TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	
1.0 INTRODUCTION AND BACKGROUND	
1.1 Objectives	1-1
1.2 General Background	1-2
1.3 Brief Review of Available Data	1-5
1.4 References	1-8
2.0 SURVEY DESIGN AND PROTOCOL	
2.1 Selection of Pollutants and Other Measurement Parameters	2-1
2.2 Determination of Sample Size	2-5
2.3 Measurement Instrumentation, Configuration, and Testing	2-13
2.4 Selection of Flights to be Monitored	2-26
2.5 Monitoring Protocol	2-41
2.6 Pretest Protocol and Results	2-57
2.7 References	2-67
3.0 DATA COLLECTION AND PROCESSING	
3.1 Types of Information Collected	3-1
3.2 Data Processing Procedures	3-10
4.0 MONITORING RESULTS	
4.1 Characteristics of Monitored Flights	4-1
4.2 Environmental Measurements	4-18
4.3 Quality Control Samples	4-49
5.0 SYNTHESIS AND DISCUSSION	
5.1 Synthesis of Monitoring Results	5-1
5.2 Further Analysis of Monitoring Results	5-11
5.3 References	5-29
6.0 GENERAL APPROACH TO RISK ASSESSMENT	
6.1 Pollutants and Health Effects of Interest	6-2
6.2 Populations of Interest and Frequency of Flying	6-3
6.3 References	
7.0 RISK ASSESSMENT FOR ENVIRONMENTAL TOBACCO SMOKE	
7.1 Review of Health Effects	7-1
7.2 Quantitative Estimation of Cancer Risk	7-5
7.3 Quantitative Estimation of Acute Respiratory Effects	7-32
7.4 Estimation of Cardiovascular Effects	7-36
7.5 Effects of ETS on Special Populations	7-37
7.6 References	7-38

TABLE 0F CONTENTS
(Continued)

Page

8.0 RISK ASSESSMENT FOR OTHER CONTAMINANTS
- 8.1 Bioaerosols 8-1
- 8.2 Cosmic Radiation 8-15
- 8.3 Ozone 8-28
- 8.4 References 8-31

9.0 MITIGATION
- 9.1 General Framework for Assessing Mitigation Options 9-1
- 9.2 Application of Framework to ETS Contaminants 9-3
- 9.3 Application of Framework to Pollutants 9-30
- 9.4 References 9-33

10.0 CONCLUSIONS AND RECOMMENDATIONS
- 10.1 Conclusions 10-1
- 10.2 Recommendations 10-8

APPENDIX A -- Explanation and Sensitivity Analysis of the Modified Armitage and Doll Model (LesLife)

APPENDIX B -- Incremental Risks of Premature Lung Cancer Death Among Nonsmokers from Exposure to Respirable Suspended Particulate, Ascribable to Environmental Tobacco Smoke on Smoking Flights

LIST OF TABLES

		Page
2-1	Pollutants and Other Parameters Measured in the Airliner	2-2
2-2	Percent Error in Estimating an Average Concentration by Sample Size and Coefficient of variation	2-8
2-3	Error in Estimating the Proportion of Flights with Measured Concentrations Above a Stated Level, by Sample Size and Estimated Proportion	2-11
2-4	Measurement Parameters and Methods	2-14
2-5	Results of Tests Comparing RSP Measurement with Gravimetric Method, Piezobalance, and Minirams	2-24
2-6	Airports of Departure Chosen for Domestic Flights	2-32
2-7	Frequency Distribution by Flight Duration for Domestic Smoking Flights and International Flights Departing from U.S. Airports	2-33
Z-8	U.S. Airports of Departure/Arrival Chosen for International Flights and Associated International Destinations	2-35
2-9	Distribution of Flights to be Monitored for the First Six Flight Chains Developed for the Study	2-37
2-10	Illustrative Chain Involving International Flights	2-38
2-11	Illustrative Chain Involving Nonsmoking Flights	2-40
2-12	Distribution of Flights to be Monitored for the Last Four Flight Chains Developed for the Study	2-42
2-13	Summary of Measurement Locations for Each Parameter	2-46
2-14	Summary of the Operational Protocol for Air Quality Monitoring on a Flight	2-51
2-15	Summary of Quality Control Procedures Implemented During the Monitoring Program	2-56
2-16	Nicotine Concentrations Measured at Eight Locations on Four Pretest Flights	2-61
2-17	RSP Concentrations Measured at Eight Locations on Four Pretest Flights	2-62

LIST OF TABLES
(Continued)

Page

4-8 Smoking Passengers, Smoking Quantity, and Smoking Rates for Flights That Were Monitored 4-15

4-9 Estimated Smoking Rates for Different Smoking Durations and Departure Times 4-19

4-10 Nominal Cabin Volumes, Extents of Air Recirculation, and Air Exchange Rates for Different Types of Aircraft 4-20

4-11 Nominal and Measured Air Exchange Rates by Aircraft Type 4-22

4-12 Measured Air Exchange Rates for Smoking and Nonsmoking Flights Involving Selected Aircraft with Recirculation 4-24

4-13 Summary of Temperature, Relative Humidity and Pressure Measurements 4-24

4-14 Measured Nicotine Concentrations for Smoking and Nonsmoking Flights 4-27

4-15 Measured RSP (Gravimetric) Concentrations for Smoking and Nonsmoking Flights 4-30

4-16 Measured Average RSP (Optical) Concentrations for Smoking and Nonsmoking Flights 4-34

4-17 Measured Peak RSP (Optical) Concentrations for Smoking and Nonsmoking Flights 4-37

4-18 Ratio of Peak-to-Average RSP (Optical) Concentrations for Smoking and Nonsmoking Flights During Period when Smoking Was Allowed 4-38

4-19 Measured Average CO Concentrations for Smoking and Nonsmoking Flights 4-40

4-20 Measured Peak CO Concentrations for Smoking and Nonsmoking Flights 4-42

4-21 Ratio of Peak-to-Average CO Concentrations for Smoking and Nonsmoking During Period when Smoking Was Allowed 4-43

LIST OF TABLES
(Continued)

Page

4-22 Levels of ETS Contaminants Measured on Domestic Smoking and International Flights 4-45

4-23 Measured C02 Concentrations for Smoking and Nonsmoking Flights 4-46

4-24 Measured Bacteria Concentrations for Smoking and Nonsmoking Flights 4-48

4-25 Measured Fungi Concentrations for Smoking and Nonsmoking Flights 4-50

4-26 Percent of Flights on which Different Types of Bacteria were Detected 4-51

4-27 Percent of Flights on Which Different Types of Fungi were Detected 4-52

4-28 Measured Ozone Concentrations for Smoking and Nonsmoking Flights 4-53

4-29 Measurement Precision for Selected Parameters 4-54

5-1 Average Values on Smoking and Nonsmoking Flights for Parameters Related to ETS Contaminants 5-2

5-2 Comparison of Respirable Particle Measurements by Two Different Methods on Domestic Smoking Flights, International Flights, and Domestic Nonsmoking Flights 5-3

5-3 Results of Statistical Tests of ETS Levels on Smoking Versus Nonsmoking Flights 5-8

5-4 Results of Statistical Tests of ETS Levels in Different Sections on Smoking Flights 5-9

5-5 Average Values on Smoking and Nonsmoking Flights for Parameters Related to Pollutants 5-10

5-6 RSP Measurement Results Obtained by Two Different Methods on Five Nonsmoking Flights with Northwest Airlines as the Carrier 5-16

L I ST OF TABLES
(Continued)

Page

5-7 Relationship of Nicotine Measurement Results for Domestic Smoking Flights to Selected Factors 5-20

5-8 Relationship of Gravimetric RSP Measurement Results for Domestic Smoking Flights to Selected Factors 5-22

5-9 Relationship of Optical RSP Measurement Results During the Smoking Period on Domestic Smoking Flights to Selected Factors 5-23

5-10 Relationship of CO Measurement Results During the Smoking Period on Domestic Smoking Flights to Selected Factors 5-24

5-11 Relationship of ETS Measurements in the Boundary Section to Technician Distance from Smoking Section 5-25

5-I2 Relationship of C02 Measurement Results for All Smoking Flights to Selected Factors 5-28

5-13 Relationship of Bacteria Measurement Results for All Smoking Flights to Selected Factors 5-30

5-14 Relationship of Fungi Measurement Results for All Smoking Flights to Selected Factors 5-31

6-1 Average Number of Hours Flown by Members of the Association of Flight Attendants (AFA). Figures Represent Combined Domestic and International Flights 6-6

7-1 RSP Values (ug/m3) Used in the Risk Calculations 7-9

7-2 Proportion of Time Spent in Different Sections of Cabin 7-12

7-3 Calculation of Exposure for Domestic Flights (ug/person/flight hour) 7-13

7-4 Calculation of Exposure for International Flights (ug/person/flight hour) 7-14

7-5 Comparison of Cancer Risk Assessment Models ETS Exposure 7-17

7-6 Comparison of the Phenomenological Model and the Modified Armitage and Poll Model 7-22

7-7 Summary of Data Contained in the Example Calculations of Risk 7-26

LIST OF TABLES
(Continued)

		Page
7-8	Risk Coefficients for a Range of Chemicals in Comparison with ETS in Aircraft Cabins	7-31
8-1	Airborne Concentrations of Various Bacteria and Fungi Measured in 240 Homes	8-10
8-2	Prevalence Parameters for Fungi Encountered Indoors in Winter	8-11
8-3	Isolation, Frequency, and Concentration of Viable Molds Identified in a Survey of 68 Homes in Southern California	8-12
8-4	Dose Equivalents from Galactic Cosmic Radiation Received on Airliner Flights	8-19
8-5	Risk Coefficients for a Range of Health Effects Associated with Exposure to Cosmic Radiation	8-22
8-6	Cumulative Doses (20 Years) for Cabin crewmembers and Passengers on Representative Domestic Flights	8-26
8-7	Cumulative Doses (10 Years for Cabin crewmembers and Passengers on Representative International Flights	8-27
9-1	Major Options Considered for Mitigation of ETS Contaminants	9-5
9-2	Selected Characterizations of Flights/Aircraft Used for RSP Modeling	9-13
9-3	Measured and Modeled RSP Concentrations for Three Study Flights	9-14
9-4	Relative Frequencies for Domestic Flights of Different Durations	9-17
9-5	Predicted RSP Concentrations for Three Study Flights with Hypothetical Reductions in Smoking Due to Curtailment of Smoking Periods	9-19
9-6	Predicted RSP Concentrations for Three Study Flights with a Hypothetical Increase in the Fresh-Air Intake Rate	9-22

LIST OF TABLES
(Continued)

Page

9-7 Predicted RSP Concentrations for Two Study Flights with a Hypothetical Increase in Filter Efficiency 9-25

9-8 Estimation of Annual Expected Deaths Due to Passenger and Flight Attendant Exposures to ETS with Unrestricted Smoking on Domestic Flights 9-28

9-9 Projected Annual Benefits and Costs for Alternative Mitigation Strategies to Reduce ETS Exposures 9-29

9-10 Predicted C02 Concentrations for Three Study Flights with Hypothetical Increases in the Fresh-Air Intake Rate 9-34

9-11 Predicted C02 Concentrations for Two Study Flights with Hypothetical Increases in Filter Efficiency 9-35

LIST OF FIGURES

		Page
2-1	Relationships Between Percent Error in Estimating an Average Concentration and Sample Size for a Coefficient of Variation of 1.0	2-9
2-2	Components of the Airliner Cabin Monitoring Package Included are Two Continuous Monitors, Three Pumps, Temperature, Relative Humidity and Pressure Sensors and Data Logger	2-22
2-3	Target Monitoring Locations for Three Types of Aircraft (Smoking Flights)	2-43
2-4	Example of Page 2 of the Start of Day Documentation Log	2-48
2-5	Example of the Pre-Flight Log, Page 1 of the Flight Documentation Log	2-50
2-6	Example of Page 3 of the Flight Documentation Log Used to Document the Start of the Sample Collection	2-53
2-7	Example of the Page of the Flight Documentation Log Used to Record Smoking Section Counts	2-54
2-8	Example of Chain-of-Custody Form	2-58
3-1	Data Processing Procedure for Continuous Monitoring Data	3-13
3-2	Example Report for Continuous Monitoring Data	3-14
3-3	Data Processing Procedure for Calculating Gravimetric RSP and Nicotine Concentrations	3-16
3-4	Procedure for Calculating Air Exchange Rates Within Aircraft Cabins Using CATs Following Source Release	3-18
4-1	Representativeness of Monitored Domestic Smoking Flights with Respect to Airline	4-3
4-2	Representativeness of Domestic Smoking Flights with Respect to Type of Aircraft	4-6
4-3	Representativeness of Monitored Domestic Smoking Flights with Respect to Flight Duration	4-9
4-4	Correspondence Between Estimated Smoking bevels (Cigarettes Smoked Per Flight) Based on Technician Observations Versus Counts of Cigarette Butts)	4-13

LIST OF FIGURES
(Continued)

Page

4-5 Frequency Distributions for Passengers in the Smoking Section and Total Cigarettes Smoked on Smoking Flights That Were Monitored 4-16

4-6 Frequency Distributions for Cigarettes Smoked per Hour and Cigarettes Smoked per Passenger per Hour on Smoking Flights That Were Monitored 4-17

4-7 Frequency Distribution of Measured Air Exchange Rates Involving Aircraft with Recirculation 4-23

4-8 Frequency Distributions for Temperature and Relative Humidity, Based on All Monitored Flights 4-26

4-9 Cumulative Frequency Distributions for Nicotine Concentrations Measured on Domestic Smoking and Nonsmoking Flights 4-28

4-10 Cumulative Frequency Distributions for Gravimetric RSP Concentrations Measured on Domestic Smoking and Nonsmoking Flights 4-32

4-11 Average RSP (Optical) Concentrations Before Versus During Smoking (Before Takeoff Versus While Airborne for Nonsmoking Flights) 4-33

4-12 Cumulative Frequency Distributions for Time-Averaged Optical RSP Concentrations Measured on Domestic Smoking and Nonsmoking Flights 4-36

4-13 Cumulative Frequency Distributions for Time-Averaged CO Concentrations Measured on Domestic Smoking and Nonsmoking Flights 4-41

4-14 Frequency Distributions for C02 Levels Measured on Smoking and Nonsmoking Flights 4-47

5-1 Optical RSP Parameter Estimates and Associated 95-Percent Confidence Intervals 5-5

5-2 Nicotine Parameter Estimates and Associated 95-Percent Confidence Intervals 5-6

LIST OF FIGURES
(Continued)

Page

5-3 Comparison of Optical and Gravimetric Measurement Results with Values Predicted Using a Single-Chamber Mass-Balance Model 5-14

5-4 Correspondence Between Nicotine and RSP Measurements in the Smoking Section for Domestic Smoking Flights 5-18

5-5 Comparison of C02 Measurement Results with Values Predicted Using a Single-Chamber Mass-Balance Model 5-27

6-1 Populations, Pollutants, and Health Effects of Interest 6-5

7-1 Relationship of Different Components in the Estimation of Risk of Lung Cancer Death, Ascribable to ETS, from Exposure to Respirable Suspended Particulate (RSP) 7-7

7-2 Risk of Cancer Death Using the Modified Armitage and Doll Model for Varying Duration and Commencement of Exposure to ETS 7-23

7-3 Risk of Cancer Death Using the Phenomenological Model, for Varying Durations of Exposure to ETS 7-24

7-4 Cumulative Frequency Distribution of Carbon Monoxide Concentrations at Smoking, Boundary, and Nonsmoking Seat Positions on Domestic Smoking Flights, and Percent of Individuals Dissatisfied at the 2-ppm and 5 ppm Levels 7-33

7-5 Cumulative Frequency Distribution of Nicotine Concentrations at Smoking, Boundary, and Nonsmoking Seat Positions on Domestic Smoking Flights, and Thresholds for No, Moderate, and Marked Perceptions of Irritation 7-35

8-1 Adult Cancer Risk (Leukemia and Solid Tumors) from Exposure to Cosmic Radiation 8-23

8-2 Cancer Risk Per 100,000 Children Exposed in Utero to Cosmic Radiation 8-24

8-3 Risk of Mental Retardation (MR) and Birth Defects (BD) in the Fetus Exposed in Utero to Cosmic Radiation 8-25

LIST OF FIGURES
(Concluded)

Page

9-1 General Framework for Assessment of Alternative Mitigation Strategies 9-2

9-2 Schematic of Two-Chamber Model for Cabin Air Quality 9-10

9-3 Percent of Flight Hours During Which Smoking Would be Permitted Under Partial Smoking Bans Related to Flight Duration 9-18

9-4 Relationship Between RSP Concentrations and Rates of Increase in Fresh-Air Intake for One Study Flight 9-25

9-5 Relationship Between RSP Concentrations and Filter Efficiency for One Study Flight with 21-Percent Air Recirculation 9-24

9-6 Relationship Between Increase in Fresh-Air Intake and Fuel Cost Per Passenger-Hour 9-31

EXECUTIVE SUMMARY

In February 1987, the U.S. Department of Transportation received recommendations from the National Academy of Sciences related to airliner cabin air quality. In response to their recommendation that smoking be banned on all commercial domestic flights, the Department indicated its intention to conduct a study to Quantify pollutant levels in airliner cabins and to assess the associated health risks. The study was conducted during the period when smoking was banned on scheduled commercial flights having durations of two hours or less, pursuant to Public Law 100-202.* This report presents methodological aspects and results of that study.

METHODOLOGY

The study addressed the broader topic of airliner cabin air quality rather than the single issue of environmental tobacco smoke (ETS). The purpose of this work was to develop information to be used for determining health risks from exposures to ETS for nonsmoking airliner occupants as well as risks from other pollutants of concern for all airliner occupants. To meet this primary objective, secondary objectives were established to (1) identify air contaminants and other parameters requiring measurement, (2) select appropriate instrumentation, (3) develop measurement protocols for collection of data that are representative of in-flight conditions, (4) develop a statistical sampling frame that enables representation of commercial flights departing from major U.S. airports, (5) collect data on flights chosen for monitoring, (6) analyze data to characterize concentration patterns in different types of aircraft under different conditions, (7) identify health effects of the chosen contaminants and select populations of interest for developing a risk assessment framework, (8) apply the framework for risk assessment, and (9) develop and evaluate options for mitigation of contaminants as required.

---

* ALL of the work described in this report preceded passage of Public Law 101-164, which will ban smoking on all scheduled domestic commercial flights.

Pollutants were selected for monitoring that had known or suspected sources in the aircraft and could be monitored or sampled in airliner cabins with small, unobtrusive instrumentation. The monitoring package configured for the study consisted of instruments and sensors for measurement of time-varying concentrations of contaminants in addition to samplers for collection of time-integrated samples. It also included a data acquisition system for recording outputs from the continuous monitors. The instrument was packaged in a single, compact carry-on bag typical of that carried by airline passengers. Electromagnetic compatibility tests of all monitoring devices were performed by the Federal Aviation Administration (FAA) to ensure that they did not interfere with aircraft navigation or communication systems.

The ETS contaminants monitored during the study were nicotine, respirable suspended particles (RSP), and carbon monoxide (CO). Nicotine was measured through collection of time-integrated samples and CO was measured with portable continuous monitors; RSP was measured both by integrated and continuous methods. The other pollutants that were monitored were ozone and microbial aerosols. In addition, carbon dioxide (C02) was monitored. C02 and ozone were measured with time-integrated samples whereas short-term samples were collected for microbial aerosols (bacteria and fungi) near the end of each tight, prior to descent.
Temperature, relative humidity, and cabin air pressure were monitored continuously with portable sensors; these measurements were used to further characterize the cabin environment and to provide appropriate correction factors for the flow rates of pumps used for sampling. Air exchange rates were measured using constant release and integrated sampling of perfluorocarbon tracers. All aspects of the measurement protocol were pre-tested on four commercial flights that were monitored over a three-day period in March 1989.

Monitoring was to be performed by each technician at an assigned seat. Based on pretest monitoring at a variety of locations, the following four locations were chosen for monitoring on smoking flights:

(1) coach smoking section; (2) boundary region of the no-smoking section within three nonsmoking rows near the coach smoking section; (3) middle of the no-smoking section; and (4) remote no-smoking section (i.e., as far as possible from coach smoking, usually near the first-class smoking and nonsmoking sections). Because less substantial variations were expected on nonsmoking flights, two locations (middle and rear of the plane) were chosen for those flights. ETS contaminants were monitored at all seat locations and other pollutants were monitored at half of the locations. The instrument package was typically placed on the technician's lap or lap tray to obtain measurements of contaminants most representative of passenger breathing levels.

The target sample size for the study was 60 to 120 smoking flights on jet aircraft, including some international flights. A smaller set of 20 to 40 nonsmoking flights was targeted to provide a baseline for comparison. The target sample size for nonsmoking flights was smaller because flight-to-flight variations in ETS contaminant levels were expected to be lower than for smoking flights.

A total of 70 airports that collectively accounted for 90 percent of U.S. enplanements during 1987 was used as the sampling frame for selection of flights to be monitored. Airports of departure were selected for study flights to provide proportional representation of airports associated with all smoking and nonsmoking flights scheduled for departure during January 1989, based on computer data files supplied by DOT. The specific flights to be monitored were chosen by randomly chaining together the selected airports of departure, subject to constraints relating to the smoking/nonsmoking status of flights. For a typical chain of flights, four technicians monitored six smoking flights and then split into two teams to monitor five nonsmoking flights. In total 92 flights were monitored between April and June 1989; 23 nonsmoking flights and 69 smoking flights which included eight international flights were monitored.

The monitored smoking flights proved to be representative with respect to airlines, types of aircraft, flight durations, and times of day for departures. A wide range of smoking rates was observed, ranging from as little as one cigarette per hour to as much as one cigarette per minute. Comparative analyses indicated that smoking rates based on technician observations agreed very well with rates based on collected cigarette butts. An average of 20 cigarettes per hour, or 68 cigarettes per flight, was smoked by passengers in the coach smoking section on smoking flights that were monitored.

FINDINGS

ETS contaminants occur in both the gaseous and particulate phases; measurements were made for both phases. Levels of ETS contaminants that were measured on smoking and nonsmoking flights are summarized in Exhibit 1. Based on both Gravimetric and optical measurements, RSP concentrations were highest in the smoking section, averaging near 175 micrograms per cubic meter (ug/m3) compared to a background level of 35 to 40 ug/m3 on nonsmoking flights. Differences across the no-smoking sections of the aircraft for smoking flights, and differences between these no-smoking sections and nonsmoking flights, were less pronounced. The optical measurement method indicated some migration of ETS contaminants into the no-smoking sections on smoking flights in terms of one-minute peak RSP concentrations.

Observed effects of tobacco smoking, based on gas-phase measurements, were more discernible for nicotine than for C0. Beyond the marked increase in nicotine in the smoking section, the boundary region of the no-smoking section was most affected. Differences between nicotine levels for the remaining no-smoking locations and levels on nonsmoking flights were within the range of measurement uncertainty, but nicotine levels were more often above detection limits in the no-smoking locations of smoking flights than on nonsmoking flights. The only discernible effect for CO was in the smoking section itself. CO levels were generally highest before aircraft were airborne, both for smoking and nonsmoking flights, due to intrusion of ground-level emissions.

Measured RSP levels in the boundary region were strongly related to observed smoking rates (i.e., higher levels when smoking rates were

EXHIBIT I. AVERAGE CONCENTRATIONS OF ETS CONTAMINANTS ON SMOKING AND NONSMOKING FLIGHTS

	Smoking Flights`					
	Smoking Section	No-smoking Section			Nonsmoking flights	
Parameter		Boundary Rows	Middle Rows	Remote Rows	Rear Rows	Middle Rows
Particle-Phase Measurements						
Average RSP*, ug/m3	175.8	53.6	30.7	35.0	34.8	40.0
Peak RSP+ (1 minute), Ng/m3	883.4	211.8	68.7	69.6		
Gas-Phase Measurements						
Average Nicotine, ug/m3	13.43	0.26	0.04	0.05	0.00	0.08
Percent Nicotine Samples Below Minimum Detection	4.3	54.4	82.6	66.7	100.0	78.3
Average C0, ppm'	1.4	0.6	0.7	0.8	0.6	0.5
Peak CO (1 minute), ppm	3.4	1.4	1.7	1.6	1.3	0.9

` An average of 13.7 percent of the passengers were assigned to the coach smoking section on monitored smoking flights.

*Average of Gravimetric and optical measurement results; micrograms per cubic meter (ug/m3)

+Optical method measurements

' ppm: parts per million

higher) and to the distance from the coach smoking section (i.e., higher levels at shorter distances). Measured levels of nicotine and CO in the boundary region did not correlate with smoking rates or distance from the smoking section, but measured levels of all ETS contaminants in the smoking section were strongly related to smoking rates.

Relatively high C02 levels were measured, averaging over 1,500 parts per million (ppm) across all monitored flights (Exhibit 2). Measured C02 concentrations exceeded 1,000 ppm, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) level associated with satisfaction of comfort (odor) criteria, on 87 percent of the monitored flights. Depending on assumed C02 exhalation rates, measured levels were as much as twice those predicted by a cabin air quality model. Even if the measured levels were to be lowered by half, however, C02 concentrations would still exceed 1,000 ppm on 24 percent of the study flights.

Monitored ozone levels were relatively low, averaging an order of magnitude below the FAA three-hour standard of 0.10 ppm and never exceeding this level. Bacteria levels were higher than fungi levels and somewhat higher in smoking than nonsmoking sections, but the measured bacteria and fungi levels in all cases were low, relative to those that have been measured in other indoor environments.

Some difficulties were encountered in measuring air exchange rates, particularly for aircraft without recirculation, due to (1) the limited number of tracer sources and samplers that could be deployed within the constraints of remaining unobtrusive and (2) the lower extent of lateral air movement within the airliner cabin. Based on measurement results for aircraft with recirculation, there were some indications that air exchange rates were higher on smoking than nonsmoking flights, but the number of measurements was too limited to allow firm conclusions.

Relative humidity levels measured during the study were quite low, below 25 percent for about 90 percent of the monitored flights.

