concerned whether or not specific types of combustion sources were used while the subjects were in their residences. It is likely that additional information, such as details of combustion-source operation and ventilation practices, would have further increased the percentage of variance that was explained. It was concluded that the amount of information sought from participants during the study was not excessive and could have been more extensive without jeopardizing participation rates.

Texas Indoor Air Quality Survey. We are currently conducting a field study of indoor air quality in approximately 150 homes in north-central Texas, many of which have unvented gas appliances for heating and/or cooking.[7] The principal objectives of the study are to determine the concentration ranges of CO and NO_2 in these homes and to determine the usage patterns of unvented appliances. Because this study focuses on indoor air quality rather than personal exposures, the mass balance equation was used extensively as a reference point for formulating questions to characterize both dynamic and static factors.

A critical mass balance parameter for this study is the indoor generation rate of pollutants, which depends on both appliance characteristics and occupant usage patterns; thus, both static and dynamic factors require treatment to adequately characterize this component of the mass balance equation (Table III). The premonitoring stage of the study includes a brief canvassing questionnaire that is administered when the participant is recruited and a screening questionnaire that is administered by telephone to those who have agreed to participate. The canvassing questionnaire addresses only static factors whereas the screening questionnaire addresses both types of factors. During monitoring, technicians record detailed characteristics of combustion appliances and activity log forms are used by the participants to record real-time usage patterns for the unvented appliances. For a limited number of factors, technicians ask participants for information about the appliances.

For most survey items in the study, respondents were able to provide complete and accurate information. One exception was questions concerning age of the house and of specific unvented combustion appliances. Respondents who had lived in their homes for a long time generally knew all needed information, but those who rented or had bought their home recently often did not. There were some inaccuracies or omissions on the canvassing questionnaire concerning heating and cooking appliances, but more accurate information concerning these characteristics was obtained at later stages of the study.

The respondent's reporting burden for the study generally was 5 minutes or less for canvassing, 15 minutes or less for screening, and 15 minutes or less for completing activity logs and answering supplemental questions from technicians. Thus, the overall reporting burden was approximately 30 minutes per home.

The data base of measurement results and questionnaire responses was only partially complete at the writing of this paper. To illustrate the evaluation of questionnaire efficacy, a complete set of data was assembled for 35 houses that participated during the first several weeks of the study. The contribution of different components of the survey (canvassing questionnaire, screening questionnaire, technician questionnaire, and activity log) to the interpretation of monitoring results was assessed in four stages of regression analysis. For the first stage, only variables from the canvassing questionnaires were used. For stages 2 to 4, variables were successively added from the screening questionnaires, technician questionnaires, and logs of actual appliance use.

The analysis was applied independently to two pollutants--nitrogen dioxide (NO_2) and carbon monoxide (CO); the results are summarized in Table IV. The limited set of information from the canvassing questionnaire explained approximately 25 percent of the variation in measured NO_2 and CO concentrations across the 35 houses. With the addition of variables from the screening questionnaire, the percentage of explained variance increased substantially for NO_2 and somewhat for CO. The majority of explanatory variables that were chosen for the ultimate equation by the stepwise method were from the screening questionnaire. The higher explanatory power for NO_2 (73 percent) than for CO (37 percent) is probably due to the fact that NO_2 concentrations were measured over a 4- to 5-day period whereas CO concentrations were measured over a 14- to 18-hour period. Thus, the CO concentrations should be more heavily influenced by short-term variations in appliance use.

When variables from the technician questionnaire were added, the explained variance increased somewhat for NO_2 (from 73 to 87 percent) and substantially for CO (from 37 to 71 percent). For both pollutants, the largest contribution to the explained variance came from the screening questionnaire and the smallest contribution was from the canvassing questionnaire. The addition of variables based on activity logs did not improve the explained variance for NO_2 but did raise the percentage to 80 percent of CO. In general, the variables from activity logs replaced variables from the technician questionnaire whereas the number of screening variables retained was the same as for the previous stage of analysis.