EXHIBIT 2. AVERAGE CONCENTRATIONS OF SELECTED POLLUTANTS ON SMOKING AND NONSMOKING FLIGHTS

	Smoking Flights		
	Smoking Rows	Middle Rows	Nonsmoking Flights
Parameter			
Average C02, ppm*	1562	1568	1756
Percent C02 Samples z 1,000 ppm	87.0	88.1	87.0
Average Ozone, ppm	0.01	0.01	0.02
Percent Ozone Samples > 0.1 ppm	0.0	0.0	0.0
Average Bacteria', CFU/m3	162.7	131.2	131.1
Average Fungi, CFU/m3	5.9	5.0	9.0

*ppm: parts per million

'CFU/m3: colony-forming units per cubic meter

Humidity levels were lower on smoking flights (average of 15.5 percent) than on nonsmoking flights (average of 21.5 percent). Temperatures averaged near 24 C (75 F) for both smoking and nonsmoking flights.

RISK ASSESSMENT

Estimates of lifetime lung cancer risk for nonsmoking cabin crew members (flight attendants) and nonsmoking passengers were developed by combining data on measured RSP concentrations with assumptions concerning relative amounts of time spent in different sections of the cabin, respiratory rates for each group, and models expressing dose-response relationships for cancer. Two dose-response models were used, one with risk linearly related to dose (phenomenological model) and one based on the multistage theory of carcinogenesis, which takes into account the age at which exposure begins (multistage model). Resultant estimates of lifetime lung cancer risk (i.e., premature deaths per 100,000 persons at risk) for nonsmokers exposed to ETS are summarized in Exhibit 3 for crewmembers, business passengers (frequent flyers), and casual passengers. The estimated risks were highest for cabin crew members; it was assumed that cabin crew members sustain higher exposures due to larger amounts of time flying, higher respiratory rates and more time spent in the smoking section of aircraft cabins. Estimates from the two dose-response models were quite consistent except in the case of business passengers; for this group, the assumption that frequent flying begins at a later age resulted in lower estimates with the multistage model.

Applying the risk estimates in Exhibit 3 to the entire U.S. cabin crew population results in an estimated O.18 premature lung cancer deaths per year for domestic flights (that is, approximately 4 premature deaths can be expected every 20 years) and 0.16 premature deaths per year for international flights. Corresponding estimates for the U.S. flying population are 0.24 premature lung cancer deaths per year for domestic flights and 0.18 premature deaths per year for international flights.

Acute upper respiratory and ocular irritation effects of ETS exposure were estimated using CO concentrations as a proxy for ETS levels.

EXHIBIT 3. ESTIMATED LIFETIME RISKS OF PREMATURE LUNG CANCER DEATH-ASCRIBABLE TO ETS ON SMOKING FLIGHTS PER 100,000 NONSMOKING CABIN OCCUPANTS

Cancer Risk per 100,000 Cabin Occupants

Type of Flight/ Model	Cabin Crew Member*	Business Passenger`	Casual Passenger'	Risk
Domestic Flights				
Phenomenological Model	12.06	0.83	0.11	
Multistage Model	14.86	0.27	0.08	
International Flights				
Phenomenological Model	13.46	0.61	0.08	
Multistage Model	16.59	0.20	0.06	

*Assumed to fly 960 hours per year for 20 years, starting at age 25.

`Assumed to fly 480 hours per year for 30 years, starting at age 35.

'Assumed to fly 48 hours per year for 40 years, starting at age 25.

Measured 30-minute peak CO concentrations were compared with empirical data provided by human chamber studies on the numbers of individuals experiencing irritation by various levels of CO as an ETS surrogate. Based on this comparison, it was estimated that on one-third of smoking flights about one in eight persons -- smokers and nonsmokers -- seated in the smoking section would experience irritation due to ETS exposure. A similar type of analysis, using nicotine as a surrogate for eye and nose irritant effects of ETS, indicated that on about one-third of smoking flights ETS levels in the smoking section would be sufficiently high to evoke a marked sensory response in the eye and nose of an airliner cabin occupant.

Cosmic radiation levels were not monitored because an assessment performed at the outset of the study indicated that extensive existing data provided a sufficient basis for risk assessment. Cancer risk estimates, dependent primarily on flight altitude and latitude, were developed for a number of different flight paths using dose-response data developed by the United Nations Scientific Committee on the Effects of Atomic Radiation. As indicated in Exhibit 4, the highest risks are associated with longer domestic and international flights, primarily due to higher altitudes. Because the risks scale linearly with dose, the estimates for cabin crewmembers assumed to fly 960 hours per year are double those of passengers assumed to fly 480 hours per year (Exhibit 4).

MITIGATION

Mitigation options were not explored for ozone or biological aerosols because of the low levels that were measured in this study. For ETS, procedural options such as restriction of smoking and technological options such as increased ventilation were assessed. Of these options, a total ban on smoking was estimated to provide the greatest benefit at least cost. Estimated benefits were based on reduced lung-cancer mortality risks. Costs for procedural options associated with smokers' inconvenience and discomfort, or displacement of smokers to other modes of transportation, could not be estimated due to data limitations.

EXHIBIT 4. ESTIMATED LIFETIME RISKS OF PREMATURE CANCER DEATH ASCRIBABLE TO IN-FLIGHT COSMIC RADIATION EXPOSURE PER 100,000 FLYING CABIN OCCUPANTS

	Cancer Risk per 100,000 Cabin Occupants	
Type of Flight/Path	Cabin Crew Members Flying 960 Hours Per Year	Passengers Flying 480 Hours Per Year
Domestic Flights*		
East-West (<_2 hours)	299 to 714	149 to 357
East-West (>3 hours)	988 to 1,026	494 to 513
North-South (<_2 hours)	90 to 526	45 to 263
North-South (>3 hours)	830	415
International Flights'		
Long, circumpolar (13 hours)	512	256
Medium, non-circumpolar (7 - 9 hours)	387 to 484	194 to 242
Short, non-circumpolar (<_3 hours)	220 to 291	110 to 146

*Assuming 20 years of flying.

'Assuming 10 years of flying.

Relative to the case of unrestricted smoking, the two-hour ban in effect during the past two years would reduce risks ascribable to ETS exposure on domestic flights by about 45 percent. A four-hour ban would reduce risks by about 86 percent, and a six-hour ban would reduce risks by approximately 98 percent. A different type of strategy to curtail smoking, such as allowing smoking during a 10-minute period every two hours, could reduce average exposures to ETS by as much as 70 percent. However, such a strategy could substantially increase the risks of respiratory and other irritant effects from acute exposure to ETS during the brief periods when smoking would be allowed.

Increasing ventilation rates could lower ETS exposures by as much as 33 percent, but associated fuel penalties would result in costs estimated to be greater than the benefits. Improved filter efficiency was estimated to provide only a marginal reduction (about 5 percent) in ETS exposures.

Exposure management was considered to be the only viable option for reducing exposures of cabin crewmembers and passengers to cosmic radiation. In the case of cabin crewmembers, this strategy would involve careful scheduling of personnel to avoid persistent exposure to higher cosmic radiation levels generally associated with high-altitude flights and flight paths toward extreme northern or southern latitudes.

For removal of C02, sorption on solid adsorbent beds whose absorbent capacity for C02 can be regenerated by heating was considered to be a method with potential benefits for aircraft with recirculation. Cost or reliability data were not available for comparison with costs of additional ventilation, which could also be used to bring C02 levels closer to the guidelines specified by ASHRAE.

in other confined environments (e.g., residential, office, public access buildings) and ambient outdoor environments began to shed light on previously unstudied phenomena, such as bioaerosols, and began to illustrate previously unrecognized chemical complexity. Continuing studies of exposure to ETS, for example, cast some doubt on the utility of the much earlier FAA/PHS study because more effective marker constituents had been identified, and, of at least equal importance, improved measurement capabilities allowed more precise monitoring of a wider range of field environments.

In that light, it came as no surprise that a series of Congressional hearings held in 1983 and 1984 concluded that the available data on the airliner cabin environment were contradictory and that present standards and practices could be questioned. As a result of the hearings, Congress, through Public Law 98-466, directed the Secretary of Transportation to commission an independent study by the National Academy of Sciences to examine the adequacy of industry practices and FAA rules and regulations as they affect the health and safety aspects of the airliner cabin environment aboard civil commercial aircraft.

This mandate served as a major collection point to review previous work directed specifically to the environmental quality aboard aircraft and to examine other pollutants and sources that, based on emerging concerns from other fields, could be responsible for health problems in the long or short run. The Academy was directed to recommend remedies for problems discovered and to outline safety precautions to protect passengers from smoke and fumes produced by in-flight fires.

To maintain the independence of the study, FAA did not participate or take any actions that could affect findings, conclusions, or recommendations of the study. At the request of the Academy, however, FAA provided data and rendered assistance to the committee established in the National Research Councils Commission on Life Sciences that was assembled to conduct the study. In the course of the study, the Committee on Airliner Cabin Air Quality reviewed the available technical literature including characteristics of various models of modern aircraft. The Committee also held a series of technical meetings and briefings with experts in relevant fields and made a number of site visits to evaluate specific issues.

The Committee's report (NRC 1986a), issued in August of 1986, identified several potential sources of environmental quality problems on aircraft including tobacco smoke, ozone, cosmic radiation, humidity, and microbial aerosols. The Committee noted, however, that available empirical evidence was of insufficient quality and quantity for a scientific evaluation. Unique aspects of the airliner cabin environment precluded drawing valid conclusions on the basis of data from other environments. Consequently, recommendations from the study focused largely on defining areas of data collection necessary to more fully understand potential exposures.

The Committee recommended that smoking be banned on all commercial flights to lessen irritation and discomfort and to reduce potential health hazards associated with ETS by bringing that aspect of cabin air quality into line with established standards for other closed environments. The smoking ban was also cited as a means to eliminate the possibility of fires caused by cigarettes.

There has been a growing concern that exposure to ETS may be associated with adverse health and comfort effects among nonsmokers. This concern is further enhanced by the growing interest in indoor air quality, the recognition that ETS is a major indoor contaminant source, and the fact that a large number of people are exposed to ETS. The health and comfort effects of involuntary smoking have been extensively reviewed by the Committee on Passive Smoking of the National Research Council (NRC 1986b) and by the U.S. Surgeon General (DHHS 1986). Both reviews concluded that exposure of nonsmokers results in:

* Acute irritation of the eyes, nose, and throat along with perception of odor

* Upper airway problems in children including increased prevalence of respiratory symptoms (cough, sputum production, wheezing), decreased lung function, increased lower respiratory illness, and increased rates of chronic ear infections

* Increased risk of lung cancer.

The reviews also noted other outcomes related to the growth and health of children, including lower birth weight.

After completing a review of the Academy report on the airliner cabin environment, DOT assembled a report to summarize its responses (DOT 1987) to accompany submittal of the Academy report to Congress in February 1987. DOT accepted in full or in part most of the recommendations made in the Academy report. While recognizing that exposure to ETS could be viewed as a problem by some crewmembers and passengers, DOT suggested that further study was needed to better define health effects, concentrations and possible technical solutions before proposing a definitive response to a smoking ban on all commercial aircraft.

In December of 1987, Public Law 100-202 was enacted, prohibiting smoking by passengers on any scheduled commercial flight of two hours or shorter duration. This limited smoking ban is effective for 24 months beginning April 23, 1988. At the same time, DOT also received Congressional approval to conduct a study to resolve technical questions that must be answered before continuing or broadening the prohibitions contained in PL 100-202.

1.3 REVIEW OF AVAILABLE DATA

The information incorporated into the Committee on Airliner Cabin Air Quality report constitutes a comprehensive survey of the published literature to about 1985 (NRC 1986a). This section briefly summarizes the results of relevant studies identified by the Committee together with research results that have been published since that time.

Environmental tobacco smoke is a complex mixture of gas- and particulate-phase contaminants. More than 3,800 compounds have been identified in ETS. Field monitoring studies, however, seek to quantitate a relatively small number of marker constituents. The aircraft environment has not been systematically investigated for ETS contaminant levels. Early studies conducted by FAA and PHS (1971) measured cabin levels of C0, hydrocarbon vapors, TSP, and PAH on twenty Military Airlift Command flights and fourteen domestic flights over an 18-month period. Environmental sampling revealed very low levels of each contaminant measured, well below occupational and environmental air quality standards, and these contaminants were not judged to represent a hazard to non-smoking passengers. Analysis of subjective questionnaires, however, also revealed that a significant proportion of nonsmoking passengers were bothered by tobacco smoke, leading to regulations to segregate smoking passengers.

Other ETS studies of the airliner cabin environment identified by the committee utilized measures of CO and RSP. Anecdotal measurements carried out by Committee members during the Academy study included very limited measurements of N02, RSP, and C02 using portable instruments on commercial flights. Although suggesting the possible range of concentrations of ETS-based contaminants, none of these earlier data provide definitive results.

More recent sampling studies aboard commercial airliners have been published by Oldaker and Conrad (1987) and by Mattson et al. (1989). Oldaker and Conrad measured vapor-phase nicotine in no smoking and smoking sections of three types of commercial aircraft (Boeing 727-200, 737-200 and 737-300). Forty-nine measurements were conducted in no-smoking sections, out of which 40 measurements were conducted in the boundary region (i.e., two rows in no-smoking sections adjacent to smoking sections).
Additionally, 26 measurements were conducted in smoking sections. Average nicotine concentrations (+_standard deviations) were 22.4 t 28.4 Ug/m3 in smoking sections, 10.6 +_ 9.7 Ug/m3 in the boundary region of no-smoking sections, and 3.3 +_3.6 Ug/m3 in the remainder of the no-smoking sections. They did not find any significant correlation between nicotine concentrations and the number of smokers; however, smoking rates were not

measured but assumed to be 2 cigarettes per hour per passenger seated in the smoking section.

Data on nicotine exposures, cotinine (a major metaoblite of nicotine) excretion levels, and acute symptoms from a subsequent study of passive smoking on commercial airliner flights showed that a total separation of smoking and nonsmoking sections was not achieved (Mattson et al. 1989). The study was conducted with 9 subjects on tour flights lasting approximately 4 hours each. Two of the four flights were on aircraft with 100 percent outside air ventilation (Boeing 727) and the other two were on aircraft with 50 percent recirculation (Boeing 767). The observed nicotine levels were similar to those measured in the Oldnker and Conrad study: 13.6 +_ 23.0 ug/m3 in the boundary region of no-smoking sections and 16.5 +_ 7.1 ug/m3 in smoking sections. Aircraft with no recirculation had significantly lower nicotine concentrations than those with recirculation. Urinary cotinine levels were related to nicotine exposure for the subjects -- those with the highest nicotine exposures had the highest levels of cotinine excretion. Eye and nose symptoms indicative of acute symptoms were related to nicotine and cotinine levels.

Although these studies have been useful in suggesting ranges of concentrations of ETS tracers encountered in the general airliner cabin environment, the samples were not randomly selected and the number of observations was generally small, precluding any generalization of the results. Similarly, determining factors (e.g., ventilation systems, eating patterns) of ETS concentrations for the general airliner cabin environment have not been systematically investigated.

Although ETS is of obvious importance in the context of PL 100-202, additional pollutants and factors identified by the Committee warrant attention. Essentially no published measurement data exist with regard to ventilation rates (i.e., fresh-air dilution rates in the passenger breathing zone), carbon dioxide levels, or microbial aerosols. As cited in the Academy report (NRC 1986a), some data exist to confirm expectations of low relative humidity. Similarly, the committee identified fairly abundant data to confirm intrusions of stratospheric ozone into the flight cabin, but also cited the need for additional data to establish compliance with FAA standards. Issues surrounding potential exposures to cosmic radiation (particularly at high altitudes) were also raised.

1.4 REFERENCES

U.S. Department of Health and Human Services. 1986. The Health Consequences of Involuntary Smoking . Report of the Surgeon General. Rockville, MD.

U.S. Department of Transportation. 1987. Report to Congress: Airline Cabin Air Quality . Prepared Pursuant to Public Law 98-466 by the U .S . Department of Transportation, Washington, DC.

Federal Aviation Administration Public Health Service. 1971. Health Aspects of Smoking in Transport Aircraft. U.S. Federal Aviation Administration and U. S. National Institute for Occupational Safety and Health. Available from the National Technical Information Service (Report No. AD736097).

Federal Aviation Administration. 1980. Results of FAA Cabin Ozone Monitoring Program in Commercial Aircraft in 1978 and 1979. Report No. FAA-EE-80-10 , Office of Energy and Environment, U .S . Federal Aviation Administration, Washington, DC.

Federal Aviation Administration. 1985. Air Carrier Operation Pollution. Consolidated Reprint, U.S. Federal Aviation Administration, Washington, DC.

Federal Aviation Administration. 1989. Draft Advisory Circular on Radiation Exposure of Air Carrier Crew Members.U.S. Federal Aviation Administration, Washington, DC.

Mattson, M.E., et al. 1989. "Passive Smoking on Commercial Airlines." J. Am. Med. Assoc., Vol. 261, No. 6, pp. 867-872.

National Research Council. 1986a. The Airliner Cabin Environment. National Academy Press, Washington, DC.

National Research Council. 1986b. Environmental Tobacco Smoke: Measuring Exposures and Assessing Health Effects. National Academy Press. Washington, .

Oldaker, G.B., and F.C. Conrad. 1987. "Estimation of Effects of Environmental Tobacco Smoke on Air Quality Within Passenger Cabins of Commercial Aircraft." Environ. Sci. Technol., Vol. 21, No. 10, pp. 994-999.

Section 2.0
SURVEY DESIGN AND PROTOCOL

2.1 SELECTION OF POLLUTANTS AND OTHER MEASUREMENT PARAMETERS

The air quality in an airliner cabin is related to several factors including pollutant sources inside the aircraft, outdoor pollutants, the volume of the airliner cabin, ventilation rates, and air mixing within the cabin. To assess the air quality in the airliner cabin environment in this study, pollutants were selected for monitoring that (1) had known or suspected sources in the aircraft and (2) could be monitored or sampled in occupied airliner cabins with small, unobtrusive instrumentation that would not concern passengers or alert the flight crew to the sampling activity which could cause them to take steps to alter ventilation rates.

The parameters selected for measurement in this study are listed in Table 2-1. The pollutants measured included components of ETS (nicotine, respirable particles, and carbon monoxide), carbon dioxide, ozone, and microbial aerosols. The rationale for selection of these parameters is given below.

Environmental tobacco smoke consists of a complex mixture of air contaminants in both the gaseous and particulate phases -- more than 3,800 compounds have been identified in cigarette smoke. To assess the health risks due to exposure to ETS, it is necessary to accurately quantify ETS. Because it is not possible to measure all ETS contaminants, marker or tracer contaminants must be used as indicators of exposure to ETS. The tracers to be measured should have the following characteristics:

* Be unique to tobacco smoke

* Occur in sufficient quantities in ETS to facilitate accurate detection and quantification

* Have similar emission rates across a variety of tobacco products

* Occur in a consistent ratio to other contaminants in ETS.

TABLE 2-1. POLLUTANTS AND OTHER PARAMETERS MEASURED IN THE AIRLINER CABIN

Pollutant/Measurement Parameters
ETS Contaminants
Nicotine
Respirable Particles
Carbon Monoxide
Microbial Aerosols
Fungi
Bacteria
Other Pollutants
Ozone
Carbon Dioxide
Other Parameters
Temperature
Relative Humidity
Cabin Pressure
Air Exchange Rate

Of the 3,800 compounds identified, and the 300 to 400 compounds that have been measured in ETS, there are numerous vapor-phase organic compounds, particles, particulate phase organics, nitrogen oxides, and some tobacco-specific nitrosamines. Most of these compounds, however, have not been adequately studied to permit their use as ETS tracers. Some, such as N-nitrosonornicotine, meet some of the criteria as a tracer, but the current measurement technologies are inadequate for accurate quantification at the low levels present in indoor environments, even with heavy smoking.

Nicotine meets most of the criteria as an ETS tracer. It is unique to ETS; in most environments, tobacco smoke is the only source of nicotine. Nicotine is the major constituent in ETS, after water, and sensitive analytical methods are available to quantify it, even in environments with low levels. Nicotine exists primarily in the vapor phase. Data from Hamnond et al. (1987) and Murnmatsu et al. (1984) suggest that nicotine/particulate matter ratios are more constant than those previously measured in studies that used smoking machines to generate ETS. Nicotine also serves as a good tracer because nicotine in sidestream smoke does not vary substantially for different brands of cigarettes (Rickert et al. I984).

Carbon monoxide has been measured in numerous studies to represent ETS. In areas with heavy smoking or where other sources of CO do not exist, CO provides a measure of ETS exposure.

Respirable particles (RSP) are a major component of ETS. In numerous studies summarized by Repace (1987), tobacco smoke has been shown to play a predominant role in the concentration of RSP indoors. As a result of these studies, RSP is currently the most extensive database for modeling ETS in indoor environments and is considered to be among the best tracers for ETS and associated human exposure (NRC 1986).

Ozone was selected for measurement in this study because it has been demonstrated to be a pollutant of concern in aircraft cabins. Data collected in the GASP program (Nastrom and Holdeman 1980) have shown that ozone concentrations increase with increasing latitude, are maximal during spring, and vary with weather systems. The importance of ozone is obvious from the fact that standards of 0.25 ppm of peak concentrations and 0.1 ppm for 3-hour intervals have been established by the FAA. The data on ozone concentrations in occupied airliner cabins are, however, limited and not current. Therefore, collection of ozone data in this study was warranted.

The sources of carbon dioxide (C02) in the airliner cabin are the passengers. Because of the high density of passengers on some flights, it is important to measure C02. Current guidelines for exposure to carbon dioxide (C02) include the ACGIH time-weighted average (TWA) limit of 5,000 ppm, and ASHRAE's guideline of 1,000 ppm (ASHRAE 1989). The ASHRAE guideline of 1,000 ppm, recommended to satisfy comfort (odor) criteria, is widely used as an indicator of the adequacy of ventilation in indoor environments. Carbon dioxide measurements were performed on each flight for comparison to the relevant standards and guidelines and as an indicator of air quality and ventilation.

Airborne microbial aerosols have been quantified in a variety of indoor environments. Concentrations of biological aerosols in aircraft cabins, however, have not been measured. The aircraft cabin represents a unique environment with its high density of occupants and specialized ventilation system. Although ventilation air during flight may contain very few biological particles, these particles may infiltrate the cabin during ground activities, be carried on by passengers, and most importantly, may be generated from passengers by skin shedding or coughing, sneezing, and talking.

In this study, fungi and bacteria were sampled on each aircraft. The sampled organisms were cultured and quantified to determine the three to five most prevalent genera of bacteria and fungi on each flight. Additionally, <u>Staphylococcus aureus</u> and <u>Streptococcus pyogenes</u>, two organisms that can be directly related to dispersion from passengers, were quantified in bacterial samples.

In addition to pollutant measurements. temperature relative humidity, and cabin air pressure were measured at each sampling location. Temperature and pressure are required parameters for calculating volumetric sampling rates, and relative humidity is recognized as an important parameter in airliner cabins.

Air exchange rates were also measured on each flight. Data on air exchange rates are important for use in interpretation of pollutant measurements, modeling, and development of mitigation strategies.

Cosmic radiation was also included as a parameter for which a risk assessment would be performed in this study. However, measurements of cosmic radiation were not made on the flights during the monitoring program. A decision was made not to perform measurements after a review of currently available data in draft and final reports (FAA 1989) and the UNSCEAR reports (1982, 1986, and 1988). The evaluation of this information indicated that the available data was adequate to perform the risk assessment.

2.2 DETERMINATION OF SAMPLE SIZE

Determination of an appropriate sample size (i.e., number of flights to be monitored) was based primarily on study needs relating to risk assessment for exposure to ETS contaminants. In the context of risk assessment, two types of potential health effects of ETS exposure are of primary concern:

* Chronic health effects related to average ETS concentrations encountered by airline passengers or flight attendants
* Acute health effects related to occasions on which the peak concentrations encountered are sufficiently high to trigger human health responses.

Thus, the sample size required for the study was one that would enable estimation of both average ETS concentrations and the proportion of flights where certain concentration levels were exceeded with a reasonable degree of precision. Each of these perspectives for estimation of sample size is discussed in greater detail below.

2.2.1 <u>Estimating an Average Concentration</u>

To properly support a risk assessment for chronic effects of ETS exposure, the average concentration of ETS contaminants on both smoking and nonsmoking flights needs to be estimated as precisely as possible. A common estimation goal is to have a 95 percent confidence that the average measured concentration differs from its true, but unknown, value for specific sampling conditions by a relatively small margin of error. The formula for the sample size (n) necessary to meet this objective is as follows (Cochran 1963)

$$n= \frac{t2 * s2}{d2} \qquad (1)$$

where:

t - represents the number of standard deviations (approximately two) that account for the central 95 percent of the area under a normal curve

s - is the estimated standard deviation for the ETS contaminant

d - is the margin of error (expressed as a fraction of the average) that can be tolerated in estimating the average concentration of the ETS contaminant.

In practice, it is difficult to obtain estimates for the value of s that can be expected, as this quantity depends both on the mean concentration and the extent of variation about the mean. A more stable quantity is the coefficient of variation (CV), or ratio of the standard deviation to the mean, which often lies in the range from 0.5 to 2.0 for environmental measurements. It the margin of error in equation (1) is expressed as a fraction of the mean, (i.e., d = f ╖ x) and the standard deviation is also expressed relative to the mean (i.e., s = CV ╖ x), then the above equation can be restated as:

$$n= \frac{t2 * CV2}{f2} \qquad (2)$$

or, solving for f,

f= t * CV(square root) n (3)

Equation (3) expresses the precision with which the mean concentration can be estimated as a function of the CV and sample size. For example, assuming a CV of 1.0 and a sample size of 100 flights, the associated value of f is 0.2, meaning that there is a 95 percent confidence of estimating the average concentration within +_20 percent.

Some estimated values of f for different values of the CV and sample size are given in Table 2-2. When the sample size initially is fairly small, relatively rapid improvement in precision can be achieved with modest increases in sample size (e.g., from 20 to 40 or 40 to 60). The marginal gain in precision drops off rapidly as the sample size exceeds 100. For example, for a CV of 1.0, the precision improves by 6 percentage points (from +_32 percent to +_26 percent) when the sample size is increased from 40 to 60 but improves by only one percentage point (from +_15.5 percent to +_14.6 percent) when the sample size is increased from 160 to 180 flights.

Thus, as indicated above and illustrated in Figure 2-1, the optimal sample size appears to lie in the range between 60 and 120 flights. A further consideration is the magnitude of the CV that can be expected. If RSP measurements in residential environments (e.g., Spengler et al. 1985) are indicative, then a CV on the order of 0.8 could be expected for smoking flights, meaning that the average concentration could be estimated within f25 percent through measurements on 40 to 50 flights. However, recent data collected by Oldaker and Conrad (1987) in the airline cabin environment indicate that a CV on the order of 1.3 can be expected for nicotine measurements in smoking sections of aircraft. In this case, approximately 80 flights would be required to estimate the nicotine average with a reasonable degree of precision (e.g., +_30 percent); if the CV turned out to be as high as 1.5, then 100 flights would be needed to achieve this degree of precision.

TABLE 2-2. PERCENT ERROR IN ESTIMATING AN AVERAGE CONCENTRATION BY SAMPLE SIZE AND COEFFICIENT OF VARIATION

Sample Size*	Coefficient of Variation** 0.6	0.8	1.0	1.2	1.4	1.6
20	28.0%	37.3%	46.7%	56.0%	65.4%	74.7%
40	19.1	25.5	31.9	38.3	44.7	51.1
60	15.4	20.6	25.8	30.9	36.1	41.3
80	13.4	17.8	22.3	26.8	31.3	35.7
100	11.9	15.9	19.9	23.8	27.8	31.8
120	10.8	14.4	18.0	21.6	25.3	28.9
140	10.0	13.3	16.7	20.0	23.4	26.7
160	9.3	12.4	15.5	18.6	21.8	24.9
180	8.7	11.6	14.6	17.5	20.4	23.3
200	8.3	11.0	13.8	16.6	19.4	22.1

* Number of flights to be monitored.
** Ratio of standard deviation to mean concentration for contaminant to be monitored.

FIGURE 2-1. RELATIONSHIPS BETWEEN PERCENT ERROR IN ESTIMATING AN AVERAGE CONCENTRATION AND SAMPLE SIZE FOR A COEFFICIENT OF VARIATION OF 1.0

2.2.2 Estimating the Proportion of Flights for Which a Concentration is Exceeded

To properly support a risk assessment for acute effects of ETS exposure, the proportion of flights for which the peak concentration exceeds some level of concern (e.g., the concentration at which sensitive individuals may have reactions such as respiratory or eye irritation) needs to be estimated as precisely as possible. The formula for the sample size necessary to estimate a proportion (p) within a certain margin of error (d) is similar to equation (1); substituting the variance (p x q, where q = 1 - p) about an estimated proportion for s2 in that equation, the following relationship is obtained:

$$n = \frac{t^2 * p * q}{d^2} \qquad (4)$$

or, solving for d,

$$d = t * \sqrt{pq/n} \qquad (5)$$

Some estimated values of d for different values of p and n are given in Table 2-3. As in the case of estimating the mean concentration, the greatest marginal gain in precision is made at relatively low sample sizes. For example, for an estimated average proportion of 0.5, the margin of error would be reduced by 0.03 (from 0.16 to 0.13) if the sample size were to be increased from 40 to 60 flights, whereas the error would be reduced by only 0.005 (from 0.078 to 0.073) if the sample size were to be increased from 160 to 180 flights.

The interpretation of the table entries can be illustrated as follows: if the measured proportion is 0.5 and the sample size is 100 flights, then the estimated error is 0.1; thus, there is a 95 percent confidence that the true proportion is in the interval from 0.4 to 0.6. As few as 60 flights could be adequate to estimate a proportion such as 0.5 (interval from 0.37 to 0.63) or 0.25 (interval from 0.14 to 0.36), but this number would not be adequate for estimating smaller proportions. For

TABLE 2-3. ERROR IN ESTIMATING THE PROPORTION OF FLIGHTS WITH MEASURED CONCENTRATIONS ABOVE A STATED LEVEL, BY SAMPLE SIZE AND ESTIMATED PROPORTION

Sample Size*	Estimated Proportion of Flights 0.50	0.25	0.10	0.05
20	0.234	0.202	0.140	0.102
40	0.160	0.138	0.096	0.070
60	0.129	0.112	0.077	0.056
80	0.112	0.097	0.067	0.049
100	0.100	0.086	0.060	0.043
120	0.090	0.078	0.054	0.039
140	0.084	0.072	0.050	0.036
160	0.078	0.067	0.047	0.034
180	0.073	0.063	0.044	0.032
200	0.069	0.060	0.042	0.030

* Number of flights to be monitored.

example, if the estimated proportion were 0.05 and the number of sampled flights were 60, then the interval surrounding this estimate would have a lower bound below zero, meaning that the estimated proportion could not be statistically distinguished from zero. On the other hand, it may not be necessary to estimate relatively small proportions with any great certainty; it is probably sufficient to know that the proportion is relatively small.

2.2.3 Target Sample Size

Whether viewed from the perspective of estimating means or estimating proportions, a sample size in the range of 60 to 120 smoking flights was considered to be sufficient to meet the needs of the study. Resources adequate to obtain this range of sample size were requested and received for the study. The exact number of flights that could be monitored with these resources could not be determined at the outset of the study, due to fluctuations in air fares and some uncertainty in the amount of technician time required for monitoring flights together with pre- and post-flight activities.

Nonsmoking flights were also to be monitored by study design. Although the primary emphasis of the study was on smoking flights, nonsmoking flights needed to be monitored to provide a benchmark for comparison with smoking flights and to verify the assumption that levels of ETS contaminants were relatively low on such flights. Because the coefficient of variation for nonsmoking flights was expected to be about one half to two-thirds that of smoking flights, the same relative precision could be obtained with one-half to one-quarter the number of smoking flights. Thus, a sample size in the range of 20 to 40 nonsmoking flights was considered to be sufficient.

In selecting flights to be monitored (see Section 2.4), smoking and nonsmoking flights were sampled independently, subject to the overall constraint that 75 percent of all monitored flights be smoking flights and the remaining 25 percent be nonsmoking flights. This approach was consistent with the target sample sizes of 60 to 120 smoking flights and 20 to 40 nonsmoking flights.

2.3 MEASUREMENT INSTRUMENTATION, CONFIGURATION, AND TESTING

To meet the objectives of the study, while performing the monitoring under the constraints associated with an occupied airliner cabin environment, the instrumentation package used in the cabin had to meet the following criteria:

* Produces data that meet requirements for risk assessment
* Unobtrusive and small size -- all instruments and sensors fit in a single, compact carry-on bag
* Lightweight
* No requirement for external power
* Quiet operation
* Compliance with FAA regulations -- will not interfere with the aircraft navigation or communication systems
* Compliance with DOT regulations relating to the carriage of hazardous materials
* Will not cause concern to passengers during use.

The monitoring package configured for the study consisted of instruments and sensors for measurement of time-varying concentrations of contaminants in addition to samplers for collection of integrated samples. It also included a data acquisition system for recording outputs from the continuous monitors. The instrumentation was packaged in a single, compact carry-on bag typical of that carried by other airline passengers. Details of configuration of the instrumentation package are provided below.

2.3.1 Description of Measurement Methods and Instrumentation

The measurement parameters of the study, sample collection methods, analysis methods, and relevant references are summarized in Table 2-4.

TABLE 2-4. MEASUREMENT PARAMETERS AND METHODS

Parameter	Sample Collection Method	Analysis Method	References
<u>ETS Contaminants</u>			
carbon monoxide	Continuous monitor	Solid polymer electrolyte	Nagda and Koontz, 1985
Nicotine	Sodium-bisulphate treated filter	Gas chromatography -- nitrogen selective detector	Hammond et al., 1987
Respirable particles (integrated)	Filtration with cyclone separator	Gravimetry	Hammond et al., 1987
Respirable particles (continuous)	Continuous monitor	Nephelometry	Ingebrethsen et al., 1988
<u>Microbial Aerosols</u>			
Fungi	Impaction	Culture/microscopy	Burge et al., 1987
Bacteria	Impaction	Culture/microscopy	Burge et al., 1987
<u>Pollutants</u>			
Ozone	MBTH-coated filter*	Spectrophotometry	Lambert et al., 1989
Carbon dioxide	Detector tube	Length of stain	Lynch, 1981
<u>Other Parameters</u>			
Temperature	Continuous	Platinum RTD	ASHRAE, 1985
Relative humidity	Continuous	Thin film dielectric sensor	ASHRAE, 1985
Barometric pressure	Continuous	Piezoresistance	ASHRAE, 1985
Air exchange (passive)	Sorbent tube	Gas chromatography of perfluorocarbon	Dietz and Cote, 1982

tracer

*3-Methyl-2-benzothiazolinone 2-14

The requirement that the instrumentation be small , unobtrusive and battery-powered placed a major constraint on the selection of instrumentation; some compromises had to be made to accommodate smaller sampling devices that could be used in the airliner cabin. Because of the accelerated schedule of the project and resource constraints, new instrumentation designed specifically for this study could not be developed. Measurement methods and instruments were those with accepted performance in past studies and commercial availability

Carbon monoxide was monitored continuously on the aircraft with a General Electric (GE) Model l5ECS3CO3 Carbon Monoxide Detector. The detector uses a solid polymer electrolyte technology for measurement of C0. The detector has been used extensively in field monitoring programs conducted by the U.S. Environmental Protection Agency (Akland et al. 1985) and by GEOMET (Nagda and Koontz 1985).

Like other portable CO monitors, the GE CO detector has a lower detectable limit of 1 ppm, but its resolution of p.l ppm is better than many other detectors. The manufacturer specifies an accuracy of 1+_0 percent. In a GEOMET field survey (Nagda and Koontz 1985) measurement error at 4.5 ppm was shown to be less than 9 percent, and the precision was +_10 percent or better. Interferences with the detector have been well characterized and are effectively eliminated by use of a solid chemical filter (Ott et al. 1986).

Carbon monoxide was measured at all monitoring locations in the airliner cabin as described in Section 2.5. The analog output signal of the detector was scanned every 10 seconds and 1-minute averages were recorded by the data acquisition system (DAS) in the instrumentation package.

Nicotine was measured with the filtration method described by Hammond et al. (1987). The method involves collecting RSP on a pre-filter and vapor phase nicotine on a second filter treated with sodium bisulphate. This sampling method was selected because it has a number of

advantages over the use of other solid Sorbent methods such as the NIOSH (1977) method that uses XAD-2 resin and the method of Muramatsu et al. (1984) that uses Uniport-S coated with 10 percent silicon OV-17. With the method developed by Hammond, a single pump and sampler can be used for efficient collection of both RSP and vapor phase nicotine. With Sorbent tubes, the 1.7 1/min flow rate required for separation by the cyclone can generate excessively high pressure drops adversely affecting sampler pump performance and noise levels. The performance of the nicotine collection method has been demonstrated in environmental chamber tests by Hammond et al. (1987). The collection efficiency of the filter method has been shown to be greater than 99 percent. Recovery of nicotine from the filter has been shown to be greater than 98 percent. The pumps used in this study had built-in pressure compensation to maintain constant flow rates at +_5 percent of the set point. The limit of detection for the method is 0.1 ug/m3 for a 2-hour sample. Nicotine analysis was performed by gas chromatography (GC) with a nitrogen selective detector (Hammond et al.
1987).

Respirable particles (RSP) were measured during each flight by two complementary methods -- a Gravimetric method for the measurement of the integrated average respirable particle mass during the smoking period and an optical method for real-time measurement of peak and time-varying RSP concentrations for the entire period between departure and arrival at the airport gates. A 10-mm nylon cyclone (MSA Inc.) was used as a pre-separator to remove particles larger than 3.5 um diameter for both methods. Use of the 10-mm cyclone in the instrumentation package was desirable because it could be used as a pre-separator for both the MINIRAM and the filter cassette used for Gravimetric determinations, thereby providing comparable particle size distributions for each method. The compact size of the cyclone made its use more unobtrusive than larger impactors that are available and that would need to be exposed above the instrument bag. The lower airflow rates needed for the cyclone limited the volume of air that could be sampled, and therefore the amount of particle mass that could be collected, particularly on short flights. However, the lower airflow rate and pressure drop placed less of a load on the sampling pumps, enabling their use on battery power for extended flight durations and multiple flights during a day. Integrated average RSP measurements were performed by standard methods of collection on preconditioned, tared filters. Filters were weighed under controlled temperature and relative humidity conditions on a microbalance with a resolution of 1.0 ug. Lower limits of detection with the analytical system were approximately 15 ug of mass (absolute) on a filter, considering the combined errors of the two weightings required (tare weight and final weight) for the Gravimetric analysis.

A MINIRAM Model PDM-3 (MIE, Bedford, MA) was used to provide the time varying (1-minute average) and peak concentrations of respirable particle mass during each flight. The MINIRAM is a compact, light-scattering aerosol monitor that was configured with a pump and a cyclone pre-separator for measurement of RSP, rather than total suspended particles. Concentrations of RSP were recorded automatically every minute with the "package" DAS. RSP measurements were performed at each sampling location in the cabin.

Prior to use in aircraft, the accuracy of the MINIRAM was validated by calibration in an environmental chamber, described by Leaderer et al. (1984), at the John B. Pierce Foundation Laboratory. The monitors were calibrated dynamically during exposure to ETS-RSP generated by occupants in the chamber, as described in Section 2.3.3. RSP concentrations with the MINIRAM were compared to measurements with a piezoelectric microbalance and with Gravimetric methods to enhance the comparability of data from this study with previous studies of ETS-RSP (e.g., Repace and Lowrey 1980, 1982).

Microbial aerosols were sampled on each flight with a portable, battery-powered sieve plate sampler, the Surface Air System (SAS) compact air sampler. Selection of the SAS compact sampler represented a compromise between collection efficiency, sampler size, and logistical constraints in the airliner cabin.

The Bioaerosols Committee of the American Conference of Government Industrial Hygienists has stated that slit to agar samplers and All-Glass Impingers most efficiently collect viable bioaerosols (Burge et al. 1987). The slit to agar sampler, however, is bulky and requires AC power. The All-Glass Impingers require use of a liquid solution for collection making it difficult to use unobtrusively on an aircraft. Viable aerosols have also been collected on filter cassettes. But, loss of organisms due to desiccation can be highly variable and would be a critical problem in this study because of the low relative humidity on aircraft and the need to store samples between flight legs. A large model of the SAS that samples at 180 1/min and has higher collection efficiency was also considered. But the size of the instrument precluded its use.

Two types of media, R2 agar (R2A) and Tryptic Soy Agar (TSA) were used for collection of microbial aerosols. The R2A supported both saprophytic bacteria and fungi. The TSA was included to ensure that human pathogens such as Staphylococcus aureus and Streptococcus pyogenes were efficiently recovered.

To ensure that representative samples were collected and plates were not underexposed or overexposed, time-bracketing exposure was done at 40, 60, 80, 120 and 180 seconds per collection site, at a flow rate of 90 1/min. Microbial aerosol samples were collected at two locations in the coach section of aircraft on smoking flights and at one site (centre of coach) on nonsmoking flights. Samples were collected near the end of the flight, prior to descent.

Ozone was measured by collecting it on treated filters, with subsequent laboratory analysis by a spectrophotometric method. A number of alternative methods were evaluated for unobtrusive measurements of ozone during flights. Commercially available ozone monitors for real-time measurements of ozone did not meet the criteria for sampling because they are large, bulky instruments that require A.C. power, require ethylene for reaction with ozone, use liquid dyes for reaction with ozone, or have inadequate sensitivity for ambient air measurements. Length-of-stain detector tubes for measurement of short-term (grab sample) concentrations were also considered. However, detector tubes have poor accuracy and precision at low concentrations and the applicability of grab samples for the assessment of ozone concentration for flights of extended duration would be limited.

The method selected for this study was based on work by Lambert et al. (1989) on solid Sorbents for measurement of ozone. Glass-fiber filters were treated with 3-methyl-2-benzothiazolinone-acetone azine and 2-phenylphenol in 1:4 molar solid mixture prepared according to the method of Lambert et al. (1989). The coated filters were placed in opaque 37-mm filter cassette holders. Samples were collected by drawing air across the filter at a rate of approximately 1 1/min. Because aircraft altitude could not be measured in this study, a standardized protocol was implemented that involved sampling during the period from 15 minutes after takeoff until 30 minutes prior to the scheduled arrival. Collection efficiency and recovery efficiency of each lot of samplers was addressed by exposing a subset of each lot of filters to known ozone concentrations at low (approximately 10 percent) relative humidity. Both spiked and blank filters were included with field samples to address storage and handling effects.

Carbon dioxide was measured during each flight with length-of- stain diffusion detector tubes. The diffusion tubes, Draeger Carbon Dioxide 500/a-D, allow for integrated measurements of C02 over periods from less than an hour to 8 hours. The tubes had a range from 500 to 20,000 ppm-hour, making them suitable for the flight durations encountered in this study. Although real-time monitoring of C02 concentrations would have been preferable, the non-dispersive infrared analyzers currently available with well-documented performance characteristics were too large to be used in the unobtrusive instrument package.

The detector tubes used in this study were opened after becoming airborne (no-smoking light off). The sample collection was terminated when the no-smoking light was illuminated, at which time the length-of- stain was recorded. Resolution of the reading was approximately 125 ppm.

Air exchange was measured on all flights with a .passive perfluorocarbon tracer (PFT) method (Dietz and Cote 1982). The method employs miniature PFT sources for constant release of tracer gas and capillary adsorption tubes (CATs) for sample collection by passive diffusion; no pumps are required.

PFT sources were carried by half of the members of each flight's technician team. The samplers were carried and used by the other half of the team, facilitating release and sampling at distinctly different locations in the aircraft. On nonsmoking flights, a single tracer gas was released by the technician sitting near the centre of the plane. The CAT sampler was deployed by the technician near the rear of the aircraft. On smoking flights, samples were collected at two locations in the coach section, in the centre of the nonsmoking section, and in the boundary section. On these fights two different types of perfluorocarbon tracers were released in the smoking and nonsmoking sections. Use of the two tracers enabled assessment of the transport of air from the smoking section to the nonsmoking section of the airliner cabin.

In addition to instrumentation for measurement of the ETS contaminants and other pollutants described above, the monitoring package also included a thermohygrometer for measurement of temperature and relative humidity and an analog barometer for cabin pressure.

The thermohygrometer (Solomat Model 455) was a thin film dielectric sensor for measurement of relative humidity (RH) over the range from 0 to 100 percent. The accuracy of the sensor is +_2 percent with a resolution of 0.1 percent RH. Temperature was measured with a platinum RTD having an accuracy of +_0.5 C (0.9 F) and a resolution of 0.1 C.

Cabin air pressure was recorded with a genthe measure (Model 7105-A) analog output barometer. The device has a piezoresistive diaphragm sensor for measurements over a range from 600 to 1100 mbar with an accuracy of ±0.88 mbar.

A Metrosonics DL-714 data logger was used in the instrumentation package to record outputs from the CO detector, MINIRAM RSP monitor, thermohygrometer and barometer. All channels were scanned every 10 seconds and 1-minute averages were recorded. The data logger was downloaded each evening with a personal computer and data were recorded on diskettes.

2.3.2 Configuration of the Monitoring Instrumentation Packaae. All instruments selected for use in this study were compact and lightweight, so that they could be readily configured into an unobtrusive monitoring package in the form of a single carry-on piece of baggage. An example of one of the instrumentation packages is depicted in Figure 2-2.

The basic instrument package included two continuous monitors (CQ and MINIRAM); three low-volume pumps for sample collection; temperature, relative humidity, and pressure sensors; and the data logger. The instrument bag was approximately 18 inches long, 9 inches wide, and 9 inches high, and conformed to regulations for carry-on baggage. The total weight of the bag with instruments was less than 10 pounds. It was typical of bags carried by many airline passengers. Probes were inconspicuously located along the edge of the bag near the handles and zippers for intake of air. The package was designed with external switches such that it did not need to be opened at any time during a flight.

2.3.3 Instrumentation Testing

The measurement methods used in this study were standard or accepted methods, the performance of which have been documented in scientific literature. The monitoring instruments, such as the CO and the RSP monitors, were commercially produced with well-documented performance specifications from previous field monitoring programs by GEOMET and other researchers, as indicated by the references included previously in Table 2-1.

For this study, it was necessary to perform electromagnetic compatibility tests on all of the devices to be used on the aircraft to ensure that they did not interfere with the aircraft navigation or communication systems. These tests were performed by the Federal Aviation Administration (FAA) Technical Center's Communication, Navigation and Spectrum Engineering Branch, ACN-210.

Emission measurements were conducted with the instrumentation package located one meter from the receiver antenna. A calibrated antenna and a spectrum analyzer were used to receive the radiated emissions and a plotter was used to record the data. These emission measurements were conducted over a frequency range of 10-kilohertz (kHz) to 1 gigahertz (GHz). Results of the tests showed that even the worst-case emission levels measured would not be of sufficient magnitude to interfere with aircraft operations.

Also included in the preparation and calibration of instrumentation for the monitoring program were exposures of the MINIRAM optical particle monitors to ETS-generated RSP to derive calibration equations specific to ETS-generated RSP. A series of three exposures was performed in a controlled environment test chamber with relatively constant ETS-RSP concentrations generated by human smokers at low, moderate, and high smoking rates. A second set of tests was conducted in a closed office, where ETS-RSP was generated intermittently to obtain varying RSP concentrations during the measurement period. The MINIRAMs, fitted with the 10-mm cyclone to remove particles larger than 3.5-nm diameter, were collocated with a TSI Model 8510 piezobalance and a triplicate set of Gravimetric filter samplers during each of the five tests. Measurements were made approximately once every 10 minutes with the piezobalance over each 3- to 4-hour test period for comparison to the MINIRAM readings. Results of the piezobalance and MINIRAM measurements were also integrated over the 3-hour period for comparison to the integrated Gravimetric sample.

As shown in Table 2-5, the integrated average concentrations of RSP measured with the piezobalance over the duration of each test were

TABLE 2-5. RESULTS OF TESTS COMPARING RSP MEASUREMENTS WITH GRAVIMETRIC METHOD, PIEZOBALANCE, AND MINIRAMS

Test Number	Average ug/m3 for Method		
	Gravimetric*	Piezobalance**	MINIRAM***
1	169.3 ▒ 57.0	191.1	162.0 ▒ 21.8
2	126.4 ▒ 22.4	140.6	89.5 ▒ 17.3
3	56.8 ▒ 20.3	86.7	62.8 ▒ 15.4
4	170.2 ▒ 39.5	214.2	176.1 ▒ 20.2
5	149.4 ▒ 16.1	261.3	206.0 ▒ 17.5
Average	134.4	178.8	139.3

* Average ▒ standard deviation for triplicate samples collected during test

** Integrated average concentration over the duration of the test

*** Integrated average ▒ standard deviation for multiple instruments higher than both the MINIRAM and Gravimetric measurements in all five tests. The MINIRAM average readings ranged from 64 to 86 percent of the average readings with the piezobalance. The integrated average MINIRAM concentrations d1d not exhibit a bias with respect to the Gravimetric measurements, with the MINIRAM measurements being higher in one case, lower in two cases, and nearly the same in the other two cases.

A linear regression was performed of the MINIRAM measurements against the piezobalance measurements to derive the calibration equations for the real-time optical measurements with each of the eight MINIRAMs used in the study. Piezobalance measurements were used (1) to maximize the number of observations and measurement range underlying the regression equation and (2) for comparability to other ETS fled studies in which piezobalances were used for near real-time measurements (Repace 1987).

For this regression procedure, the measurement obtained by the piezobalance was treated as the independent variable and the MINIRAM measurement as the dependent variable. For the eight units, the calibration equations for the MINIRAM (after rearranging algebraically to predict MINIRAM concentrations relative to the piezobalance as the reference device) had slopes that ranged from 1.08 to 1.33 and the intercept ranged from 0 to 12 ug/m3. The R-squared value for all eight equations was greater than 0.95. The specific equation for each unit was used during data processing to calculate RSP concentrations measured continuously during each flight. As noted by Repace (1987), the piezobalance method may overestimate particle mass at low aerosol concentrations due to artifact formations in the Corona discharge.

Consequently, MINIRAM mass estimates were referenced to the Gravimetric method by multiplying the calibrated results by 0.75, the ratio of Gravimetric to piezobalance results from the chamber tests (Table 2-5).

2.4 SELECTION OF FLIGHTS TO BE MONITORED

2.4.1 Alternative Approaches

Alternative approaches to selecting flights can vary according to features such as (1) completeness of the sampling frame (i.e., set of flights from which the sample is to be selected), (2) degree of stratification of flights (i.e., placement into categories) prior to selection, (3) extent to which randomization is used 1n selecting flights, and (4) associated costs and logistics. Three basic approaches covering the range of alternatives were considered for the study:

- Sample of flights to and from a fixed location
- Stratified sample of flights
  - Sample of flights selected with equal probabilities.

All three approaches included the notion of randomization. For example, for the approach involving flights to and from a fixed location such as Washington, D.C., the other locations (airports) could be selected at random. Thus, this set of flights would involve round trips to and from Washington, D.C. The main advantages of the approach would be lower fares associated with round trips and relatively simple field logistics.

Because each trip would begin and end in Washington, D.C., the costs associated with hotel accommodations and time between flights could also be minimized. Despite these attractions, this approach was dismissed because of the possibility that the relatively narrow sampling frame could result in substantial biases. For example, flights departing from or arriving at Washington, D.C., could have different smoking rates, levels of biological contamination, or ozone levels than flights involving other points of departure or arrival.

A stratified sample of flights would involve grouping flights by major factors expected to cause variations in concentrations before selecting flights within each group at random. Such factors would include type of aircraft (reflecting differences in cabin volume, passenger capacity, air exchange rates, and extent of air recirculation) and geographic area (reflecting different flight paths and possibly differences in ground-level biological contamination or passenger smoking rates).

Major advantages of this approach would be (1) the ability to represent various types of flights and (2) greater control over potential factors affecting measured concentrations.