At the final stage of analysis, there were four predictors for NO_2 and seven predictors for CO for which regression coefficients were significant at the 0.01 level. Two of these predictors were common to both pollutants--the usual extent of gas range use (screening questionnaire) and the average heat setting of unvented gas space heaters during the respective pollutant sampling periods (activity log). Other significant predictors for NO_2 were the number of unvented gas space heaters with pilot lights in use (screening questionnaire) and the number of unvented gas space heaters in poor or fair condition (technician questionnaire). For CO, other predictors included the number of dinner meals usually cooked per week with the gas range (screening questionnaire) and the proximity of the house to a major roadway (technician questionnaire).

The above exércise leads to several conclusions:

- The higher explained variance for CO in the Texas indoor air quality study than in the study of personal exposures is probably due to two factors:
  - Closer adherence in the Texas study to the framework for questionnaire development outlined in this paper
  - The fact that the Texas study focused on residential exposures and monitored the indoor environment exclusively whereas the study of personal exposures monitored the indoor environment only when subjects were in their residences

- The quantitation of general practices of appliance use from the screening questionnaire contributed substantially to the interpretation of monitoring results, particularly for NO_2

- Variables from the technician questionnaire and the activity logs competed in explaining variance, suggesting that one or both of these components could be simplified and thereby reduce time requirements for participants and/or technicians. Of course, this simplification will be useful only if the monitoring results are time-integrated concentration averages; if real-time concentration data are collected, activity-log information is still likely to be valuable.

These conclusions must be considered tentative until the entire data base from the study has been analyzed. The analytical results will be used to weigh the relative contributions of specific questionnaires against the respondent burden and to assess the relative importance of specific questionnaire items.

Concluding Remarks

A framework for the systematic development of survey instruments is outlined in this paper. It was shown through two sample studies that this framework is useful for (1) categorizing factors that can be quantified with survey instruments and (2) judging the relative efficacy of different types of questionnaires and specific questionnaire items. Thus, the framework can be used as a basis for the construction, evaluation, and discussion of indoor air quality survey instruments. The use of similar approaches by other investigators will enable the research community to make comparisons across studies.

Acknowledgment

This work has been supported by the Electric Power Research Institute (EPRI) under RP 2159-1 and RP 2373-1 and the Gas Research Institute (GRI) under Contract No. 5083-251-0941. Encouragement provided by Dr. Irwin Billick, GRI, and Dr. Cary Young, EPRI, is sincerely appreciated.

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Table I. Methods of characterizing factors, classified according to nature of factor and stage of monitoring

Stage of monitoring for characterizing factors	Nature of factor requiring characterization	
	Static	Dynamic
Premonitoring	Description by participants of general characteristics of structure and contents	Description by participants of general habits or practices
Monitoring	Observations by technicians or questions from technicians to participants concerning more detailed characteristics of structure and contents	Recording by participants of actual practices on a real-time or short-term-recall basis
Postmonitoring	Clarification from participants concerning previously obtained information or provision of limited supplemental information	Supplemental information concerning participants' real-time records asked by field technicians on a short-term-recall basis

Table II. Factors characterized in a study of personal exposures to CO, classified according to nature of factor and stage of monitoring.

Stage of monitoring	Nature of factor	
	Static	Dynamic
Premonitoring	Screening Questionnaire: 1. Age/sex of participant 2. Size of household 3. Type/age of residence 4. Types of combustion appliances in residence 5. Type of garage at residence or workplace 6. Principal means of transportation to major activities outside the home (housewives) or to work	Screening Questionnaire: 1. Days/hours usually at work 2. Typical commuting distance and time 3. Usual extent of tobacco smoking encountered at home, at work, and during travel 4. Major activities away from home; associated travel time and extent of tobacco smoking
Monitoring	None	Activity card--recording by participants: 1. Environment type 2. Presence of tobacco smoke 3. Time of change in environment type 4. Accumulated CO exposure at time of environment change
Postmonitoring	None	Activity card--supplemental questions asked by technicians: 1. Use of unvented combustion appliances 2. Traffic level encountered during travel 3. Use of public parking garage during travel 4. Extent of tobacco smoking encountered

Table III. Pollutant generation factors characterized in an indoor air quality study, classified according to nature of factor and stage of monitoring.