The stratified sampling approach would essentially involve defining strata representing different types of aircraft (e.g., narrow body and wide body) and different points of departure (e.g., four geographic regions). For an initial subset of flights, each stratum would be represented either equally or in proportion to the number of departing flights. Based on a review of the initial results, the strata with the largest variances could be represented more heavily 1n the next subset of flights to achieve a more efficient sampling design. The ultimate sample of flights chosen in this manner would have known but unequal selection probabilities.

The stratified sampling approach was also rejected, primarily because the need to review initial results would jeopardize the study schedule. Due to time lags associated with laboratory analysis of samples, at least one to two months would be required after monitoring the initial subset of flights for receipt of laboratory results, analysis of these results, and corresponding adjustments to the sampling design. Because some of the field technicians were hired and trained specifically for this project and the study had an extremely tight time schedule, such a hiatus in the field effort could not be entertained.

The approach chosen for this study was to randomly sample flights with equal probabilities of selection. This approach involved developing a list of all flights originating in the United States and selecting flights at random from this list. Through reliance on randomization, this approach has a high likelihood of representing various types of flights. Through use of quota sampling (described later), constraints can also be introduced to guarantee that different types of aircraft are represented. Further advantages of this approach are (1) that development of parameter estimates (e.g., mean concentration, variance about the mean, or proportion of flights with a peak concentration above a certain level) is very straightforward and (2) any modifications to the overall sample size needed to accommodate resource constraints can be accomplished by expanding or contracting the set of flights selected for monitoring, without invalidating the overall sampling design.

2.4.2 Implementation of the Chosen Approach

One possible drawback of the chosen approach (and of the stratified approach as well) is potential inefficiencies in linking together the flights selected for monitoring. For example, if the first flight selected were from New York to Dallas and the second flight selected were from Denver to Atlanta, then additional resources would be required to transport the field team from Dallas to Denver for monitoring of the second flight. This interim flight could not be legitimately monitored because it was not part of the random sample of flights selected for monitoring. The approach described below was designed to reduce this type of inefficiency yet constitute an equal-probability-of-selection method (EPSEM) (Kish 1965).

With recognition that each flight involving a U.S. airport 1s uniquely associated with a specific airport of departure, a random sample of flights can be selected in a different yet virtually equivalent manner. For example, if the number of flights scheduled for a given month is 100,000 and the number of flights to be monitored is 100, then the probability of selection any flight is 1/1,000. If an airport is first selected at random with a probability proportional to the number of flights (n) departing from this airport and a specific flight departing from the airport is then chosen at random as one of the 100 flights to be monitored, then the probability of selection (p) for that flight can be expressed as follows:

$$p = 100 \times (n/100{,}000) \times (1/n) = 1l1{,}000$$

With this approach, the probability of selection (1/1,000) is still the same for any flight, regardless of the airport of departure.

However, the approach offers the added advantage that all airports of departure can be randomly chosen at the outset, after which individual flights can be randomly selected. By imposing the further constraint that the flights chosen for monitoring link the randomly selected airports of departure, the efficiency of the sample can be greatly increased while maintaining a randomized procedure for flight, selection.

Operationally, this procedure required the following steps:

- A set of airports of departure was chosen at random with probabilities proportional to the number of flights departing from each airport; this step was performed separately for 120 airports for smoking flights and 40 airports for nonsmoking flights; sampling was performed with replacement, such that any airport could be chosen more than once.

- Chains of smoking and nonsmoking flights were randomly constructed by initially choosing an airport at random from the set as the starting point, then choosing a second airport of departure from the set at random; for smoking flights, the second airport was chosen subject to the constraint that the flight from the first to the second airport be of sufficient duration to be a smoking flight; for nonsmoking flights, the second airport was chosen subject to the constraint that the flight be of shorter duration (i.e., less than two hours); this process was continued by applying similar constraints in selecting the third airport, and so on.

Chains of flights lasting approximately six days were constructed in the manner described above. Some of the chains consisted of a series of smoking flights followed by a series of nonsmoking flights; this approach was taken so that a team of four technicians responsible for monitoring smoking flights could later split into two teams of two technicians for monitoring nonsmoking flights (see Section 2.6). By design, some of the smoking flights involved international destinations; in these cases, the entire chain involved only smoking flights. Further details on selection of airports and construction of chains are provided below.

Selection of Airports. In constructing chains of flights, difficulties would be encountered if relatively small airports were included, because (1) the number of other airports with which smaller airports connect is limited and (2) the distances flown from smaller airports are generally short, making it difficult to find smoking flights involving such airports. Consequently, candidate airports for selection were restricted to those located in large and medium air traffic hubs (i.e., communities accounting for at least 0.25 percent of the total enplaned passengers in all services and operations in the United States).

According to airport activity statistics compiled by the U.S. Department of Transportation (1987), these hubs collectively accounted for more than 90 percent of all passenger enplanements in the United States during the 12-month period ending December 31, 1987. Within these hubs, the sampling frame was further restricted to 70 individual airports that individually accounted for at least 0.25 percent of 1987 U.S. enplanements. These 70 airports collectively accounted for slightly less than 90 percent of 1987 U.S. enplanements.

For smoking flights, a total of 120 points of departure were selected--102 departure points for domestic flights and 18 points of departure or arrival for international flights. A magnetic tape containing records for all flights scheduled to depart from U.S. airports during January 1989 was obtained from the U.S. Department of Transportation and used to tabulate departures from each airport for domestic smoking flights, domestic nonsmoking flights, and international flights.

Domestic smoking flights were defined as follows:

- Flights of greater than two hours duration for all carriers except United and Northwest Airlines

- Flights for United Airlines of greater than 1,000 miles distance

- Flights for Northwest Airlines involving an airport in H_11 as the port of arrival or departure and an airport in the continental United States as the other port.

These definitions are generally consistent with smoking/nonsmoking designations made by major U.S. airlines. International flights were readily identifiable from a special code provided in the database. All remaining flights (i.e., those that were not domestic smoking flights or not international flights) were defined to be domestic nonsmoking flights.

The 102 points of departure for domestic smoking flights were chosen in accordance with the proportion of smoking flights for which each airport accounted, as tabulated from the data base provided by DOT; that is, the proportion was multiplied by 102 and rounded to the nearest whole number to determine the number of times that the airport should appear in the sample as a point of departure. Thus, apart from differences due to rounding, the sample of 102 points of departure to be used for domestic smoking flights in this study represented airports in virtually the same proportion as these airports were represented by domestic flights departing during January 1989.

In total, 47 airports were selected as departure points (see Table 2-6); of these, 25 airports appeared once in the sample, five appeared twice, 10 appeared three times, three appeared four times, and four appeared five or more times. Dallas-Ft. Worth (DFW) international airport appeared the most times (nine) because its location in the southern central part of the country resulted in many flights of sufficient duration to allow smoking, including flights to the east and west coasts as well as to locations in the northeast and northwest regions of the country. In some cases, individual cities were represented by more than one airport (e.g., Los Angeles by LAX, ONT, and SNA).

International flights were included in the sample to provide flights of greater duration, and possibly with different smoking rates than domestic smoking flights. As summarized in Table 2-7, fewer than 10 percent of the domestic smoking flights were of a 5-hour or greater duration, whereas more than a third of the international flights were of this duration.

Expressing international flights of a 5-hour or greater duration (approximately 10,000) as a ratio to all domestic smoking flights (approximately 122,000) indicates that nine international flight: should be monitored (compared to 102 domestic smoking flights) to preserve this

Table 2-6. Airports of Departure Chosen for Domestic Flights

Airport (City)	Number of Flights	Airport (City)	Number of Flights
Smoking Flights			
DFW a Jas	9	BDL (Hartford)	
ORD (Chicago)	6	BNA (Nashville)	
DEN (Denver)	5	BWI (Baltimore)	
LAX (Los Angeles)	5	CLE (Cleveland)	
ATL (Atlanta)	4	CLT (Charlotte)	
EWR (Newark)	4	CVG (Cincinnati)	
LGA (New York)	4	DAY (Dayton)	
BOS (Boston)	3	DTW (Petroit)	
IAH (Houston)	3	HNL (Honolulu)	
JFK (New York)	3	HOU (Houston)	
MCO (Orlando)	3	IAD (Washington, DC)	
MIA (Miami)	3	IND (Indianapolis)	
PHL (Philadelphia)	3	LAS (Las Vegas)	
PHX (Phoenix)	3	MCI (Kansas City)	
SEA (Seattle)	3	MDW (Chicago)	
SFO (San Francisco)	3	MSP (Minneapolis)	
STL (St. Louis)	3	MSY (New Orleans)	
DCA (Washington, OC)	2	ONT (Los Angeles)	
FLL (Ft. Lauderdale)	2	PBI (West Palm Beach)	
PIT (Pittsburgh)	2	PDX (Portland)	
SLC (Salt Lake City)	2	RDU (Raleigh)	
TPA (Tampa)	2	RSW (Ft. Myers)	
		SAN (San Diego)	
		SJC (San Jose)	
		SNA (Los Angeles)	
Nonsmoking Flights			
ATL Atlanta	3	DEN (Denver)	
ORD (Chicago)	3	EWR (Newark)	
DFW (Dallas)	2	H4U (Houston)	
DTW (Detroit)	2	IAD (Washington, DC)	
LAX (Los Angeles)	2	LAS (Las Vegas)	
MSP (Minneapolis)	2	LGA (New York)	
PIT (Pittsburgh)	2	MCI (Kansas City)	
SFO (San Francisco)	2	MCO (Orlando)	
BNA (Nashville)	1	MEM (Memphis)	
BOS (Boston)	1	PHL (Philadelphia)	
BWI (Baltimore)	1	PHX (Phoenix)	
CLE (Cleveland)	1	RDU (Raleigh)	

CLT (Charlotte)	1	SAN (San Diego)
CVG (Cincinnati)	1	SLC (Salt Lake City)
DCA (Washington, _)	1	STL (St. Louis)

TABLE 2-7. FREQUENCY DISTRIBUTION* BY FLIGHT DURATION FOR DOMESTIC SMOKING FLIGHTS AND INTERNATIONAL FLIGHTS DEPARTING FROM U.S. AIRPORTS

	Percentage of Flights	
Duration of Flight (Hours)	Domestic Smoking	International (Smoking)
C2.0	--	23
2.0 - 2.49	34	8
2.5 - 2.99	27	10
3.0 - 3.99	22	16
4.0 - 4.99	10	6
Z5.0	7	37
Total	100	100

*Based on 122,434 domestic smoking and 27,249 international scheduled flights for January 1989; smoking was permitted on all international flights monitored in this study.

ratio in the study sample. However, in recognition that the statistics in Table 2-7 represent only international flights departing from the United States (i.e., excluding the arriving flights), the number of international flights to be monitored was doubled to 18, yielding a total sample of 120 smoking flights to be monitored.

U.S. airports of departure/arrival for international flights were chosen in proportion to their relative frequencies during January 1989 for such flights, as determined from analysis of the data file provided by the Department of Transportation. International destinations were then chosen from the most frequent destinations for the chosen U.S. airports. As with the domestic smoking flights, some airports were chosen more than once.

The chosen U.S. airports and associated international destinations are summarized in Table 2-8. The only constraint in choosing the international destinations was that each destination be used an even number of times (i.e., once to serve as an airport of arrival and once to serve as an airport of departure). The international arrival/departure points included London for six flights, Frankfurt and Tokyo for four flights each, and Paris and Rio de Janeiro for two flights each.

Points of departure for nonsmoking flights were determined in the same manner as for smoking flights -- by (1) calculating the proportion of nonsmoking flights represented by each airport of departure, as tabulated from the data base provided by DOT and (2) multiplying this proportion by 40 and rounding to the nearest whole number. In total, 30 airports were selected as departure points (see Table 2-6); of these, 22 airports appeared once in the sample, six appeared twice, and two appeared three times.

TABLE 2-8. U.S. AIRPORTS OF DEPARTURE/ARRIVAL CHOSEN FOR INTERNATIONAL FLIGHTS AND ASSOCIATED INTERNATIONAL DESTINATIONS

Airport (City)	Number of Flights	Associated International Destinations(s)
JFK (New York)		Frankfurt, London (2), Paris, Rio de Janeiro
ATL (Atlanta)	2	Frankfurt, London
DFW (Dallas)	2	Frankfurt, London
HNL (Honolulu)	2	Tokyo (2)
BOS (Boston)	1	London
CYG (Cincinnati)	1	London
LAX (Los Angeles)	1	Tokyo
MIA (Miami)	1	Rio de Janeiro
ORO (Chicago)	1	Frankfurt
RDU (Raleigh)	1	Paris
SFO (San Francisco)	1	Tokyo

Construction of Chains. As mentioned previously, two types of chains were developed:

- Chains involving domestic smoking flights and international flights

- Chains involving domestic smoking and nonsmoking flights.

Six chains were initially developed using a subset of airports drawn from the randomly selected pool of 102 airports of departure for domestic smoking flights, 18 airports of departure/arrival for international flights, and 40 airports of departure for domestic nonsmoking flights.

One-third of the airports (i.e., 34 for smoking flights, 6 for international flights, and 13 for nonsmoking flights) were chosen at random from the larger pool as a basis for constructing these six initial chains.
Based on the costs incurred in monitoring this initial subset of flights, it would then be possible to determine the number of additional flights that could be monitored with the remaining resources.

The distribution of flights (i.e., domestic smoking, international, nonsmoking) for each of the initial six chains is summarized in Table 2-9. All chains included domestic smoking flights; three of the chains also included international flights and the other three chains also including nonsmoking flights. Each chain began with an airport of departure for a smoking flight.

An example chain that included international flights is shown in Table 2-10. The type of flight is indicated in the first column as S (domestic smoking), I (international) or P (positioning). Positioning flights were needed to transport field technicians from Washington, OC to the first airport of departure for the chain and from the final airport of arrival back to Washington; these flights were not monitored. Boston was randomly selected as the first airport of departure for this chain, requiring an initial positioning flight from Washington to Boston. The only other constraint in constructing the chain was that the last smoking flight end at an airport of departure for the first international flight;

TABLE 2-9. DISTRIBUTION OF FLIGHTS TO BE MONITORED FOR THE FIRST SIX FLIGHT CHAINS DEVELOPED FOR THE STUDY

	Number of Flights		
Chain	Domestic Smoking	International (Smoking)	Nonsmoking
A	6		5
B	7		3
C	6	--	5
D	5	2	--
E	5	2	--
F	5	2	--
Total	34	6	13

TABLE 2-10. ILLUSTRATIVE CHAIN INVOLVING INTERNATIONAL FLIGHTS

Type of Flight*	Dny of Monitoring	Airport of Departure	Airport of Arrival	Local Time of Departure	Local Time of Arrival	Duration (Hours)
P	1	DCA	BOS	8:40	10:00	1.33
S	1	BOS	MCO	12:15	15:04	2.81
5	2	MCO	DFW	7:08	8:50	2.70
S	2	OFirl	ORD	11:05	13:18	2.22
S	3	ORD	DFN	7:39	10:01	2.37
S	3	DFii	JFK	12:05	16:38	3.58
I	4	JFK	FRA**	18:45	8:20	7.58
I	6	FRA	ORD	14:25	17:05	8.67
P	6	ORD	DCA	19:20	21:58	1.63

* P = positioning flight (not monitored); S = domestic smoking flight;
I = international flight

** Frankfurt

this airport was randomly selected from the two (JFK and ORD) associated with the international destination (Frankfurt) that was randomly chosen for this chain. A final positioning flight was required to transport the field team from the last arrival point (Chicago) to Washington.

In most cases, two domestic smoking flights could be monitored per day (the first day was an exception because of the need for a positioning flight). The domestic smoking flights for this chain ranged in duration from 2.2 to 3.6 hours. By comparison, both international flights were close to eight hours in duration, meaning that only one such flight could be monitored per day. In addition, due to the relatively long flight duration coupled with required pre- and post-flight duties, the technicians remained at the international destination for a day before monitoring the return flight.

An example chain that included nonsmoking flights is shown in Table 2-11. Six smoking flights and five nonsmoking flights were monitored for this chain. A positioning flight was required to get the technicians from Washington to the startling point for the chain (La Guardia airport in New York). The last smoking flight was constrained to arrive at an airport of departure (San Francisco) for a nonsmoking flight.

Because the team of four technicians split into two teams of two technicians (designated A and B in the table) and San Francisco could be used as a departure point for only one flight, a positioning flight was required to transport the B team to Kansas City (MCI), the other randomly selected starting point. The B team's last monitored flight ended in Washington but the A team's last monitored flight ended in Denver, requiring a positioning flight to return them to Washington. The smoking flights had durations ranging from 2.1 to 4.2 hours and the nonsmoking flights ranged in duration from 0.7 to 2.2 hours. Thus, the longest nonsmoking flight exceeded two hours, but the carrier (United) has a nonsmoking policy for flights of fewer than 1,000 miles.

In monitoring the first six chains, it was found that the resources required for the field team were nearly double those antici-

Table 2-II. ILLUSTRATIVE CHAIN INVOLVING NONSMOKING FLIGHTS

Type of Flight*	Day of Monitoring	Airport of Departure	Airport of Arrival	Local Time of Departure	Local Time of Arrival	Duration (Hours)
P	1	IAD	LGA	7:00	7:59	0.98
S	1	LGA'	MIA	9:30	12:30	3.00
S	2	MIA	PHL	7:15	9:53	2.63
S	2	PHL	ATL	12:30	14:36	2.10
S	3	ATL	SLC	11:49	13:35	3.77
S	3	SLC	MSP	16:25	19:46	2.35
S	4	MSP	SFO	8:20	10:33	4.22
N-A	4	SFO	SAN	12:50	14:18	1.47
N-A	4	SAN	LAX	16:30	17:14	0.73
N-A	5	LAX	DEN	8:00	11:13	2.22
P-A	5	DEN	IAD	13:25	18:52	3.45
P-B	4	SFO	MCI	12:00	17:11	3:18
N-B	5	MCI	BNA	12:47	14:16	1.48
N-B	5	BNA	IAD	18:20	20:56	1.60

*P = positioning flight (not monitored); S = domestic smoking flight;
N = domestic nonsmoking flight; A and B indicate teams of two technicians each from the starting team of four technicians.

pated, due to (1) fare increases, (2) the resources required for positioning flights, (3) flight delays that generally increased layover times when multiple flights were monitored on a single day, and (4) technician activities at the end of each monitoring day and at the end of each chain.

It was determined that the remaining resources enabled monitoring of 39 additional flights; these flights were divided among four chains, as summarized in Table 2-12. In total, 92 flights were monitored--69 smoking flights (including eight international flights) and 23 nonsmoking flights.

2.5 MONITORING PROTOCOL

2.5.1 Monitorin9 Locations

During the program, teams of four technicians performed air quality monitoring on smoking flights. Teams of two technicians performed the monitoring on nonsmoking flights.

Air quality monitoring was performed by each technician at an assigned seat. Technicians could not move about the aircraft to perform any measurement activities. The four monitoring locations selected on each smoking flight included the following:

- Coach smoking section
- Nonsmoking section -- boundary (within three nonsmoking rows of the coach smoking section)
- Nonsmoking section -- middle
- Nonsmoking section -- remote (i.e., most remote rows from the coach smoking section, except on international flights, on which seat was in business class).

Examples of the target monitoring locations for three different types of aircraft are depicted in Figure 2-3. Some aircraft, such as the Boeing 747 and DClO, sometimes have the coach smoking section in the front of the coach nonsmoking section. As shown in the figure, the monitoring location in the smoking section was generally near the rear of the section to facilitate accurate counting by the technician of smoking during the

TABLE 2-12. DISTRIBUTION OF FLIGHTS TO BE MONITORED FOR THE LAST FOUR FLIGHT CHAINS DEVELOPED FOR THE STUDY

	Number of Flights		
Chain	Domestic Smoking	International (Smoking)	Nonsmoking
G	6	5	
H	6	5	
I	5	Z	
	10		
Total	27	2	10

flight. The target boundary monitoring location was within three rows of the smoking section. Although technicians in the boundary section were assigned seats in advance of the flight, they were instructed to change seats if the size of the smoking section was modified at the time of passenger check-in in order to stay within three rows of the smoking section. Technicians were not assigned to the first-class section, but the remote location in the coach section was to be within two to four rows of first class. Technicians could not sit in the first row of the coach section or at any bulkhead sections because the instrument package needed to be stored under n sent in front of them for takeoff and landing.

On international flights, which were all smoking flights, one technician was located in the nonsmoking portion of the Business class section. This location was used instead of the nonsmoking random location. The size of the business class section on international flights is significant and it usually has multiple rows allocated to smoking. The number of smokers and their close proximity to nonsmokers warranted monitoring in this section.

On nonsmoking flights two locations were monitored. Those locations corresponded to the locations depicted in Figure 2-3, labeled as (1) nonsmoking section -- middle and (2) smoking section.

Within each assigned section, the seat was selected randomly so that middle, aisle, and window seats would each be represented during the study.

During the flight, the monitoring instrumentation package was placed on the technician's lap or the seat in front, resulting in measurements at a height within approximately 12 inches of the technicians breathing zone. The technician was allowed to place the monitoring package on an adjacent unoccupied seat to facilitate trips to the lavatory or eating on longer flights. The instrument package was stored under the seat during takeoff and landing. However, as described in a following subsection, this period did not include the period of integrated measurements of nicotine and RSP.

ETS contaminants and the physical parameters were measured at all locations on each flight. However, the other pollutants were measured at a subset of locations, as summarized in Table 2-13.

2.5.2 Monitoring Schedule

Field monitoring activities for this study were initiated in March 1989, by conducting a pretest that included four flights over a 3-day period. Details of the pretest are described in Section 2.6.

The formal monitoring program was initiated on April 4, 1989. Two teams of four technicians each performed monitoring on ten chains of flights. Each chain covered periods of 5 to 8 days with 7 to l2 flights per chain. International flights were included in some chains. Monitoring continued during May and was completed in June 1989. A total of 92 flights were monitored over a period of approximately ten weeks.

Chains were started on each of the seven days of the week to provide full temporal coverage on a weekly basis. Chains also varied in duration, such that the technician's day of return to the Washington, DC area also spanned the range of the seven days of the week.

Temporal representation of the time of day for flights was achieved in the study by scheduling departures over a complete range of times from early morning to early evening.

2.5.3 Field Monitoring Protocols

Field monitoring protocols were developed to ensure uniform operational procedures by the technicians during the performance of the monitoring program. Conformance to these protocols was documented in "Daily Log" documentation forms completed by each technician on each day of monitoring.

The "Daily Log" used for documenting field activities was divided into the following five sections that were bound into a single booklet:

- Start of Day Documentation Log
- Flight Documentation Log (1st Flight)
  - Pre-Flight
  - 1st Flight
  - Post-Flight
- Flight Documentation Log (2nd Flight)
- Flight Documentation Log (3rd Flight)
- End of Day Documentation Log.

The following summary of the operational protocol for the field monitoring activity includes exchanges of pages from the log to describe the operational procedures.

The daily activities for the monitoring program can be broken into these categories:

- Start of Day preparations
- Monitoring of flights
- End of Day calibrations, instrumentation checkout, sampler handling, and chain of custody procedures.

Figure 2-4 depicts a page from the Start of Day Documentation Log that shows the types of checkout activities that occurred at the start of each day. These activities included the following:

- Programming of the data logger
- Checkout and zero reading of the MINIRAM
- Operational checkout of the CO monitor
- Operational checkout of the temperature, relative humidity, and pressure sensors

START OF DAY DOCUMENTATION COC Page 2 of 3

Date: / / lech:

(3) MINIRAM Checkout

( ] Press TIME and MEAS _o get C.GO
[ ] Turn on pump (Switch 3)
( ] Check that pump is operating
( ] Data logger to CH1
( ] Wait 2 minutes
( ] CH1 Readings: mV, mV, mV
( ] Previous night's zero reading was: mV
( ) Check pump battery (If light does not come on or
Low Batt displayed, replace battery.)
Battery OK? ( ) Yes ( ) No
If no, battery replaced? ( ) Yes ( ] No
( ] Turn pump OFF
( ) Turn MINIRAM OFF

(4) CO Detector Checkout

( ] Turn ON
( ) Battery OK?
( ] Data logger to CH2
( ] Wait 2 minutes
[ ] CH2 readings: mY, mV, mY
( ) Detector panel meter reading: ppm
[ ] Turn detector OFF

(5) Solomat Checkout

( ] Solomat ON (Switch 1)
[ ] Data logger to CH3
[ ] CH3 readings: F, F, F
( ] Press NEXT on data logger for CH4
[ ] CH4 readings: rh, rh, rh
[ ] Turn Solomat OFF

FIGURE 2-4. EXAMPLE OF PAGE 2 OF THE START OF DAY DOCUMENTATION LOG

- Operational checkout of all pumps
- Operational checkout of the microbial aerosol sampler
- Inventory of samplers for the day
- Final preparations for the day's flights.

All "Start of Day" preparations were performed at the technician's hotel just prior to departure for the airport.

After arrival at the airport, check-in of luggage, and passage through security, the technician proceeded to the boarding area to perform pre-flight activities. Pre-flight activities, summarized on page 1 of the FLIGHT DOCUMENTATION LOG (Pre-Flight), depicted in Figure 2-5, included the following:

- Sampler identification numbers were recorded on the log
- The nicotine/RSP-sampling cassette was loaded on the cyclone assembly
- The ozone cassette was installed
- PFT sources and samplers were logged, as appropriate
- The temperature, relative humidity, and pressure sensors were turned on
- The MINIRAM and CO detectors were turned on
- The operational status of the data logger was verified.

As part of the pre-flight activities, the technicians in the boundary and smoking sections also checked their seat locations at the gate in case the size of smoking section was changed during gate check-in.

Technicians boarded the planes as regular passengers, with no special pre-boarding requirements. After taking their seats, the technicians began sampler deployment, monitoring and documentation activities.

The operational protocol for each flight is summarized in Table 2-14. The

FLIGHT DOCUMENTATION LOG (Pre-flight   Page 1 of 9
(1st Flight)

Airline: Flight No.:

Date: /   /   tech:

Prepare New Samplers

(1) Nicotine Cassette number:

( ) Bottom of cassette faces up
( ) Cyclone assembly locked in place
( ] All sampling lines connected (Inlet_cyclone_pump)
( ) Sample line inlet capped

(2) C02 Diffusion Tube number:

(3) Ozone Cassette number:

(4) CAT Sampler number:

(5) PFT Sources with this package:

( ] None
( ] Silver (NS + S sections)
( ] Blue   (NS only)
[ ] Lime   (S only)

[Turn _N _sensors_   Time:

[ ] Solomat ON (Switch 1)
( ] Pressure sensor ON (Switch 2)
[ ] MINIRAM ON (TIME + MEAS)
[ ] CO detector ON
[ ] Is the data logger collecting data (displays L)?
( ] Yes   ( ] No
( ] If no, reprogrammed to start at:
[ ] Is battery OK? (Change if Low Battery is displayed

Comments:

FDLO2 (3/29/89)

FIGURE 2-5. EXAMPLE OF THE PRE-FLIGHT LOG, PAGE 1 OF THE FLIGHT DOCUMENTATION LOG

TABLE 2-14. SUMMARY OF THE OPERATIONAL PROTOCOL FOR AIR QUALITY MONITORING ON A FLIGHT

Time Period Activity

Post-boarding - Technician in smoking section checks that ashtrays are empty

- PFT sources deployed
- Temperature/RH sensor exposed
- Sampling lines exposed and uncapped
- MINIRAM pump turned on
- Instrument bag placed under set for takeoff
- Documentation log entries made

Depart gate - Record time

Takeoff - Record time

Airborne: No smoking light - Start nicotine/RSP pump
turned off
- Open C02 diffusion tube
- Uncap CAT (PFT) sampler
- Make log entries

Cruise altitude (15 minutes - Turn ozone pump on
after no smoking light - Make log entry
turned off)

Smoking period - Technician in smoking section records number of smokers on 15-minute intervals

Pre-descent - Perform microbial aerosol sampling

Cruise descent (30 minutes - Turn off ozone pump before scheduled arrival)

No smoking flight on - Turn off nicotine/RSP sampler
- Cap CAT (PFT) sampler
- Read CO2 diffusion tube
- Stow bag under seat for landing
- Make log entries

Gate arrival - Turn off MINIRAM pump
- Cap sampling lines

- Collect cigarette butts
- Collect information on passenger load and previous flight
- Deplane

activities summarized in the table were documented on pages 2 through 9 of the Flight Documentation Log. Page 3, depicted in Figure 2-6, for example, was used to record activities related to the start of sample collection.

The technician assigned to the smoking section was responsible for a series of activities related to smoking. As shown in Figure 2-7, this technician completed n section on snaking information and also made counts at 15-minutes intervals of the number of cigarettes being smoked.
At the end of the flight this technician also collected cigarette butts from ashtrays. These were then counted in the airport to obtain an accurate count of cigarettes smoked. It the butts could not bc collected from all seats in the smoking section due to time constraints, the number of seats of collection was recorded.

After deplaning, the technician performed a series of procedures in the airport that included turning off various sensors, removing sampling media, and documenting sampler IOs. These activities were recorded on page 9 of the Flight Documentation Log.

The On-fly Log contained identical but color-coded sections for up to three flights a day. On days with multiple flights, the pre-flight, flight, and post-flight protocols described above were repeated and documented.

The final section of the Dafly Log was the END OF DAY DOCUMENTATION LOG used to record instrument checkout and calibrations following the last flight of each day. These activities, summarized on the 8 pages of this section of the log, included the following:

- Downloading, verification, and backup of data to diskette
- Checkout of tarperztsre/relative humidity sensor
- Checkout of pressure sensor
- CO detector checkout and maintenance

FLIGHT DOCUMENTATION LOG (2nd Flight) Page 3 of 9

Airline: Flight:

Date: ! / Tech:

[Board_ng 1 Time:

( ] PFT Sources deployed:
( ) Sampling Lines and Temp%Ri_Sensor Exposed
( ] Uncap sampling lines
( ] MINIRA_I pump ON (Switch 3): _ _ _ _

[Depar Gate Time:

a to Time: _

[Airborne: _I- g Time:

( ] Nicotine pump ON (Switch 4):
( ] CO diffusion tube opened:
( ] CA_ sampler uncapped: _ _ _ _

[Cruise due Time:

( ] Ozone pump ON: _ _
(15 minutes after N-S light OFF)
Comments:

FIGURE 2-6. EXAMPLE OF PAGE 3 OF THE FLIGHT DOCUMENTATION LOG USED TO DOCUMENT THE START OF THE SAMPLE COLLECTION

FLIGHT DOCUMENTATION LOG (1st Flight)   Page 4 of 9

Airline: Flight No.:

Date: /   /   Tech:

_Smoking   section Information

Ashtrays empty at start of flight: ( ] Yes   ( ) No

Smoking rows: to
Number of passengers n smoking section:
Number of passengers in boundary section:
(Three rows nearest to smoking section)

-- A -minute intervals
beginning on first 5-minute block after N-S flight of

Time	Count	Time	Count

FDLO2 (3l29/89)

FI6URE 2-7. EXAMPLE OF THE PAGE OF THE FLIGHT DOCUMENTATION LOG USED TO RECORD SLICING SECTION COUNTS

- ╥ Zero and span of the CO detector
- ╥ Zero reading of MINIRAM
- ╥ Calibration of MINIRAM pump
- ╥ Calibration of nicotine/RSP sampling pump
- ╥ Calibration of ozone sampling pump
- ╥ Calibration of duplicate sampling pumps
- ╥ Archival of all samplers

╥ Shipment of microbial aerosol samples

- ╥ Completion of logs
- ╥ Chain of custody procedures.

2.5.4 Quality Assurance and Quality Control Procedures

Quality assurance (QA) 1s an important element of field monitoring program. For this study, a QA program was developed that included appropriate quality control (QC) procedures to ensure that monitoring instrumentation was performing properly in the field and that precision and accuracy of the measurement results conformed to QA objectives.

QC procedures during the monitoring program are summarized in Table 2-15 and briefly described below.

Quality control procedures for integrated samples, including nicotine, RSP, and ozone, consisted of measurements of sampler pump flow rates in the field on a daily basis, submission of field blanks and duplicates to the analytical laboratory, and standard laboratory QC procedures.
Sampling pump airflow rates were measured with Matheson precision rotseters calibrated 1n GEOMET's laboratory against an NBS-traceable Teledyne-Hastings mass flowmeter. The airflow rates of sampling pumps were measured at the end of each day and were adjusted and recalibrated if the flow differed by more than 5 percent of the target flow rate.

Over ten percent of the total number of nicotine, RSP and ozone samplers were dedicated as quality assurance samples, as shown in

TABLE 2-15. SUMMARY OF QUALITY CONTROL PROCEDURES IMPLEMENTED DURING THE MONITORING PROGRAM

Parameters	QC Procedures	Number of QC Samples	Total Number of Samples	Percent QC Samples
Nicotine	Field blanks	20	322	6
	Field duplicates	35	322	11
	Analytical blanks	1 per session		
	Analytical spikes	3 per session		
	Duplicate injections	322	322	l00X
RSP (Gravimetric)	Field blanks	20	322	6
	Field duplicates	35	322	11
	Control filter	1 per session		
Ozone	Field blanks	21	123	17
	Field duplicates	8	123	6
	Analytical spikes	5 per session		
	Analytical blanks	3 per session		
Carbon dioxide	Field blanks	N/A	161	9
	Field duplicates	14	161	
Carbon monoxide	Iero check (field) -- 2 to 3 times/week*			
	Span check (field) -- 2 to 3 times/week*			
	multipoint calibrations -- twice weekly			
RSP (optical)	Zero check (field) -- twice daily			
Microbial aerosols	Sampler flow checks -- weekly			
Sampler pump airflow rates	Calibration with precision rotameters -- daily			
Sampler transfers	Chnln-of-custody procedures			

*Dependent on duration of each chain

Table 2-15. These were submitted to the analyst as routine samples. In the laboratory, the QC procedures included analytical blanks, analytical spikes, multipoint calibrations of the gas chromatograph or spectrophotometer and control filters for RSP.

Multipoint calibrations of the CO detectors using certified calibration gases were performed at the GEOMET Indoor Air Laboratory at the beginning and end of each chain. Additionally, the performance of the CO detectors was assessed in the field by means of zero and span checks. Zero air and calibration gas at a concentration of _.65 ppm of CO were carried by each team of technicians in gas sampling bags. Air was drawn from the bags by the detectors during the End of Day activities to obtain zero and span check rending.

Chain-of-custody procedures were implemented throughout the field monitoring program to document transfers of sampler media and documentation logs. An example of the chain-of-custody log 1s depicted in Figure 2-8. As shown in the figure, every transfer of sampler media required the signature of the recipient, who then assumed responsibility for that sampler. Similar forms were used to document shipments to the analytical laboratories.

2.6 PRETEST PROTOCOL AND RESULTS

2.6.1 Pretest Protocol

A pretest was performed prior to the formal field monitoring program. Activities in the pretest mimicked, to the fullest extent possible, the field monitoring program. The pretest provided a final shakedown of instrumentation, measurement methods, and operational protocols; results of the pretest were used to refine operational protocols and documentation procedures.

The pretest for the monitoring program was performed in March 1989. It consisted of monitoring on four commercial airline flights over a three-day period. The flights were selected and developed into a chain that originated and terminated 1n Washington, DC, to mimic the chaining procedure that would be used in the formal monitoring program. Aircraft represented in the four flights included a 767, DC-10, and two 737-300s.

The four flights monitored were smoking flights, with durations of 4 to 5.5 hours. Flights of longer duration were selected for the pretest because one objective was to assess spatial variation of nicotine and RSP concentrations. To address this objective, eight locations were selected in each aircraft to examine horizontal variations. At four of the eight locations, a vertical array was configured to sample nicotine and RSP at 25 cm (10 inches) and 150 cm (59 inches) above the floor, in addition to the breathing-height sample. Integrated samples were collected throughout the "smoking" period.

The pretest was also used to assess various methods for obtaining information on smoking during the flight. Three different approaches to counting smokers were used:

- Counting smokers at 15-minute intervals
- Counting smokers at 10-minute intervals
- Counting smokers during visits to the lavatory at fixed intervals.

These counts were compared to counts of smokers made on n continual basis by one or two technicians seated in the smoking section. The results of the various counting methods were also compared to the number of cigarette butts collected from the ashtrays at the end of the flight.

The pretest provided an opportunity to test procedures for measurement of air exchange rates with the PFT method. PFT deployment and sampler placement methods were tested at all eight locations in the airliner cabin to determine the appropriate sites for placement of sources and samplers.

In addition to the shakedown of methodologies and instrumentation, the pretest conducted on commercial flights provided the opportunity to assess logistical problems related to airport security clearance;
pre-flight and post-flight activities in airport waiting areas; start-of-day and end-of-day preparation, maintenance and calibration activities; and passenger and flight attendant reaction to technician activities.

2.6.2 Pretest Results

The four pretest flights provided a good range of smoking rates, with cigarette butt counts ranging from a low of 33 on the second flight (Boeing 737-300 aircraft) to a high of 166 cigarette butts collected on the first flight (Boeing 767).

On the four flights, nicotine concentrations ranged from non-detectable to 67.6 ug/m3, as shown in Table 2-16. Concentrations of nicotine 1n samples collected in the smoking and boundary sections were highly variable. There were no clear biases in concentration related to sampler height, with three of five sample sets collected in smoking sections having the highest nicotine concentration (in the vertical plane) located near the floor and the other two having highest concentrations at 60 inches (i.e., above breathing height).

RSP concentrations on the four flights ranged from 8 to 317 Ng/m3 (Table 2-17). Concentrations were generally lowest in the nonsmoking sections, highest in smoking sections, and intermediate in the boundary section. There was often substantial vertical variation. For the sample sets, the highest concentrations were measured near the floor, whereas
three sample sets had the highest concentration at the 150-cm height.

Results of nicotine and RSP measurements confirmed that selection of the four target locations for monitoring (smoking, boundary, nonsmoking middle, and nonsmoking remote) would be appropriate and required for data interpretation. The measurements performed at the three heights above the floor did indicate substantial differences in concentrations at the three heights. Although the data base for the four flights was too small to

Table 2-16. NICOTINE CONCENTRATIONS MEASURED AT EIGHT LOCATIONS ON FOUR PRETEST FLIGHTS

Seat Location (section)	S_n_n 1 e r Height*	Nicotine Concentration (ug/m3) Flight 1	Flight 2	flight 3	Flight 4
Nonsmoking	High	0		0	0
(Remote) -1	Middle	0	0	0	0
	Low	0.2		0	0
Nonsmoking	High				
(Ranote) -2	Middle	0			0
	Low				
Nonsmoking	High	0	0.4	0	0
(Middle) -1	Middle	0	0	0	0
	Low	0	0	0	0
Nonsmoking	High				
(Middle) -2	Middle	0	0	0	0
	Low				
Boundary -1	High				0
	Middle	0	1.7	0.3	0
	Low	0			
Boundary -2	High				
	Middle		9	0	0
	Low				
Boundary -3	High		**	0	
	Middle		**	0	
	L_		0	5.9	
Smoking -1	High	29.3	12.9	1.0	0.7
	Middle	33.0	7.0	0.3	0.3
	Low	54.6	1.2	6.1	0.3
Smoking -2	High				
	Middle	67.6	2.5	0.9	1.7
	Low				

Smoking -3	High	44.1
	Middle	31.8
	Low	48.3

* Samples placed at "high" were 150 cm above the floor, at "medium rare near breathing height, and at "low" were 25 cm above the floor. Samples were collected at the three heights at four of eight locations. At the other four locations, samples were collected only at the "middle" height.

** Samples invalid

TABLE 2-17. RSP CONCENTRATIONS MEASURED AT EIGHT LOCATIONS ON FOUR PRETEST FLIGHTS

Seat Location (section)	Sampler Height*	RSP Concentration (ug/nr3) Flight 1	Flight 2	Flight 3	Flight 4
Nonsmoking	High	36		59	55
(Remote) -1	Middle	63	'74	46	120
	Low	46		56	58
Nonsmoking	High				
(Remote) -2	Middle	44			61
	Low				
Nonsmoking	High	34	8	117	67
(Middle) -1	Middle	32	╖-	70	67
	Low	27	51	73	56
Nonsmoking	High				
(Middle) -2	Middle	87	34	72	22
	Lo_r				
Boundary -1	High				60
	Middle	151	29	80	67
	L_			127	
Boundary -2	High				
	Middle		83	79	72
	Low				
Boundary -3	High		**	5g	
	Middle		**	132	
	L_		63	145	
Smoking -1	High	177	164	143	150
	Middle	197	223	114	180
	r	**	133	199	195
Smoking -2	H1 gh				
	Middle	317	I99	269	163
	Low				
Smoking -3	High	161			
	Middle	183			
	Low	210			

* Samples placed at "high" were 150 cm above the floor, at "medium" were near breathing height, and at "low" were 25 cm above the floor. Samples were collected at the three heights at four of eight locations. At the other tour locations, samples were collected only at the "middle" height.

** Samples invalid

determine the significance of the differences, the data suggested that measurements in the formal monitoring program should be performed with the instrument package on the technician's lap or lap tray to obtain measurements of contaminants most representative of the passenger breathing level.

Correct placement of the PFT sources and samplers in the airliner cabin was essential to the performance of the measurement system. Because the n siber of technicians during the monitoring program would be limited to our on smoking flights and two on nonsmoking flights, tests were performed during the pretest flights to determine how source and sampler locations could be optimized. For example, during the pretest some technicians carried both sources and samplers to determine how far the source needed to be from the sampler.

Results of a1r exchange measurements during the pretest are presented in Table 2-18 and compared to nominal air exchange rates for the four flights. For three cases where technicians sat within one row of one another measurements with the samplers agreed within 6 percent of each other. Air exchange rates were underestimated by as much as 80 percent, if the samplers were located at the same seat location as the sources, but separation of sources and samplers by as little as one row of seats yielded acceptable measurement results. Based on the results, deployment of sources by technicians in the nonsmoking (remote) and smoking sections and samplers at the other two seats was used in the study.

During the pretest flights, two different counting methods and three different estimation methods were used to estimate the number of cigarettes smoked during a flight. The counting methods consisted of (1) counting or collection of cigarette butts f ran ashtrays at the end of the flight and (2) recording of every smoking event independently by two technicians. The estimation methods included (1) recording the count of smoking events observed during a one-minute interval every 10 minutes, (2) recording the count of smoking events observed during a one-minute interval every 15 minutes, and (3) recording the count of cigarettes being smoked during a trip to the lavatory every 30 minutes.

Results of the counting and estimation tests are shown in Table 2-19. Compared to the counting of butts, the most definitive method 1n the pretest because of airline cooperation" the 15-minute interval counts appeared to be the most appropriate method for estimation of smoking events. Both 10-minute interval and l.5-minute interval counts gave reasonable estimates on some of the fights, but 10-minute intervals did not improve the accuracy of this estimation method. The major factor affecting the accuracy of smoking counts was seat location. The ability to see smokers in front of the technician most strongly affected counting accuracy, and technicians seated toward the front of the smoking section tended to underestimate smoking rates. Therefore, seat locations near the rear of the smoking section were to be selected for the formal monitoring program. Technician trips to the lavatory as a method to count smokers were not logistically feasible due to food and beverage service and resulted 1n highly inaccurate counts on two of the four flights.

During the pretest flights, attempts were made initially to count the number of cigarette butts in the ashtrays on the aircraft at the end of the flight. This was generally difficult. Collection of cigarette butts in bags at the end of the flight for subsequent counting in the airport proved to be a better approach, particularly on flights requiring a fast turnaround. This method was used in the normal monitoring program.

2.7 REFERENCES

Akland, G.G., T.O. Hartwell, T.R. Johnson, and R.W. Whitmore, 1985. 'Measuring Henan Exposure to Carbon Monoxide in Washington, D.C. and Denver, Colorado, During the Winter of 1982-83." Environ. Sci. Tech. 19:911-918.

ASHRAE, 1989. "Ventilation for Acceptable Indoor A1r Quality" ANSI/ASHRAE 62-1989. American Society of Heating, Refrigerating, and A1r Conditioning Engineers.

ASHRAE, 1985. ASHRAE Handbook -- 1985 Fundamentals. American Society of Heating, Refrigerating, and Air conditioning engineers, Atlanta, GA.

Burge, H.A., M. Chatigny, J. Feeley, K. Kreiss, P. Morey, J. Otten, and K. Peterson, 1987. 'Bioaerosols--Guidelines for Assessment and Sampling of Saprophytic Aerosols in the Indoor Environment" Appl. Indust. Hya. 2(5):R-10 to R-16.

Cochran, W.C., 1963. Sampling Techniques. John Wiley and Sons. New York, NY.

Dietz, R.N. and E.A. Cote, 1982. 'Air Infiltration Measurements in a Home Using a Convenient Perfluorocarbon Tracer Technique." Environ. Intern. 8:419-433.

Federal Aviation Administration (FAA). 1989. Radiation Exposure of Air Carrier Crewmembers. AAM-624. FAA, U.S. Department o transportation.

Hammond, S.K., B.P. Leaderer, A.C. Roche, and M. Schenker, 1987. 'Collection and Analysis of Nicotine As Marker for Environmental Tobacco Smoke." Atmos. Environ.. 21(2):457-462.

Ingebrethsen, B.J., D.L. Heavner, A.L. Angel, J.M. Conner, T.J. Steichen, and C.R. Green, 1988. "A Comparative Study of Environmental Tobacco Smoke Particulate Mass Measurements for an Environmental Chamber." J. Air Poll. Control Assoc. 38:413-417.

Klsh, L., 1965. Survey Sampling. John Wiley & Sons, Inc., New York, NY.

Langbert, J.L., J.Y. Paukstelis, and Y.C. Chiang, 1989. "3-Methyl-2-benzothlazolinone Acetone Azine with 2-Phenylphenol as a Solid Passive Monitoring Reagent for Ozone.' Environ. Sci. Technol. 23:241-243.

Leaderer, B.P., Cain, W.S., Isseroff, R. and Berglund, L.G., 1984. "Ventilation Requirements in Buildlngs -- II. Particulate Matter and Carbon Monoxide From Cigarette Smoking." Atmos. Environ. 18(1):99-106.

Lynch, A.L., 1981. Evaluation of Ambient Air quality Personnel Monitoring. CRC Press, Inc. Boca Raton, L.

Muramatsu, M., S. Umemura, T. Okada, and H. Tomita, 1984. 'Estimation of Personal Exposure to Tobacco Smoke with a Newly Developed Nicotine Personal Monitor." Environ. Res. 35:218-227.

Nagda, N.L. and M.D. Koontz, 1985. "Microenvironmental and Total Exposures to Carbon Monoxide for Three Population Subgroups." J. Air Poll. Control Assoc. 35(2):134-137.

Nastrom, G.D. and J.D. Holdeman, 1980. T Date

Administration, Washington, D.C.

National Research Council, 1986. Environmental Tobacco Smoke: re Exposures And Assessing Health Effects. Academy Press. Washington, D.C.

NIOSH, 1977. NIOSH Manual of Analytical Methods, Vol. 3, 2nd edition, Publication No. -1 - , National Institute of Occupational Safety and Health, U.S. Department of Health, Education and Welfare.

Oldaker, G.B. III and F.C. Conrad, Jr., 1987. 'Estimation of Effect of Environmental Tobacco Smoke on Air Quality Within Passenger Cabins of Commercial Aircraft." Environ. Sci. Technol. 21(10):994-999.

Ott, W.R., C. Williams, C.E. Rodes, R.J. Drago, and F.J. Burman, 1986. "Automated Data-Logging Personal Exposure Monitors for Carbon Monoxide" J. Air Poll. Control Assoc. 36(8):893-887.

Repace, J.L., 1987. "Indoor Concentrations of Environmental Tobacco Smoke: Field Surveys," in Environmental Carcinogens Methods of Analysis and Exposure Measurement Volume --Passive smoking, International Agency for Prevention of cancer scientific Publications No. 91, Lyon, France.

Repace, J.L., and A.H. Lowry, 1982. "Tobacco Smoke, Ventilation and Indoor A1r Quality." American Society of Heating, Refrigeration and Air Conditioning Engineers transactions . 4- 14.

Repace, J.L., and A.H. Lowry, 1980. "Indoor A1r Pollution, Tobacco Smoke and Public Health." Science 208:464-472.

Rlckert, W.S., J.C. Robinson, and N. Collishaw, 1984. "Yields of Tar, Nicotine, and Carbon Monoxide in the Sidestream Smoke From 15 Brands of Canadlan Cigarettes." Am. J. Public Health 74-228-231.

Spengler, J.D., R.D. Treitman, T.D. Tosteson, D.T. Mage, and M.L. Soxzek, 1985. Personal Exposures to Respirable Particulates and Implications for Air Pollution Epidemiology." Environ. Sci. Technol. 19:700-707.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1982. Ionizing Radiation: Sources and Biological Effects. Report to the General Assembly. Annex B. Paragraph 1 . UN Publication Sales No. E.82.IX.8. United Nations. New York. As cited in United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1988. Sources, Effects and Risks of toniginq Radiation. Report to the General Assembly.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1986. Genetic and Somatic Effects of Ionizing Radiation. Report to the General Assembly. Annex Biological effects of pre-natal irradiation. UN Publication Sales No. E.B6.IX.9. United Nations. New York.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1988. Sources, Effects and Risks of Ionizin9 Radiation. Report to the General Assembly. Annex F: Radiation carcinogenesis in man. UN Publication Sales No. E.B8.IX.7. United Nations. New York.

U.S. Department of Transportation, Federal Aviation Administration, Research and Special Programs Administration, 1987. Air ort Activity Statistics of Certified Route Air Carriers: 12 Months ending December 31 19 7. U. S. Government Pricing Office, Washington, D.C.

Section 3.0
DATA COLLECTION AND PROCESSING

3.1 TYPES OF INFORMATION COLLECTED

The types of information collected for flights monitored during the study included: (1) activities related to the flight, such as smoking information and passenger data, (2) continuous monitoring information for pollutants and other parameters, and (3) concentrations of contaminants collected as time-integrated samples. Sections 3.1.1, 3.1.2, and 3.1.3 contain descriptions of information from daily flight documentation logs, continuous monitoring and integrated sampling.

3.1.1 Daily Flight Documentation Log

As described in Section 2.5, the Daily Log was divided into 3 major sections: (1) Start of Day Documentation Log, (2) Flight Documentation Log, and (3) End of Day Documentation Log. The information collected in the Flight Documentation Log and the End of Day Documentation Log was grouped in the following four categories for purposes of data entry and processing:

* Flight characteristics, aircraft information, and passenger data
* Smoking information
* Time of particular flight activities and technician locations
* Information relating to instrumentation and sampling media.

Flight characteristics (Table 3-1) included the date of the flight, the airline and flight number, and the airports of departure and arrival. Aircraft information included the model of the airplane (e.g., Boeing 727-200 or DC10-30) and the registration number of the plane found on the outside of the aircraft. The primary passenger information was the total number of passengers, excluding the crew, on the plane.

The smoking information (Table 3-2) collected by the field technicians and recorded in the Flight Documentation Logs included the

TABLE 3-1. FLIGHT CHARACTERISTICS, AIRCRAFT INFORMATION AND PASSENGER DATA FROM THE FLIGHT DOCUMENTATION LOG

Parameter	Page Location in Flight Documentation Log
1. Flight date	2
2. Airline	2
3. Flight number	2
4. Airport of departure	2
5. Airport of arrival	2
6. Aircraft model number	2
7. Aircraft registration number	2
8. Number of passengers	2

TABLE 3-2. SMOKING INFORMATION FROM THE FLIGHT DOCUMENTATION LOG

Parameters	Page Location in Flight Documentation Log
1. Ashtrays emptied at start of flight?	4
2. Smoking rows	4
3. Number of passengers in smoking section	4
4. Number of passengers in boundary section	4
5. Smoking counts during one-minute intervals every 15 minutes	4, 5
6. Number of seats from which cigarette butts were collected	8
7. Total number of cigarette butts collected	8
8. Was previous flight smoking?	8

identification of coach smoking rows and an observation at the beginning of the flight on whether or not the ashtrays were emptied prior to boarding. Additionally, the technician in the coach smoking section was required to count the number of cigarettes smoked during a one-minute interval every 15 minutes. These observations were recorded on pages 4 and 5 of the Flight Documentation Log and the observed counts were used as an input to estimation of total cigarettes smoked during each smoking flight. Procedures for estimating total smoking in the coach section are described in Section 3.2.