Stage of monitoring	Nature of factor: Static	Dynamic
Premonitoring	Canvassing Questionnaire: 1. Heating and cooking facilities Screening Questionnaire: 1. Verification of heating/cooking facilities 2. Age of unvented gas combustion appliances 3. Ignition methods for unvented gas combustion appliances	Screening Questionnaire: 1. Usual frequency of daytime/nighttime use of unvented gas space heaters (UVGSHs) 2. Usual frequency of using multiple UVGSHs 3. Usual frequency of gas range use for breakfast/lunch/dinner 4. Usual extent of gas range use for supplemental heat 5. Usual extent of tobacco smoking
Monitoring	Technician Questionnaire: 1. Manufacturer/model Δ for gas range and each UVGSH 2. Btu rating for each UVGSH 3. Verification of ignition methods 4. Flame characteristics (each UVGSH) 5. Time last serviced (each UVGSH) 6. General condition/appearance of gas range, each UVGSH 7. Type of appliance for hot water, clothes drying	Activity Log: 1. Times on/off for each UVGSH 2. Heat setting (low, medium, high) 3. Times on/off for gas range
Postmonitoring	None	Technician Questionnaire: 1. Tobacco smokers in the residence during the monitoring period and usual quantity smoked

Table IV. Contributions of survey components to the interpretation of indoor air quality measurements for the Texas field study.

Component(s) used	Pollutant: NO_2	Pollutant: CO
1. Canvassing questionnaire	Variance explained = 25% Canvassing variables--3[a]	Variance explained = 23% Canvassing variables--3
2. Canvassing questionnaire + screening questionnaire	Variance explained = 73% Canvassing variables--2 Screening variables--6	Variance explained = 37% Canvassing variables--1 Screening variables--4
3. Canvassing questionnaire + screening questionnaire + technican questionnaire	Variance explained = 87% Canvassing variables--1 Screening variables--6 Technician variables--3	Variance explained = 71% Canvassing variables--2 Screening variables--5 Technician variables--4
4. Canvassing questionnaire + screening questionnaire + technican questionnaire + activity logs	Variance explained = 83% Canvassing variables--1 Screening variables--6 Technician variables--1 Activity log variables--2	Variance explained = 80% Canvassing variables--1 Screening variables--5 Technician variables--1 Activity log variables--2

[a]Number of variables selected on the basis of stepwise regression analysis.

Monitoring Period Number: __ __ Station Number: __ __ Date: __ __ Month __ __ Day __ __ Year

Subject Type: ☐ HW ☐ CW ☐ OW Subject Number: __ __ Study Day Number: __

Time (Circle a.m. or p.m.)	Digital Readout	General Location (Check one)			Tobacco Smoking	General or Specific Geographic Area	Office Use Only
__ __ : __ __ a.m. / p.m.	_ _ _ _ _	☐ In Residence ☐ Outdoors	☐ At Workplace ☐ Traveling	☐ In Other Building __________	☐ Yes ☐ No	__________ __________	1 2 3 4 5 6 7 8
__ __ : __ __ a.m. / p.m.	_ _ _ _ _	☐ In Residence ☐ Outdoors	☐ At Workplace ☐ Traveling	☐ In Other Building __________	☐ Yes ☐ No	__________ __________	1 2 3 4 5 6 7 8
__ __ : __ __ a.m. / p.m.	_ _ _ _ _	☐ In Residence ☐ Outdoors	☐ At Workplace ☐ Traveling	☐ In Other Building __________	☐ Yes ☐ No	__________ __________	1 2 3 4 5 6 7 8
__ __ : __ __ a.m. / p.m.	_ _ _ _ _	☐ In Residence ☐ Outdoors	☐ At Workplace ☐ Traveling	☐ In Other Building __________	☐ Yes ☐ No	__________ __________	1 2 3 4 5 6 7 8
__ __ : __ __ a.m. / p.m.	_ _ _ _ _	☐ In Residence ☐ Outdoors	☐ At Workplace ☐ Traveling	☐ In Other Building __________	☐ Yes ☐ No	__________ __________	1 2 3 4 5 6 7 8

Figure 1. Activity card used to record dynamic factors during monitoring of personal exposures to CO.