Also included as smoking information was an indication of whether the previous flight was smoking, as reported by the flight attendant. At the end of the flight, cigarette butts were collected from seats in the coach smoking section. The number of seats from which butts were collected and the total number of butts collected were recorded in the logbook.

Table 3-3 lists the information recorded about technician locations and the times of various events during flights. The location of the technician included the seat number and the section number. The target locations for technician seating on a smoking flight were the snaking section, one of the boundary rows, the middle of the nonsmoking section, and the remote location (typically near the front) in the nonsmoking section. On international flights, a boundary seat in the business class was substituted for the nonsmoking remote location, and on nonsmoking flights technicians were seated in the section of the plane where smokers would be assigned on smoking flights (usually the rear) and the middle of the nonsmoking section. Flight events that were recorded included the time when the aircraft was boarded and the time when cruise altitude was reached. Of particular importance were the times when the no-smoking light was turned off and turned on. The interval between these two events was used as the timeframe for averaging temperature, relative humidity, pressure, and pollutant measurements that were recorded with continuous monitoring devices.

TABLE 3-3. VARIABLES WITHIN THE FLIGHT DOCUMENTATION LOG RELATED TO TIMES OF VARIOUS FLIGHT MILESTONES AND LOCATION OF TECHNICIAN

Parameter	Page Location in Flight Documentation Log
1. Seat number	2
2. Section number	2
3. Boarding time	3
4. Time of departure from gate	3
5. Time of takeoff	3
6. Time when no-smoking light was turned off	3
7. Time when cruise altitude was reached	3
8. Time of cruise descent	8
9. Time when no-smoking light was turned on	8
10. Time of arrival at gate	8

-

Information related to instrumentation and sampling media, shown in Table 3-4, included identification numbers of sampling devices and the times when sampling pumps were turned on and off. Within the End of the Day Documentation Log, the MINIRAM zero values, the MINIRAM pump flow rate, the nicotine pump flow rate, and the ozone pump flow rate were recorded. Each of these items was ultimately used in the computation of measured concentrations.

3.1.2 Continuous Monitoring Data

Continuous monitoring data were collected at all four locations on smoking flights and at both locations on nonsmoking flights. A data logger was programmed to compute and record average measurement values every minute. The Julian date, hour, minute, RSP, C0, temperature, relative humidity, and pressure values were recorded on individual channels. This information was stored in the internal memory of the data logger and transferred to computer diskettes at the end of each day. The file-naming convention was keyed to the Julian date and the identification number of the data logger used by a particular technician (e.g., 102-1477.PRN). Following file transfers at the end of each day, a backup of each transferred file was made.

3.1.3 Integrated Sampling Media

As described in Section 2.3, integrated sampling devices were used to collect samples for nicotine, RSP, ozone, C02, microbial aerosols, and air exchange rates. Nicotine and RSP samples were collected at all locations on every flight. Ozone, C02, and microbial aerosols were collected at two sites on smoking flights and international flights and at one site on nonsmoking flights. Table 3-5 summarizes the locations of integrated sampling devices on smoking and nonsmoking flights. PFT sources for air exchange measurements were deployed in the remote and smoking locations, whereas samplers (CATs) were deployed in the boundary and central nonsmoking locations.

Table 3-6 lists the laboratory destination for each type of sampling device. C02 concentrations were read by the technicians during

TABLE 3-4. VARIABLES WITHIN THE FLIGHT DOCUMENTATION LOG RELATED TO INSTRUMENTATION AND SAMPLING MEDIA

Parameter	Page Location in Flight Documentation Log
1. Nicotine/RSP cassette ID numbers	1
2. C02 tube ID number	1
3. Ozone cassette ID number	1
4. CAT sampler ID number	1
5. PFT sources	1
6. Time sensors turned on	1
7. Instrument package number	2
8. SAS package number	2
9. Time PFT sources deployed	3
10. Time MINIRAM pump turned on	3
11. Time nicotine pump turned on	3
12. Time C02 tube opened	3
13. Time ozone pump turned on	3
14. Start time of bioaerosol sampling	7
15. Bioaerosol plate ID numbers	7
16. Stop time of bioaerosol sampling	7
17. Time ozone pump turned off	8
18. Time nicotine pump turned off	8
19. Time C02 tube capped	8
20. C02 tube reading/time of reading	8
21. Time MINIRAM pump turned off	8
22. MINIRAM zero checks	3
23. MINIRAM flow rate	4
24. Nicotine pump flow rate	5
25. Duplicate nicotine pump flow rate	6
26. Ozone pump flow rate	7

TABLE 3-5. PLACEMENT LOCATIONS FOR INTEGRATED SAMPLING DEVICES

					Location		
					Nonsmoking		
Measurement Parameter	Smoking		Boundary		Middle		Remote
A. Smoking Flights							
- Nicotine/RSP		X		X	X		X
- Ozone			X	X			
- C02	X			X			
- Microbial aerosols		X			X		
- PFT sources		X					X
- PFT samplers				X	X		
B. Nonsmoking Flights*							
- Nicotine/RSP		X			X		
- Ozone					X		
- C02					X		
- Microbial aerosols						X	
- PFT sources					X		
- PFT samplers		X					

* Nonsmoking seating locations include the would-be smoking section and the middle of the nonsmoking section.

TABLE 3-6. LABORATORY ANALYSIS RESPONSIBILITY FOR INTEGRATED SAMPLES

Type of Sample	Laboratory Responsible for Analysis
Nicotine/RSP	University of Massachusetts
Ozone	GEOMET
C02 diffusion tubes	Technicians (during flight)
Microbial aerosols	Pathogen Control Associates
PFT samples	Brookhaven National Laboratory

each flight; the time of the analysis and the concentration were recorded in the Flight Documentation Log. The ozone samples were analyzed by GEOMET's laboratory, whereas the nicotine RSP samples, microbial aerosol samples, and PFTs were analyzed by external laboratories.

3.2 DATA PROCESSING PROCEDURES

The field documentation collected by the technicians was returned to GEOMET for processing and analysis. Several different software packages were used during processing including dBase III Plus, Lotus 1-2-3, Microsoft QUICKBASIC, and SPSS/PC. Section 3.2.1 reviews the processing of data recorded in the Daily Flight Documentation Logs, Section 3.2.2 includes an explanation of continuous monitoring data processing, and Section 3.2.3 discusses processing of integrated sample data. Procedures for estimating total smoking rates in the coach smoking section, based on technician observations, are described in Section 3.2.4. Supplemental information that was gathered independently is described in Section 3.2.5.

3.2.1 Daily Flight Documentation Logs

Information collected by the field technicians and recorded in the Daily Log was entered into a database using dBase III Plus software. The database contained one record for each technician location on each flight. Data were entered from the Flight Documentation Logs and the End of the Day Documentation Logs. Information from the end of the day was entered for each flight during the day to which it applied. Each daily log was assigned an identification number, and this number was also entered into the database; this practice enabled easy reference to a particular log in the event that further review was needed.

Initially, each chain of flights was entered in a entered database for easy reference. Information from all ten chains was ultimately united in a single database.

The sampler identification numbers were entered into the database twice, as they appeared in the logbook. This practice enabled additional quality control checks to ensure that the first reported identification number matched the final reported number. Additional fields were provided to capture information relating to duplicate samplers.

3.2.2 Continuous Monitoring Data

The continuous monitoring data were processed using a BASIC program that combined (1) data logger outputs (voltages) for each channel, (2) calibration factors for converting the voltages to engineering units, and (3) selected information extracted from the dBase III Plus file for Flight Documentation Logs.

CO multipoint calibrations were performed at the beginning and the end of each chain at GEOMET's laboratory. Regression analysis was applied to the beginning and ending calibrations to calculate beginning and ending slopes and intercepts. This information was entered into an ASCII file along with the data logger identification number, MINIRAM identification number, initial zero value (MINIRAM), and the CO monitor identification number. These files were specific to a chain and were referred to as 'set' files. The file was sorted by instrument package identification number, and the final line in the file indicated the date and time of the initial and final CO calibrations.

In addition to the set files, the following information was extracted from the dBase III Plus tile described previously:

* Daily Log identification number
* Flight date
* Instrumentation package number
* Airline
* Flight number
* Sent number
* Section location
* MINIRAM on time
* No-smoking light off time
* No-smoking flight on time

* MINIRAM off time
* First MINIRAM zero reading
* Second MINIRAM zero rending
* Third MINIRAM zero reading

These files, each specific to a chain of flights, were referred to as "case" files. The case files and set files were used together as inputs to the processing routine.

The raw data files, as discussed in Section 3.1.2, were named according to the Julian date on which the data were collected and the technician's data logger identification number. The raw data files for a particular chain, along with the set file and the case file, were inputs to a BASIC program. Figure 3-1 contains a flow diagram depicting the procedure that was followed during processing of the continuous monitoring data. The program read the first line of the case file and identified the flight date and the instrument package identification number. within the program, the data logger assigned to each package was identified. Based on flight date and data logger number, the proper raw data file was retrieved. Then the MINIRAM identification number, the flight number, and the seat number were identified from the set and case files. The CO data were calibrated using the slope/intercept information contained in the set file; a linear drift between beginning and ending calibrations was assumed.

Reports were produced for each technician location on each flight. Figure 3-2 is an example of a report produced through the combination of the three inputs (raw data, set file, case file). Selected information from the set file and the case file is listed at the top of each report, including the instrument identification numbers, the flight date, the seat number and section location, the time when the MINIRAM pump was turned on and off, the time when the no-smoking light was turned off and on, and MINIRAM zero values. Program outputs included the input and output file names and the average, minimum, and maximum values for RSP, C0, temperature, relative humidity, and pressure. These values were reported for the entire period when smoking was allowed as well as the periods before and after the smoking period and successive hours during the smoking period.

The second type of output produced by the BASIC program was continuous calibrated data saved in files specific to each flight and seat

location. Data in these files were later used for more in-depth analyses (e.g., peak versus average concentrations)

3.2.3 Integrated Samples

Results from laboratory analysis of integrated samples were combined with information from the flight documentation logs to calculate measured concentrations. The logs provided the flight information and the length of the sampling period. In calculating the concentrations from the integrated sampling results, selected outputs (e.g., temperature, pressure) from the continuous monitoring were also needed in some instances.

The concentrations for Gravimetric nicotine/RSP were calculated using sample mass from the laboratory, flow rates and sampling duration from the flight documentation log, and temperature and pressure during the smoking period from the continuous monitoring data. Figure 3-3 illustrates the procedures used to calculate the nicotine and RSP concentrations in ug/m3.

Ozone concentrations were calculated in parts per million (ppm) in much the same way as nicotine and RSP concentrations were calculated. The duration of the sampling period and the pump flow rate were extracted from the Daily Log database and the sample mass was provided by the laboratory. The pump flow rate was measured by the field technician.

Draeger Tubes were used to collect C02 in two locations in the plane. The diffusion tubes were filled with a blue indicator compound that gradually turned white as C02 diffused into the tube. At the end of the flight the field technician read the C02 level by noting where the white coloration stopped. The analytical range for these tubes was from 500 ppm/hr to 20,000 ppm/hr.

Most of the data required to calculate the C02 concentration were extracted from the Daily Log. One field (pressure) was extracted from the continuous monitoring data; the average pressure during the smoking portion of the flight was used. The average C02 concentration, in ppm, was

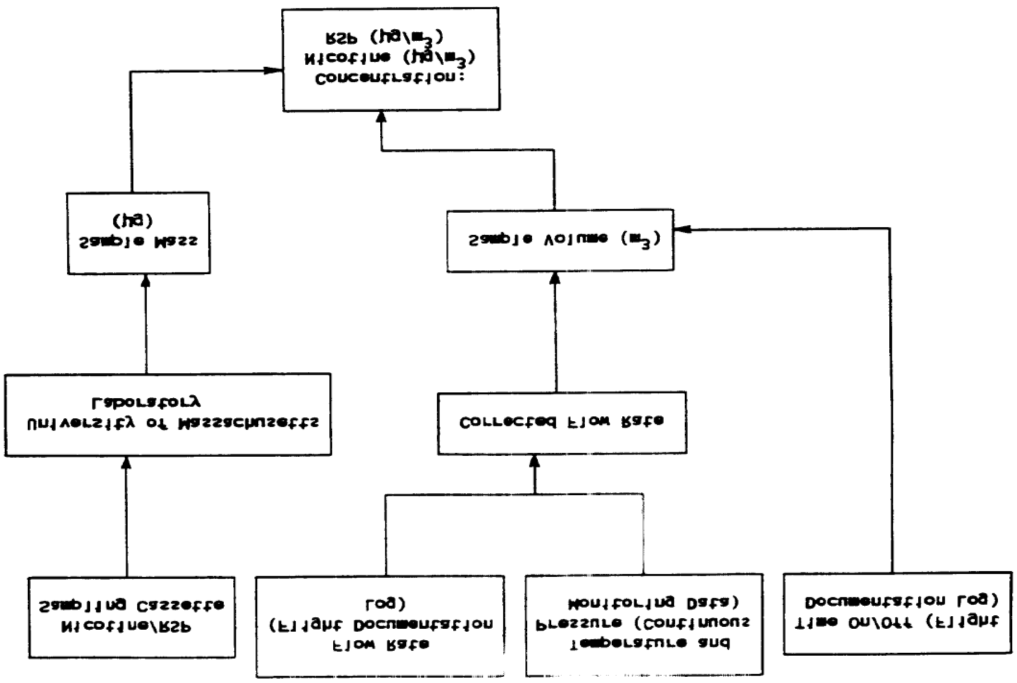

FIGURE 3-3. DATA PROCESSING PROCEDURE FOR CALCULATING GRAVIMETRIC RSP AND NICOTINE CONCENTRATIONS

calculated by (1) applying a correction factor derived from the average pressure measurement to the raw integrated value and (2) dividing the corrected integrated value by measurement durations.

Figure 3-4 is a flow chart depicting the data processing procedure for calculating the air exchange rate on each flight. Samplers (CATs) were analyzed at Brookhaven National Laboratory and the quantity of each tracer gas found in each tube was reported. This information was combined with data extracted from the Daily Log database on the type of source deployed on a particular flight and the length of exposure for the CAT. The final inputs to the calculation were average temperature and pressure during the smoking period. A file containing the above inputs was processed using a BASIC program; the output was a report including the air exchange rate per location and the average airflow rate between locations for the flight.

The results of the bioaerosol sampling were reported by the laboratory in colony-forming units per cubic meter (CFU/m3). These results were linked with the flight date, airline, flight number, seat number, and section. Total bacterial concentrations as well as concentrations of Staphylococcus aureus and Streptococcus pyogenes were reported for each sample. In addition, concentrations of several other types of bacteria were reported. For example, among the most prevalent types were:

* Staphylococcus not aureus
* Micrococcus varians
* Micrococcus luteus
* Micrococcus lylae
* Corynebacterium .

Total fungi were also reported together with the most prominent genera.

3.2.4 Estimation of Smoking Rates

Estimated smoking rates were calculated using the data recorded by the technician seated in the coach smoking section. One of the inputs

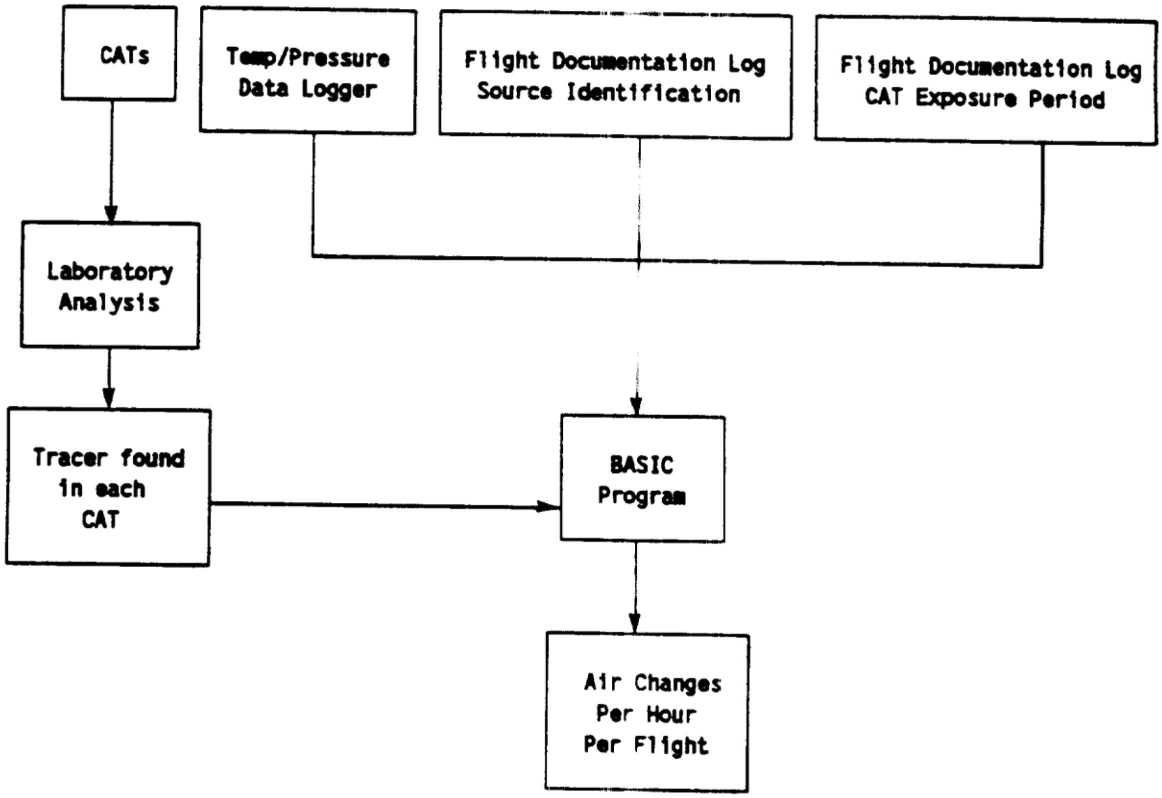

FIGURE 3-4. PROCEDURE FOR CALCULATING AIR EXCHANGE RATES WITHIN AIRCRAFT CABINS USING CATs FOLLOWING SOURCE RELEASE

to the calculation of smoking rates was the number of people smoking during a one-minute period every 15 minutes as recorded by the technician in the smoking section. The estimated quantity of cigarettes smoked during the flight, in cigarette-minutes, was, calculated by the following formula:

$$\frac{(\text{Smoking Duration} \times 60)}{(\text{Number of 15-minute intervals})} \times (\text{Smoking Count})$$

The result of this calculation was divided by 6, the typical number of minutes a cigarette was lit in the cabin environment (based on technician observations during the pretest), to obtain an estimate for the number of cigarettes smoked during the flight.

3.2.5 Supplemental Information

Additional information on aircraft characteristics was gathered from archived data and keyed into a separate database. This information included such aircraft features as the volume of the plane, whether a plane was a wide body or narrow body, and the nominal extent of cabin air recirculation for each type of aircraft. The total seating capacity was obtained for the aircraft specific to each monitored flight. The contacts with each airline were also used to verify certain data that were collected by field technicians. Each airline was requested to provide the aircraft type, aircraft registration number, total passenger count, and smoking rows for each monitored flight involving the airline.

Section 4.0
MONITORING RESULTS

As noted in Section 2.4, a total of 92 randomly selected flights were monitored during the study; smoking was permitted on 69 (75 percent) of these flights. Characteristics of the monitored flights, including airlines, types of aircraft, and flight durations, are described in Section 4.1. For smoking flights, information on passenger counts in the smoking section and observed smoking rates is also presented. Results of environmental measurements -- air exchange rates, temperatures, relative humidities, cabin pressures, ETS contaminants, and pollutants -- are presented in Section 4.2.

4.1 CHARACTERISTICS OF MONITORED FLIGHTS

4.1.1 Airlines, Aircraft Types, and Flight Times

The distribution of monitored flights by airline is summarized in Table 4-1; distributions are given separately for 61 domestic smoking flights, 8 international flights, and 23 nonsmoking flights. All major airlines except Braniff, Eastern, and Northwest were represented by smoking flights. The number of smoking flights offered by these airlines was relatively small, particularly for Eastern (whose airline services were substantially curtailed during the monitoring period due to a strike) and Northwest (for which smoking flights are restricted to those between Hawaii and the continental United States). Northwest was the carrier, however, for a substantial fraction (more than 20 percent) of the nonsmoking flights. Although the number of monitored international flights was limited, most of the major U.S. carriers offering such flights were represented.

The Representativeness of monitored flights is shown more directly in Figure 4-1, in relation to all flights (more than 100,000) that were scheduled for departure from major U.S. airports during January 1989. The comparison is restricted to domestic smoking flights, the largest subset of flights (61) that was monitored. As indicated by the

TABLE 4-1. DISTRIBUTION BY AIRLINE FOR DOMESTIC SMOKING,

INTERNATIONAL, AND NONSMOKING FLIGHTS THAT WERE MONITORED

Airline	Number of Flights		
	Domestic Smoking	International	Nonsmoking
American (AA)	10	2	0
Braniff (BN)	0	0	1
Continental (CO)	10	0	0
Delta (DL)	8	0	6
Midway Connection (ML)	2	0	0
Northwest (NW)	0	1	5
Pan American (PA)	4	2	3
Piedmont (PI)	3	0	2
Trans World (TW)	9	1	3
United (UA)	7	2	2
U.S. Air (US)	6	0	1
Western (WN)	2	0	0
Total, All Airlines	61	8	23

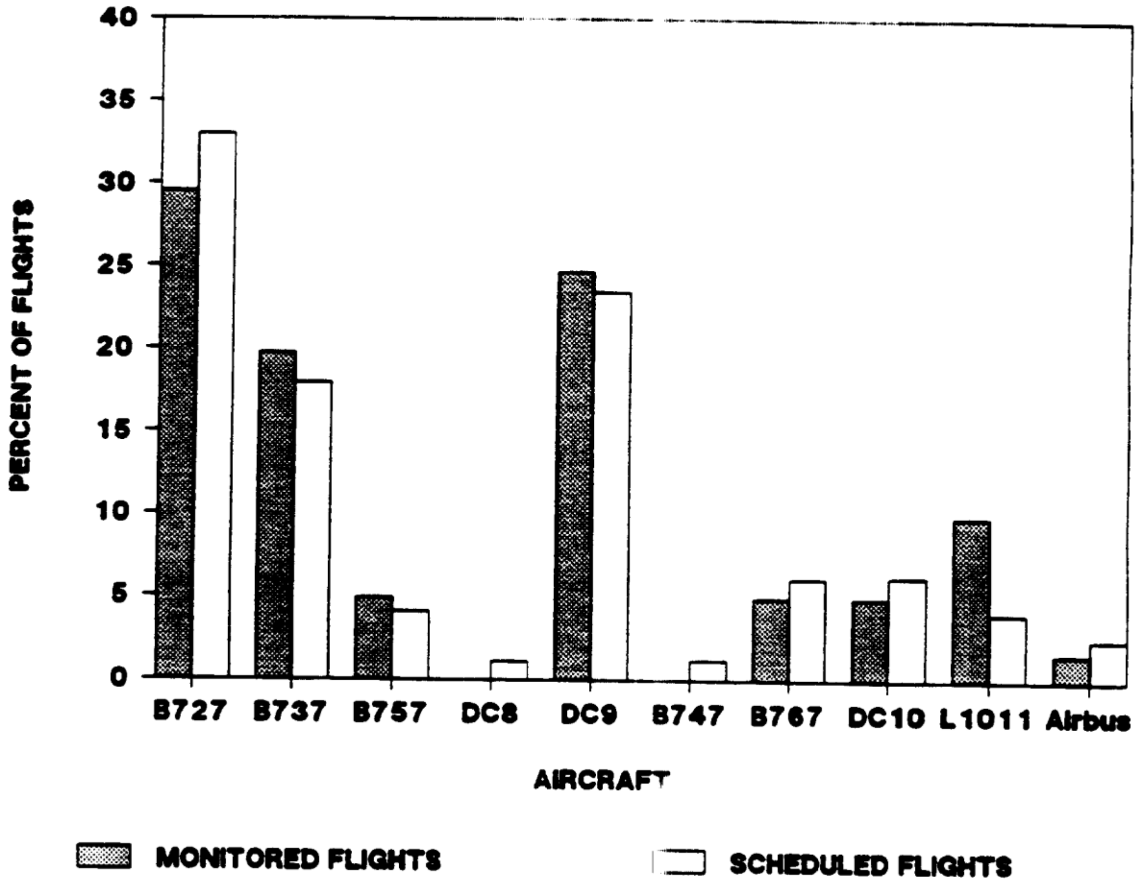

FIGURE 4-2. REPRESENTATIVENESS OF DOMESTIC SMOKING FLIGHTS WITH RESPECT TO TYPE OF AIRCRAFT

comparative percentage frequency distributions in the figure, the monitored flights were proportionately representative of most airlines. The five airlines (American, Continental, Delta, Trans World, and United) that accounted for a majority of the scheduled flights were also associated with a majority of the flights that were monitored, and these five airlines were represented in nearly the same order by relative percentage. The most notable discrepancy between monitored and scheduled flights was the lack of representation of Eastern Airlines (EA); Eastern flights were deliberately avoided during the monitoring period (early April to early June 1989) because of Eastern's curtailment of services, and associated uncertainty in flight availability, at that time.

The distribution by type of aircraft is summarized for the three subsets of flights in Table 4-2. All international flights were on widebody aircraft and all nonsmoking flights but one were on narrow-body aircraft, consistent with the relative durations of these types of flights. Domestic smoking flights involved the greatest variety in aircraft types, with about 20 percent of these flights taken on wide-body aircraft. For all three subgroups, Boeing aircraft were most frequently represented, accounting for more than half the monitored flights, and McDonnell Douglas aircraft were next most frequently represented. As indicated in Figure 4-2, the domestic smoking flights were proportionately representative with respect to aircraft type; with the exception of Lockheed aircraft, which were over-represented, the distributions for monitored and scheduled flights differed by no more than a few percentage points for each type of aircraft.

The joint distribution by aircraft width and recirculation capability is shown for smoking flights (domestic plus international) and nonsmoking flights in Table 4-3. The smoking flights were almost equally distributed on aircraft with and without recirculation, whereas the nonsmoking flights were primarily on aircraft without recirculation.

The distribution by flight duration is summarized for the three subgroups of monitored flights in Table 4-4. All international flights

TABLE 4-2. DISTRIBUTION BY TYPE OF AIRCRAFT FOR DOMESTIC SMOKING, INTERNATIONAL, AND NONSMOKING FLIGHTS THAT WERE MONITORED

	Number of Flights		
Type of Aircraft	Domestic Smoking	International	Nonsmoking
Narrow Body			
Boeing 727	18	0	9
Boeing 737	12	0	3
Boeing 757	3	0	1
McDonnell Douglas DC9/MD80	15	0	8
British Aerospace 111	0	0	1
Wide Body			
Boeing 747	0	5	0
Boeing 767	3	1	0
McDonnell Douglas DC10	3	2	1
Lockheed L1011	6	0	0
Airbus Industrie 310	1	0	0
Total, All Types	61	8	23

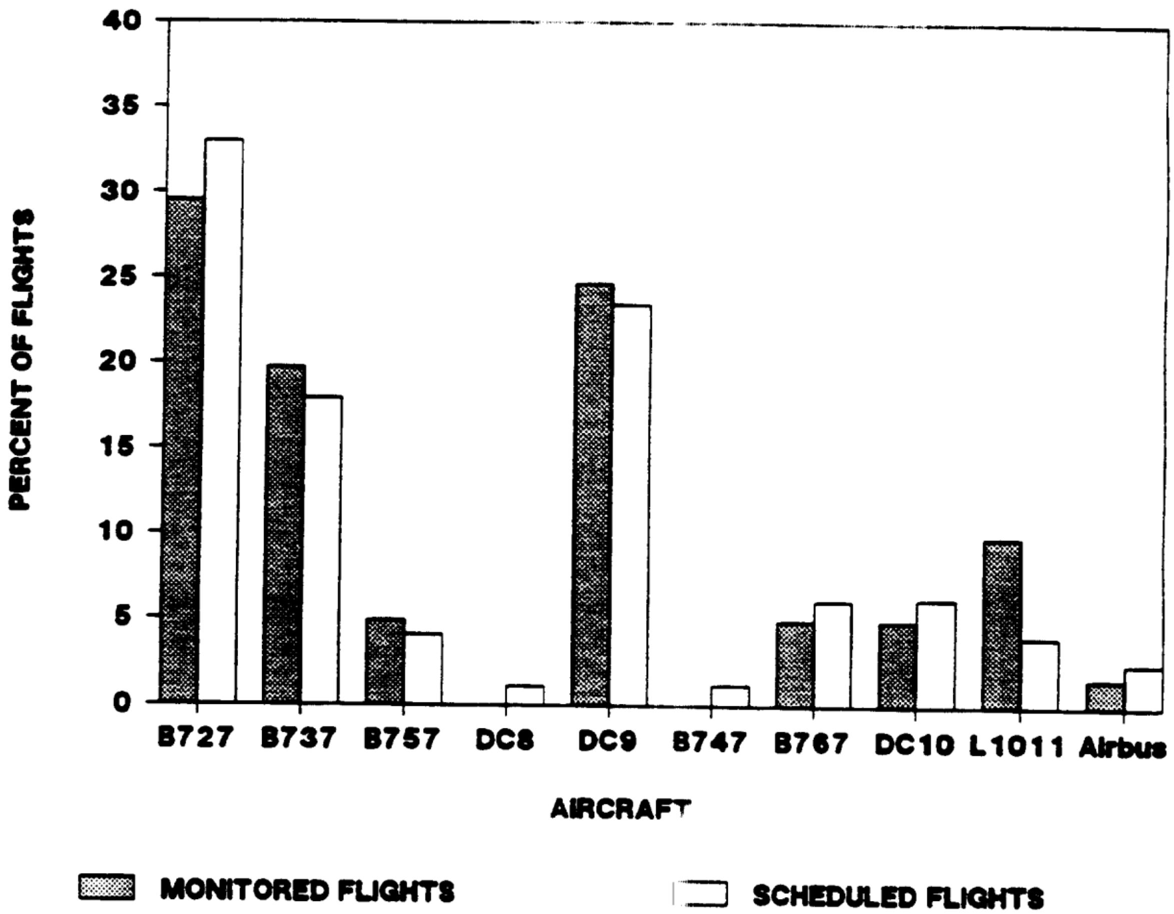

FIGURE 4-2. REPRESENTATIVENESS OF DOMESTIC SMOKING FLIGHTS WITH RESPECT TO TYPE OF AIRCRAFT

TABLE 4-3. DISTRIBUTION OF MONITORED FLIGHTS BY AIRCRAFT WIDTH AND RECIRCULATION

Aircraft Width and Recirculation	Number of Flights	
	Domestic Smoking and International	Nonsmoking
Narrow-body aircraft	48	22
with recirculation	21	5
without recirculation	27	17
Wide-body aircraft	21	1
with recirculation	11	1
without recirculation	10	0

TABLE 4-4. DISTRIBUTION BY FLIGHT DURATION FOR DOMESTIC SMOKING, INTERNATIONAL, AND NONSMOKING FLIGHTS THAT WERE MONITORED

Duration of Flight (Hours)	Number of Flights		
	Domestic Smoking	International	Nonsmoking
<2.0	1	0	18
2.0 - 2.49	17	0	2
2.5 - 2.99	13	0	1
3.0 - 3.49	8	0	1
3.5 - 3.99	12	0	1
4.0 - 4.99	6	0	0
z5.0	4	8	0
Total, All Durations	61	8	23

were greater than five hours in duration, averaging 8.9 hours. Domestic smoking flights, averaging 3.2 hours in duration, also included some that were greater than five hours long, but half were less than three hours long. One of the smoking flights was slightly less than two hours in duration, due to variability from the nominal scheduled flight duration that was slightly above two hours in this case. Most of the nonsmoking flights, averaging 1.6 hours in duration, were less than two hours; the exceptions were associated with two carriers--Northwest Airlines (all flights arriving and departing within the continental United States are nonsmoking) and United Airlines (all flights of 1,000 miles or less in distance are nonsmoking). The distribution of monitored domestic smoking flights by duration closely resembled that of scheduled flights (Figure 4-3), with the exception that flight durations between two and three hours were somewhat underrepresented and durations between 3.5 and tour hours were over-represented.

Distributions by time of departure are shown for the three subgroups of monitored flights in Table 4-5. International flights were clustered at early morning and late afternoon/evening departure times due to the limited choice of times for direct flights to and from the international destinations. The distribution of domestic smoking flights was somewhat shifted away from morning departures toward flights that departed in the middle of the day. As shown in Table 4-6, this shift was in contrast to the nearly uniform distribution of departure times for scheduled flights. The shift away from morning departures was due in part to delays relative to scheduled times of departure, as evidenced by a comparison of scheduled versus actual departure times for the monitored flights. Clustering toward the middle of the day was due in part to the desire to conserve resources by minimizing scheduled layovers for technicians between monitored flights. These differences in the distributions were not excessive, however, and all blocks of departure times were adequately covered by the monitored flights.

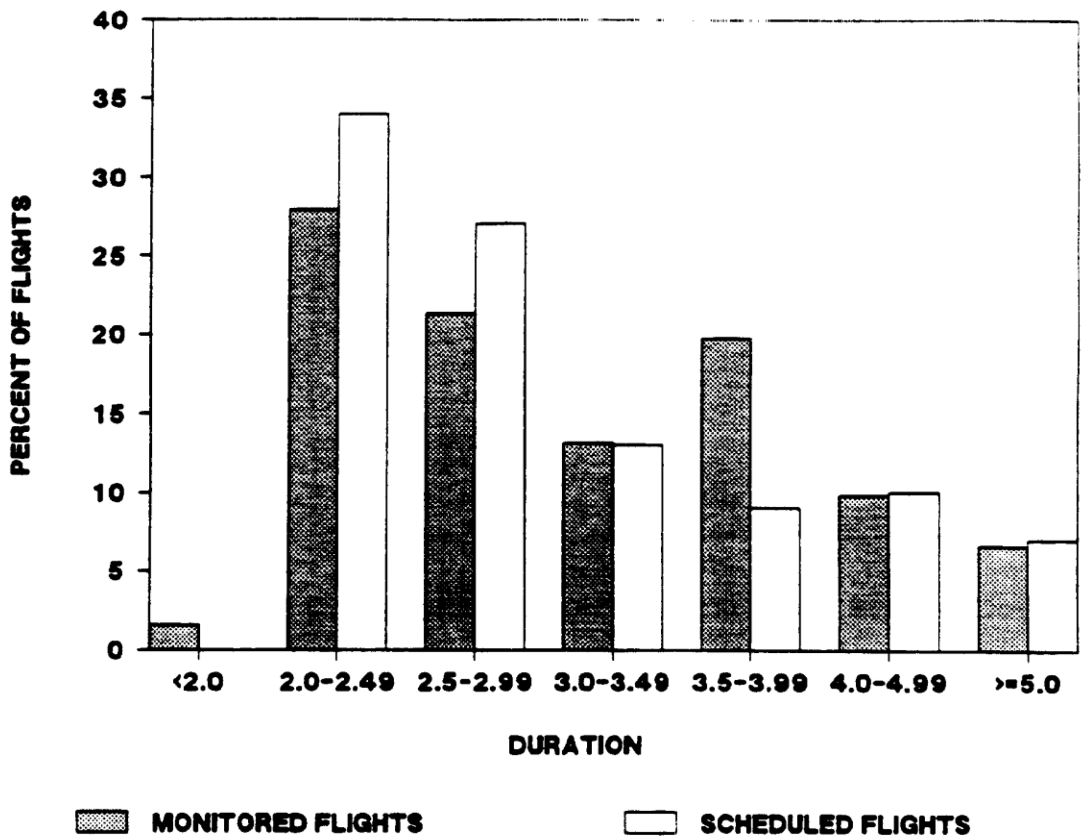

FIGURE 4-3. REPRESENTATIVENESS OF MONITORED DOMESTIC SMOKING FLIGHTS WITH RESPECT TO FLIGHT DURATION

TABLE 4-5. DISTRIBUTION BY TIME OF DEPARTURE FOR DOMESTIC SMOKING, INTERNATIONAL AND NONSMOKING FLIGHTS THAT WERE MONITORED

Time of Departure	Number of Flights: Domestic Smoking	International	Nonsmoking
Before 9:00 a.m.	5	4	1
9:00 to 11:59 a.m.	9	0	7
Noon to 2:59 p.m.	20	0	4
3:00 to 5:59 p.m.	12	1	8
After 6:00 p.m.	15	3	3
Total, All Times	61	8	23

TABLE 4-6. REPRESENTATIVENESS OF MONITORED DOMESTIC SMOKING FLIGHTS WITH RESPECT TO TIME OF DEPARTURE

Time of Departure	Percentage of Domestic Smoking Flights: Monitored Flights, as Scheduled	Monitored Flights, as Flown*	All Flights Scheduled for January 1989
Before 9:00 a.m.	13.1	8.2	19.4
9:00 to 11:59 a.m.	19.7	14.8	19.2
Noon to 2:59 p.m.	31.1	32.8	20.8
3:00 to 5:59 p.m.	21.3	19.7	17.3
After 6:00 p.m.	14.8	24.6	23.4

*Differs from monitored flights, as scheduled, due to delays in scheduled departure times.

4.1.2 Passengers and Smoking

Information concerning passenger counts, seating capacities, and load factors (i.e., percent of seating capacity filled by passengers) is summarized for the monitored flights in Table 4-7. The information for smoking flights is segregated by narrow- versus wide-body aircraft; for these flights, passenger counts were generally higher for wide-body aircraft whereas load factors were generally higher for narrow-body aircraft. Seating capacity of wide-body aircraft averaged nearly double that of narrow-body aircraft. For the nonsmoking flights (all except one of which involved narrow-body aircraft), the average seating capacity was similar to that of narrow-body aircraft associated with smoking flights, but the average load factor was somewhat lower. with the exception of one smoking flight that had only 17 passengers, the load factor consistently ranged from 30 to 100 percent for each of the three subgroups of flights listed in the table.

As described in Section 3.0, information on the number of cigarettes smoked was collected for the smoking flights in two complementary ways: (1) through collection of cigarette butts by technicians at the end of each flight for later counting and (2) through technician observations of cigarettes smoked during one-minute intervals every 15 minutes. Technicians were unable to collect cigarette butts on five of the 69 smoking flights that were monitored. For 12 other smoking flights, ashtrays were not emptied from an immediately prior flight that also was a smoking flight. For the remaining 52 flights, the correspondence between estimates for cigarettes smoked based on technician observations versus cigarette butt counts was assessed. As illustrated in Figure 4-4, very good correspondence was obtained, with a correlation coefficient of 0.89. The regression line of best fit (R2 value of 0.8) between the two estimates was as follows:

Technician Observations = 9.07 + 0.87 x Cigarette Butt Counts

The regression equation indicates that technicians observations generally yielded slightly higher estimates than butt counts when smoking

TABLE 4-7. PASSENGER COUNTS, SEATING CAPACITIES AND LOAD FACTORS FOR FLIGHTS THAT WERE MONITORED

Type of Flight (Number)	Passenger Count	Seating Capacity	Load Factor*
Smoking Flights (69)			
Narrow Body (48)			
Average	105.3	138.4	75.8
Standard Deviation	35.3	19.2	21.5
Range	17-187	107-187	12-100
Wide Body (21)			
Average	182.2	288.0	64.1
Standard Deviation	73.2	67.9	23.2
Range	80-347	184-431	31-100
Nonsmoking Flights (23)			
Average	94.4	135.2	69.9
Standard Deviation	39.7	41.8	22.4
Range	31-181	79-284	30-100

*Percent of seating capacity filled by passengers.

levels were relatively low, whereas the reverse was true for relatively high smoking levels. Given the good correspondence between the two methods of estimation, technician observations were used as the basis for analysis in this report because such observations were taken on every monitored smoking flight.

Information on passenger counts in the smoking section and observed smoking rates are summarized for the 69 smoking flights in Table 4-8. On the average, there were 18 passengers

in the smoking section smoking 68 cigarettes during the flight. The smoking rates varied from as little as one cigarette per hour to as much as one cigarette per minute for all smokers combined, averaging one cigarette every three minutes. The number of cigarettes smoked per hour per passenger in the smoking section averaged 1.5 and varied widely, ranging from 0.2 to 6.5. The estimate of 6.5 cigarettes per hour per passenger may be an artifact of the estimation procedure that was used; in this case, the estimated number of cigarettes smoked was twice as high as the number of cigarette butts collected by technicians. Discounting this case, the highest estimated smoking rate was 3.5 cigarettes per hour per passenger.

Further information on the distributions underlying the summary statistics is displayed in Figure 4-5 (for passenger counts and total cigarettes smoked) and in Figure 4-6 (for cigarettes smoked per hour and cigarettes per passenger per hour). The number of smoking passengers was fairly evenly distributed about the interval 10-19, with five cases at the upper extremes (i.e., 40 or more smoking passengers). The total number of cigarettes smoked had a less symmetrical distribution about the most frequent interval (25-49 cigarettes), with a long tail due to variations in both number of smoking passengers and flight duration. With consideration of flight duration, the smoking rate (expressed as cigarettes per hour) was more symmetrical about the most frequent interval (15-20), with 11 cases at the upper extreme (30 or more cigarettes per hour). The number of cigarettes smoked per passenger per hour was also distributed fairly symmetrically about the most frequent interval (1.0 - 1.5), with 12 cases at the upper extreme (2.5 or more cigarettes per passenger per hour).

TABLE 4-8. SMOKING PASSENGERS, SMOKING QUANTITY, AND SMOKING RATES FOR SMOKING FLIGHTS THAT WERE MONITORED

Characteristic	Average	Standard Deviation	Range
Number of Passengers in Smoking Section	18.1	12.4	2-63
Percent of Passengers in Smoking Section	13.7	6.6	1.4-41.9
Number of Cigarettes Smoked during the Flight	68.1	66.7	3-411
Number of Cigarettes Smoked per Hour	19.9	11.2	1-60
Number of Cigarettes Smoked per Passenger per Hour	1.5	1.1	0.2-6.5

Estimated smoking rates in relation to smoking duration (length of time during which smoking was permitted) and time of departure are summarized in Table 4-9. There was no distinct pattern for cigarettes smoked per hour in relation to smoking duration, but the number of cigarettes smoked per passenger per hour was distinctly lower for flights with smoking durations of five hours or longer. This lower rate most likely reflects the tendency of passengers to sleep at times on longer flights. The number of cigarettes smoked per hour was highest for flights departing between noon and 3:00 p.m., the largest time block of monitored flights. When smoking rates were expressed per passenger per hour, however, differences were less pronounced. flights departing after 3:00 p.m. had somewhat lower rates than those departing earlier in the day.

4.2 ENVIRONMENTAL MEASUREMENTS

4.2.1 Air Exchange, Temperature, Humidity and Pressure

The air exchange rate prevailing during a flight depends partly on the extent to which air can be re-circulated and the extent of control that the cockpit crew has over fresh-air intake through selective use of air-conditioning packs and recirculation capabilities. Such factors can vary with the type of aircraft. Nominal air exchange rates at a cruise altitude of 9.1 km (30,000 feet) are listed for different types of narrowbody and wide-body aircraft in Table 4-10 together with nominal values for cabin volume and extent of air recirculation. The nominal values given for air exchange rates at 9.1 km (30,000 feet) are those reported by Lorengo and Porter1 based on information collected by these researchers from equipment manufacturers and airline operators. The aircraft types with recirculation capabilities have lower nominal air exchange rates, ranging from 10/h to 15/h in most cases, than for aircraft without recirculation, for which the nominal rates vary from 23/h to 27/h in most cases.

____

Lorengo, D.G., and A. Porter. 1985. Aircraft Ventilation Systems Study. Final Report DTFA-03-84-C-0084. Atlantic City, NJ: U.S. Federal Aviation Administration Technical Center.

Air exchange rates measured with PFTs are compared with nominal rates in Table 4-11.

For aircraft without recirculation, the measured rates are much higher than the nominal rates" as much as four to five times as high for some aircraft. For aircraft with recirculation, however the measured rates are much closer to nominal values, albeit somewhat higher and still somewhat variable. This pattern of results indicates that there generally was insufficient mixing throughout the airliner cabin for the PFT results to be indicative of prevailing air exchange rates. (Due to the need to remain unobtrusive during sampling, PFT sources for release of tracer gas could be placed only at two locations on smoking flights and one location on nonsmoking flights.) The mixing problem affected measurement results on all types of aircraft, but particularly those without recirculation. The results for aircraft with recirculation are likely to be indicative of the prevailing air exchange rates. The frequency distribution of measured air exchange rates on aircraft with recirculation is given in Figure 4-7.

Air exchange rates on smoking and nonsmoking flights are compared in Table 4-12 for selected aircraft with recirculation. The average air exchange rates were higher on smoking flights for two of the three aircraft types. However, conclusions cannot be drawn because of the extremely limited number of measurements for nonsmoking flights.

Results of temperature, relative humidity, and cabin pressure measurements are summarized for smoking and nonsmoking flights in Table 4-13. The average temperature was near 24 C (75 F) for both types of flights, and the range of measurement results was similar as well. The relative humidity results were quite low, ranging from 5 to 38 percent across all flights, but were even lower for smoking (average of 15.5 percent) than for nonsmoking flights (average of 21.5 percent). The lower average relative humidity levels for smoking flights are a possible indication of higher average air exchange rates for these flights. For smoking flights, humidity levels were similar on aircraft with and without air recirculation, averaging between 15 and 16 percent in either case.

The average cabin pressure was lower for smoking than for nonsmoking flights, consistent with higher altitudes that are generally attained on longer flights for which smoking is permitted.

Frequency distributions for temperature and relative humidity across all study flights are given in Figure 4-8. More than one-third of the flights had temperatures in the interval from 24 to 25 C, and more than a third of the flights had humidity levels in the range from 10 to 15 percent. Humidity levels were below 25 percent on about 90 percent of the flights.

4.2.2 ETS Contaminants

Nicotine measurement results are summarized by technician seat location for both smoking and nonsmoking flights in Table 4-14. The results for smoking flights are for domestic and international flights combined, except for the remote seat; results are desegregated for this location because the remote sent on international flights was in the business class at the boundary near the business smoking section. Nicotine levels were substantially higher in the coach smoking section of smoking flights, averaging 13.4 ug/m3, than at any other locution. Measurements in the boundary section near coach smoking indicated some impact of tobacco smoking; although the average level (0.26 ug/m3) in this boundary section was much lower than in the smoking section, the level at this monitoring location was higher than the average levels in the middle seat (0.04 ug/m3) and remote seat (0.03 ug/m3) for domestic flights. For international flights, the average level for the remote location near business smoking (0.18 ug/m3) was similar to that for the boundary near coach smoking on all smoking flights. The levels in the middle and remote locations on smoking flights were similar to levels measured on nonsmoking flights, which in most cases were below minimum detection limits.

Cumulative frequency distributions for nicotine measurements on nonsmoking flights are shown in Figure 4-9. The distribution for the smoking section indicates a relatively smooth continuum of measured levels, with only the maximum value of 67.2 ug/m3 somewhat distant from

its nearest neighbor (47.4 ug/m3). The highest boundary result for domestic smoking flights

(3.5 ug/m3) was quite distant from the next highest result at this location (0.6 ug/m3). The highest results for the middle location were 0.9 and 0.2 ug/m3, and the highest results for the remote location were 0.4 and 0.3 ug/m3. These maximum values for the remote site are only slightly above the minimum detection level of 0.1 ug/m3 for a two-hour flight.

The Gravimetric RSP measurements are summarized by technician seat location for smoking and nonsmoking flights in Table 4-15. Because of the relatively short sampling duration and consequent measurement uncertainty, special treatment of these data was required. In most field monitoring studies, results that are negative (after netting out values obtained for field blanks) would be assigned a value of zero; however, in this situation such a practice would have exerted a significant positive bias on the results, particularly for the nonsmoking flights, because of the relatively short sampling duration. For example, historical data from the laboratory used for Gravimetric determinations indicate a standard deviation on the order of +_7 ug for analysis of blanks. Consequently, mass determinations could easily vary from -21 to +21 ug (i.e., + three standard deviations). As a result, for a one-hour sampling duration common for nonsmoking flights, corresponding to a sample volume of 0.1 m3, the measurement result for a prevailing concentration near zero could vary from -210 to +210 ug/m3 (the lowest result obtained was -195 ug/m3).

In view of the above consideration, sampling results with values below those of field blanks were kept as negative values in computing the summary statistics. With this treatment of the data, RSP levels for nonsmoking flights were similar to those measured in the boundary, middle, and remote locations on smoking flights. The levels in the smoking section for smoking flights, however, were considerably higher, exceeding those in other locations by more than 100 ug/m3 on the average. The considerably higher standard deviations for nonsmoking flights are a reflection of the measurement uncertainty due to short sampling duration. The counterintuitive result of higher RSP levels at the remote location for domestic than for international flights may also be an artifact of measurement uncertainty; the international results, for flights of considerably longer duration, had a much smaller standard deviation.

Cumulative frequency distributions for Gravimetric RSP measurements on domestic smoking and nonsmoking flights are shown in Figure 4-10. Negative results, shown in the graph as values of zero, were obtained in about five percent of the cases for the smoking section, in 15 to 25 percent of cases for other locations on smoking flights, and in 25 to 30 percent of cases on nonsmoking flights. The distributions for each location on smoking flights indicate a relatively smooth continuum of measured levels. For nonsmoking flights, the maximum values at each location (397 ug/m3 for the middle seat and 350 ug/m3 for the near seat) are more distant from their nearest neighbors (266 and 197 ug/m3, respectively),
another possible reflection of measurement uncertainty for these shorter duration flights.

Continuous monitoring with an optical sensor afforded the opportunity to quantitate RSP levels both before and during the period when smoking was allowed on smoking flights (and prior to takeoff for nonsmoking flights). As shown in Figure 4-11, RSP levels during the base-line period (prior to smoking/takeoff) consistently averaged between 20 and 30 ug/m3 across all sent locations, both for smoking and nonsmoking flights. After the baseline period, however, RSP levels declined somewhat on nonsmoking flights whereas levels on smoking flights increased by a factor of ten in the smoking section and by a factor of two in the boundary section.

Summary statistics for optically measured RSP levels, based on averaging of the continuous results across the sampling period for each flight, are given in Table 4-16. In contrast to the Gravimetric results, the optical results indicated higher levels in all sections of smoking flights than on nonsmoking flights. The difference between the boundary section and the middle/remote locations was sampled more pronounced for

the optical than the Gravimetric results. The optical results for the remote section were more in

line with expectations, with the international flights having slightly higher levels than Domestic flights. The optical results were internally consistent, with similar averages for nonsmoking and smoking flights during the baseline period, similar averages for the two locations on nonsmoking flights during the airborne period, and similar averages for the middle and remote location on smoking flights during the smoking period. Further analysis and discussion of the Gravimetric and optical results are provided in Section 5.0..

Cumulative frequency distributions are shown in Figure 4-12 for the time-averaged optical measurements during the smoking period. The distributions indicate a relatively smooth continuum of measured levels for smoking and boundary locations on smoking flights and for both monitoring locations on nonsmoking flights. For the middle and remote locations on smoking flights, the maximum values (118 and 103 ug/m3) were quite distant from their respective nearest neighbors (44 and 46 ug/m3).

The number of observations available for optical RSP measurements varied somewhat with technician location due to occasional instrument failures. For smoking flights, there were 65 observations for the smoking location, 63 observations for the boundary location, 62 observations for the middle location, and 58 observations for the remote location. For nonsmoking flights, there were 19 observations for each location.

One-minute peak RSP levels that were measured with optical sensors are summarized in Table 4-17. The peak levels on nonsmoking flights were not substantially greater than average levels, whereas on smoking flights the peak levels averaged near 70 ug/m3 in the remote and middle sections, above 200 ug/m3 in the boundary section, and near 900 ug/m3 in the smoking section. Peak levels at the remote site averaged substantially higher for international than for domestic smoking flights. The ratio of peak-to-average RSP concentrations (Table 4-18) was highest in the smoking and boundary sections, next highest in the middle and remote locations, and lowest on nonsmoking flights. These results collectively

TABLE 4-17. MEASURED PEAK RSP (OPTICAL) CONCENTRATIONS FOR

SMOKING AND NONSMOKING FLIGHTS

Type of Flight (Number)	Smoking	Boundary	Middle	Remote (Domestic)	Remote (International)
	Results by Seat Location, ug/m3				
<u>Smoking Flights</u> (69)					
Average(during smoking)	883.4	211.8	68.7	60.4	137.1
Standard Deviation	436.7	308.6	112.8	90.6	49.7
Maximum	2076.8	2275.5	732.2	614.0	198.8
<u>Nonsmoking Flights</u> (23)					
Average (while airborne)	18.2	--	16.4	--	--
Standard Deviation	8.9	--	5.9	--	--
Maximum	45.2	--	35.7	--	--

TABLE 4-18. RATIO OF PEAK-TO-AVERAGE RSP (OPTICAL) CONCENTRATIONS FOR SMOKING AND NONSMOKING FLIGHTS DURING PERIOD WHEN SMOKING WAS ALLOWED*

Type of Flight (Number)	Results by Seat Location				
	Smoking	Boundary	Middle	Remote (Domestic)	Remote (International)
Smoking Flights (69)					
Average Ratio	5.7	5.5	3.9	3.3	6.9
Standard Deviation	2.5	3.7	3.1	2.3	2.1
Maximum	13.3	18.0	17.9	14.4	9.6
Nonsmoking Flights (23)					
Average Ratio	2.5	--	2.3	--	--
Standard Deviation	1.5	--	1.8	--	--
Maximum	5. 4	--	6. 5	--	--

* While airborne for nonsmoking flights.

indicate (1) that tobacco smoking had some impacts on ETS levels in the other sections of the aircraft and (2) that the impacts were most pronounced in the boundary section.

Time-averaged CO levels on both smoking and nonsmoking flights were higher during the baseline period than the smoking/airborne period (Table 4-19) for both smoking and nonsmoking flights, due to intrusion of ground-level emissions outside the aircraft. During the smoking period, average CO levels were highest in the smoking section; the levels in the other sections of smoking flights were similar to but slightly higher than those for nonsmoking flights. Domestic and international smoking flights had similar average CO values for the remote location. The cumulative frequency distributions shown in Figure 4-13 indicate a relatively smooth continuum in of time-averaged CO levels for the smoking section, an isolated high value for the remote section, and several high values for the middle section.

The number of observations available for CO measurements varied with technician location due to occasional instrument failures. For smoking flights, there were 68 observations for the smoking location, 64 observations for the boundary location, 60 observations for the middle location, and 53 observations for the remote location. For nonsmoking flights, there were 16 observations for the location near the rear of the plane and 18 observations for the middle location.

As shown in Table 4-20, one-minute peak CO levels had a pattern similar to that of time-averaged CO levels, with the highest peaks in the smoking section and peaks in the other sections of smoking flights generally averaging somewhat higher than for nonsmoking flights. International flights had higher peak levels in the remote section, on the average, than domestic smoking flights. The ratios of peak-to-average CO levels (Table 4-21) were similar both across seats on smoking flights and for smoking versus nonsmoking flights. For nonsmoking flights, the ratios for CO were similar to those for RSP, whereas the smoking flights had higher ratios for RSP than for C0.

TABLE 4-19. MEASURED AVERAGE CO CONCENTRATIONS FOR SMOKING AND NONSMOKING FLIGHTS

Type of Flight (Number)	Results by Seat Location, ppm				
	Smoking	Boundary	Middle	Remote (Domestic)	Remote (International)
<u>Smoking Flights</u> (69)					
Baseline(before smoking)	2.0	1.7	1.9	2.0	1.9
Average (during smoking)	1.4	0.6	0.7	0.8	0.8
Standard Deviation	0.9	0.4	0.5	0.4	0.5
Maximum	4.3	1.8	2.8	2.5	1.4
Nonsmoking Flights (23)					
Baseline (before takeoff)	1.9	--	1.4	--	--
Average (while airborne)	0.6	--	0.5	--	--
Standard Deviation	0.4	--	0.4	--	--
Maximum	1.3	--	1.3	--	--

TABLE 4-20. MEASURED PEAK CO CONCENTRATIONS FOR

SMOKING AND NONSMOKING FLIGHTS

Type of Flight (Number)	Results by Seat Location, ppm				
	Smoking	Boundary	Middle	Remote (Domestic)	Remote (International)
Smoking Flights (69)					
Average (during smoking)	3.4	1.4	1.7	1.5	1.9
Standard Deviation	1.6	0.7	1.0	0.7	0.6
Maximum	8.0	3.3	6.6	4.5	2.6
Nonsmoking Flights (23)					
Average (while airborne)	1.3	--	0.9	--	--
Standard Deviation	0.6	--	0.4	--	--
Maximum	2.4	--	1.9	--	--

TABLE 4-21. RATIO OF PEAK-TO-AVERAGE CO CONCENTRATIONS FOR SMOKING

AND NONSMOKING FLIGHTS DURING PERIOD WHEN SMOKING WAS ALLOWED*

	Results by Seat Location				
Type of Flight (Number)	Smoking	Boundary	Middle	Remote (Domestic)	Remote (International)
Smoking Flights (69)					
Average Ratio	2.8	2.7	2.5	2.3	3.2
Standard Deviation	1.3	1.3	0.9	1.5	2.4
Maximum	9.0	7.5	6.0	7.0	7.5
Nonsmoking Flights (23)					
Average Ratio	2.6	--	3.2	--	--
Standard Deviation	1.5	--	2.5	--	--
Maximum	6.0	--	11.0	--	--

* While airborne for nonsmoking flights.

versus international flights are summarized in Table 4-22. RSP levels in the smoking section were lower on international than domestic flights, consistent with lower smoking rates per smoking passenger observed for longer flights (due, for example, to periods of sleeping). Average RSP levels in the other sections were similar for the two types of flights. International flights had higher peak RSP levels throughout all sections, however, most likely because of larger smoking sections with many people smoking simultaneously after takeoff or after meals. Nicotine levels and peak CO levels also were generally somewhat higher throughout the aircraft for international flights. The higher nicotine levels in the smoking section for international flights (despite lower average RSP levels) could be due to different cigarette brands used by foreign passengers, and the greater apparent migration of nicotine to the nonsmoking locations could be due either to more extensive use of recirculation or a more uniform distribution of smoking across the wide-body aircraft used for the international flights.

4.2.3 Carbon Dioxide and Pollutants

Average C02 levels (Table 4-23) were somewhat lower on smoking than nonsmoking flights, indicative of generally higher air exchange rates on smoking flights. On both types of flights, however, average C02 levels exceeded 1,000 ppm 87 percent of the time and sometimes exceeded 3,000 ppm. Thus, due to the relatively high density of occupants, C02 levels in aircraft cabins often exceeded ASHRAE guidelines associated with satisfaction of comfort criteria, despite air exchange rates that are much higher than those for ground-level indoor environments. The frequency distributions provided in Figure 4-14 indicate (1) that C02 levels were typically between 1,000 and 2,000 ppm for smoking flights and between 1,000 and 2,500 ppm for nonsmoking flights, and (2) that the two locations monitored for smoking flights had similar distributions.

Average measurement results for both total bacteria and Staphylococcus (Table 4-24) were similar for smoking and nonsmoking flights; the

TABLE 4-23. MEASURED C02 CONCENTRATIONS FOR SMOKING AND NONSMOKING FLIGHTS

Type of Flight (Number)	Seat Location: Smoking	Seat Location: Middle
Smoking Flights (69)		
Average, ppm	1562	1568
Standard Deviation	685	488
Minimum	711	597
Maximum	4943	3078
Nonsmoking Flights (23)		
Average, ppm	--	1756
Standard Deviation	--	660
Minimum	--	765
Maximum	--	3157

TABLE 4-24. MEASURED BACTERIA CONCENTRATIONS FOR SMOKING AND NONSMOKING FLIGHTS

	Total Bacteria		Staphylococcus	
Type of Flight (Number)	Smoking Seat	Middle Seat	Smoking Seat	Middle Seat
Smoking Flights (69)				
Average, CFU/m3	162.7	131.2	14.1	5.3
Standard Deviation	105.8	88.6	20.6	9.2
Maximum	556.4	462.1	97.8	45.0
Percent Below Minimum Detection	0.0	0.0	50.7	62.3
Nonsmoking Flights (23)				
Average, CFU/m3	--	131.1	--	6.5
Standard Deviation	--	123.4	--	9.6
Maximum	--	641.6	--	30.0
Percent Below Minimum Detection	--	0.0	--	56.5

levels were, however, slightly higher in the smoking than nonsmoking sections, possibly due to a higher proportion of passengers with respiratory conditions in the smoking section. Another possibility is that skinscales attach to settled particles and are resuspended by the movement of people, resulting in higher Staphylococcus levels in areas where particle concentrations are higher.

Average fungi results (Table 4-25) were very low on all flights; the levels were somewhat higher on nonsmoking flights, possibly due to slower removal (associated with lower air exchange rates) of fungi entrained at the gate and before takeoff. The most prevalent types of bacteria, measured on more than a third of the flights, were Staphylococcus aureus, Staphylococcus not aureus, Micrococcus varians, Micrococcus sedentarius, Corynebacteriun, and Arthrobacter (Table 4-26). The most prevalent types of fungi were Cladosporium and Alternaria (Table 4-27); apart from these types, only Penicillium was detected on more than 10 percent of the monitored flights.

Average ozone levels on the monitored flights (Table 4-28) also were relatively low, never exceeding 0.1 ppm. Average levels were somewhat higher for nonsmoking than smoking flights; the difference could be due to flight paths, air exchange rates, cleaning equipment for aircraft, or poorer accuracy/precision for nonsmoking flights due to relatively short sample-collection intervals.

4.3 QUALITY CONTROL SAMPLES

Samplers were deployed in duplicate on selected flights to estimate measurement precision for nicotine, RSP, C02, and ozone. The average precision for each measurement parameter is summarized in Table 4-29. With the exception of C02, the precision is poorer than would normally be expected. The poorer precision is due to the relatively short sampling duration; the typical monitoring duration for this study was several hours, whereas for most field monitoring studies the duration would be eight hours or longer.

TABLE 4-25. MEASURED FUNGI CONCENTRATIONS FOR SMOKING AND NONSMOKING FLIGHTS

Type of Flight (Number)	Seat Location: Smoking	Seat Location: Middle
Smoking Flights (69)		
Average, CFU/m3	5.9	5.0
Standard Deviation	6.4	5.8
Maximum	29.2	32.0
Percent Below Minimum Detection	11.6	13.0
Nonsmoking Flights (23)		
Average, CFU/m3	--	9.0
Standard Deviation	--	12.7
Maximum	--	61.1
Percent Below Minimum Detection	--	4.3

-

TABLE 4-26. PERCENT OF FLIGHTS ON WHICH DIFFERENT TYPES OF BACTERIA WERE DETECTED

	Smoking Flights		Nonsmoking
Bacteria	Middle	Smoking	Middle
Micrococcus varians	92.3%	9l.0%	95.5%
Staphylococcus not aureus	78.5%	65.7%	81.8%
Corynebacterium	61.5%	53.7%	86.4%
Arthrobacter	63.1%	65.7%	40.9%
Micrococcus sedentarius	53.8%	64.2%	54.5%
Staphylococcus aureus	38.5%	49.3%	45.5%
Micrococcus nishinomiyaensls	26.2%	9.0%	45.5%
Streptococcus not pyogenes	15.4%	15.4%	4.5%
Gram positive rod	13.8%	11.9%	22.7%
Bacillus	12.3%	9.0%	9.1%
Micrococcus lylae	6.2%	3.0%	0.0%
Micrococcus roseus	4.6%	3.0%	13.6%
Micrococcus kristinae	3.1%	0.0%	0.0%
Micrococcus luteus	1.5%	13.4%	0.0%
Gram negative rod	0.0%	3.0%	0.0%
Gram negative cocci	1.5%	0.0%	0.0%
Gram variable cocci	1.5%	1.5%	0.0%
Gram variable rod	1.5%	3,0%	0.0%
Stomatococcus	0.0%	1.5%	0.0%
Streptococcus pyogenes	0.0%	0.0%	0.0%

TABLE 4-27. PERCENT OF FLIGHTS ON WHICH DIFFERENT TYPES OF FUNGI WERE DETECTED

	Smoking Flights		Nonsmoking
Fungi	Middle	Smoking	Middle
Cladosporium	72.3%	70.1%	90.9%
Alternarea	46.2%	43.3%	31.8%
Aspergillus niger	9.2%	1.5%	9.1%
Penicillium	7.7%	10.4%	18.2%
Epicoccum	7.7%	6.0%	9.1%
Black yeast	1.5%	6.0%	9.1%
Aspergillus	6.2%	4.5%	0.0%
Curvalaria	4.6%	3.0%	4.5%
Arthrinium	4.6%	1.5%	4.5%
Mucor	4.6%	4.5%	4.5%
Pithomyces	4.6%	1.5%	0.0%
Drechslera	0.0%	1.5%	4.5%
Nigrospora	3.1%	3.0%	0.0%
Monilia	0.0%	0.0%	4.5%
Aspergillus glaucus	0.0%	0.0%	4.5%
Sporotrichum	0.0%	3.0%	0.0%
white yeast	1.5%	1.5%	0.0%
Aspergillus fumigatus	1.5%	1.5%	0.0%
Phialophora	0.0%	1.5%	0.0%
Erysiphe	1.5%	0.0%	0.0%
Scopularlopsis	1.5%	0.0%	0.0%
Yeast	0.0%	1.5%	0.0%
Botrytis	0.0%	1.5%	0.0%
Unidentified fungi	1.5%	0.0%	0.0%

TABLE 4-28. MEASURED OZONE CONCENTRATIONS FOR SMOKING AND NONSMOKING FLIGHTS

Type of Flight (Number)	Seat Location: Boundary*	Seat Location: Remote
Smoking Flights (69)		
Average, ppm	0.010	0.010
Standard Deviation	0.011	0.010
Maximum	0.054	0.044
Percent Below Minimum Detection	22.0	24.5
Nonsmoking Flights (23)		
Average, ppm	0.022	--
Standard Deviation	0.023	--
Maximum	0.078	--
Percent Below Minimum Detection	0.0	--

*Middle seat on nonsmoking flights.

TABLE 4-29. MEASUREMENT PRECISION FOR SELECTED PARAMETERS

Measurement Parameter	Average Precision*
Nicotine	+/- 27%
RSP	+/- 33%
C02	+/- 8%
Ozone	+/- 37%

* Precision for a set of duplicate samplers is the standard deviation for the two results expressed as a percent of the average result.

Section 5.0

SYNTHESIS AND DISCUSSION

Selected results from the previous section are synthesized and discussed in Section 5.1. In Section 5.2 ETS contaminants and pollutants are further analyzed and discussed in terms of the consistency of results and factors related to variations in measured concentrations.

5.1 SYNTHESIS OF MONITORING RESULTS

5.1.1 ETS Contaminants

Average values for various measurement parameters related to ETS contaminants are summarized by monitoring location for both smoking and nonsmoking flights in Table 5-1. The results are segregated by particle-phase versus gas-phase measurements. Both Gravimetric and optical particle-phase measurements are given in the table. As noted in Section 4.2, there was greater uncertainty for the Gravimetric measurements due to relatively short monitoring durations for a number of flights. Further, as shown later in this section, the optical results were more strongly correlated with observed smoking rates than were the Gravimetric results. At the same time, however, the Gravimetric method is a well-established technique that has been successfully used for measuring average RSP levels in many other environments, whereas the optical method has had more limited use.

The average of the RSP measurement results from the optical and Gravimetric methods was used for purposes of risk assessment. As summarized in Table 5-2, the combined results indicated that average RSP - levels in the coach smoking section exceeded those in the no-smoking section and on nonsmoking flights by approximately 100 ug/m3. Average levels in the boundary region near coach smoking were also somewhat higher than at the other no-smoking locations or on nonsmoking flights. The combined results for nonsmoking flights are consistent with RSP values that have been reported for other nonsmoking microenvironments (Repace 1987).

5-1
DIFFERENT METHODS ON DOMESTIC SMOKING FLIGHTS,
INTERNATIONAL FLIGHTS, AND DOMESTIC NONSMOKING FLIGHTS

Type of Flight/ Measurement Method	Results by Seat Location, ug/m3 Smoking	Boundary	Middle	Remote
<u>Domestic Smoking Flights</u>				
Gravimetric method	180.6	69.7	42.5	54.1
Optical method	181.7	38.9	16.9	17.4
Average of two methods	181.2	54.3	29.7	35.8
<u>International Flights*</u>				
Gravimetric method	129.0	51.2	41.9	36.7
Optical method	143.3	45.7	31.0	21.5
Average of two methods	136.2	48.5	36.5	29.1
<u>Nonsmoking Flights</u>				
Gravimetric method	59.3	--	69.4	--
Optical method	<u>10.3</u>	--	<u>10.6</u>	--
Average of two methods	34.8		40.0	

*Smoking was permitted on all international flights that were monitored

Peak RSP levels measured with optical sensors (Table 5-1) indicated even more pronounced differences between the boundary region and other no-smoking locations on smoking flights. The peak-to-average ratios for RSP were nearly identical in the smoking and boundary sections, and the ratios in these sections were higher than for the other no-smoking locations on smoking flights, The ratios in these other locations, however, were still higher than those for nonsmoking flights. Thus, tobacco smoking impacted all other sections of the aircraft in terms of peak RSP levels that were measured optically, and the effects were most pronounced in the boundary section (in addition to the distinct effects in the smoking section itself.

Effects of tobacco smoking, based on gas-phase measurements, were more discernible for nicotine than CO (Table 5-1). Beyond the marked increase in nicotine in the smoking section, the boundary region was most affected. Differences between nicotine levels for the remaining no-smoking locations and levels on nonsmoking flights were within the range of measurement uncertainty, but nicotine levels were more often above detection limits in the no-smoking locations than on nonsmoking flights. Further, cases where nicotine was detected on nonsmoking flights may reflect residual contamination from prior smoking flights. The only discernible effect for CO was in the smoking section itself. The lack of any other measurable effect may be due to the relatively low levels that prevailed, thereby increasing measurement uncertainty, coupled with background levels due in part to intrusion of ground-level emissions.

Measurement results for optical RSP (peak and average) and nicotine (average and percent above detection) are further summarized for each monitoring location in terms of 95-percent confidence intervals (i.e., parameter estimates +/-2 standard errors) in Figures 5-1 and 5-2. These confidence intervals generally reflect separation in ETS levels (1) between the smoking and boundary sections, (2) between the boundary section and other no-smoking locations for smoking flights, and (3) to a lesser extent, between the other no-smoking locations and locations on nonsmoking flights.

Results of statistical tests to contrast levels of ETS contaminants on smoking versus nonsmoking flights are given in Table 5-3. Comparisons were made for the monitoring locations common to both types of flights (i.e., smoking/rear and middle locations) using both parametric and non-parametric tests (the non-parametric tests do not require assumptions of normality or homogeneity of variances), For the smoking/rear location, levels of all six ETS measurement parameters were significantly higher (p C 0.05) on smoking than nonsmoking flights. For the middle location, levels were significantly higher for continuously monitored parameters (optical RSP and CO) but not for integrated-sample parameters (Gravimetric RSP and nicotine). The only discrepancy between the two types of statistical tests was for average optical RSP at the middle location, for which the parametric test was significant at the 0.05 level but the significance level for the non-parametric test was 0.09.

Results of statistical tests to contrast different sections within smoking flights are given in Table 5-4. Comparisons were made of the smoking versus boundary locations and the boundary versus middle locations, again using both parametric and non-parametric tests. Levels of all six ETS measurement parameters were significantly higher ($p < 0.05$) in the smoking than the boundary location. The boundary location was significantly higher than the middle location for all ETS tracers except C0. The only discrepancy between the two types of statistical tests was for nicotine at the boundary versus middle locations, for which the non-parametric test was significant at the 0.05 level whereas the parametric test had a significance level of 0.08. Thus, these tests indicate a clear difference between ETS levels in the smoking versus boundary sections and, to a lesser extent, between the boundary and middle sections (particularly for particle-phase constituents).

5.1.2 Carbon Dioxide and Pollutants

Average values for various measurement parameters related to pollutants are summarized by monitoring location for smoking and nonsmoking flights in Table 5-5. Most noteworthy are the relatively high

TABLE 5-3. RESULTS OF STATISTICAL TESTS* OF ETS LEVELS ON SMOKING VERSUS NONSMOKING FLIGHTS

	Parametric Test		Non-parametric Test	
Measurement Parameter	Smoking	Middle	Smoking	Middle
Gravimetric RSP	+	0	+	0
Optical RSP (average)	+	+	+	0
Optical RSP (peak)	+	+	+	+
Nicotine	+	0	+	0
CO (average)	+	+	+	+
CO (peak	+	+	+	+

* T-test used as parametric test; Mann-Whitney U-test used as non- parametric test; + indicates that smoking flights are significantly higher than nonsmoking flights (p (0.05); 0 indicates that the difference between flights is not significant.

TABLE 5-4. RESULTS OF STATISTICAL TESTS* OF ETS LEVELS IN DIFFERENT SECTIONS ON SMOKING FLIGHTS

	Parametric Test		Non-parametric Test	
Measurement Parameter	Smoking vs. Boundary	Boundary vs. Middle	Smoking vs. Boundary	Boundary vs. Middle
Gravimetric RSP	+	+	+	+
Optical RSP (average)	+	+	+	+
Optical RSP (peak)	+	+	+	+
Nicotine	+	0	+	+
CO (average)	+	0	+	0
CO (peak)	+	0	+	0

* Paired t-test used as parametric test; Wilcoxon matched-pairs signed-ranks test used as non-parametric test; + indicates that the first section listed is significantly higher than the second (p (0.05); 0 indicates that the difference between sections is not significant.

TABLE 5-5. AVERAGE VALUES ON SMOKING AND NONSMOKING FLIGHTS FOR PARAMETERS RELATED TO POLLUTANTS

Parameter	Smoking Flights		Nonsmoking Flights
	Smoking	Middle	
Average C02, ppm	1562	1568	1756
Percent C02 Samples >_ 1,000 Ppm	87.0	88.1	87.0
Average Ozone, ppm	0.01	0.01	0.02
Percent Ozone Samples z 0.1 ppm	0.0	0.0	0.0
Average Bacteria, CFU/m3	162.7	131.2	131.1
Average Fungi, CFU/m3	5.9	5.0	9.0

CO2 concentrations, which exceeded 1,000 ppm (the ASHRAE level associated with satisfaction of comfort criteria) on 87 percent of the monitored flights. Further discussion of the C02 measurement results is given in Section 5.2.

Ozone levels were relatively low, averaging nearly an order of magnitude below the FAA 3-hour standard of 0.1 ppm and never exceeding the standard on monitored flights. Fungi levels were also very low, indicating little problem with sources attributable to the aircraft themselves. Monitoring of fungi levels earlier in the flight might have better reflected the extent of intrusion from ground-level outdoor sources, but this strategy was avoided to remain unobtrusive throughout most of the flight. Bacteria levels were slightly higher in the smoking sections; the measured bacteria levels need to be contrasted with measurements from other environments to obtain further insights concerning their relative significance.

5.2 FURTHER ANALYSIS OF MONITORING RESULTS

Additional analyses described and discussed in this section focus on (1) comparisons between two measurement methods for RSP, (2) RSP-to-nicotine ratios that were measured in this study, (3) factors related to variations in measured levels of ETS contaminants, (4) comparisons between measured and modeled C02 levels, and (5) factors related to variations in measured levels of pollutants.

5.2.1 Comparison of RSP Measurement Methods

As previously summarized in Table 5-1, the optical RSP results were similar to the Gravimetric results for the smoking section on smoking flights, whereas the Gravimetric results were higher at all other monitoring locations, both for smoking and nonsmoking flights. One possible explanation is that the optical method is less sensitive to RSP from sources other than ETS. As indicated by Ingebrethsen et al. (1988), the mass density of ETS particulate matter is lower than that of standard test aerosols such as Arizona Road Dust. Consequently, the MINIRAM optical sensors that were calibrated in an ETS-dominated chamber environment may have under-reported RSP concentrations when the prevailing average mass density was higher, as may have been the case on nonsmoking flights.

Further insights were obtained by modeling average RSP concentrations for the entire cabin as a single chamber. A dynamic model for cabin air quality can be stated as follows:

$$\frac{d\,Cin}{dt} = \frac{F}{V} * C\ out + \frac{S}{V} - \frac{F}{V} Cin - \frac{e*R*Cin}{V}$$

where

Cin = Concentration within the cabin (ug/m3)
F = Fresh-air intake rate (m3/h)
V = Cabin volume (m3)
Cout = Concentration outside the cabin (ug/m3)
S = Emission rate (ug/h)
e = Filter efficiency for RSP removal (dimensionless fraction)
R = Air recirculation rate (m3/h).

Under steady-state conditions (i.e., dCin/dt=0), the above equation reduces to:

$$Cin = \frac{F * Cout + S}{F + e * R}$$

Modeling was performed using nominal fresh-air intake rates and recirculation rates given in Section 4.0, smoking rates estimated from technician observations, and an emission rate of 26,000 ug per cigarette (National Research Council 1986). An outdoor concentration of zero and a filter efficiency of 90 percent were assumed. Measured cabin-wide RSP concentrations were determined by weighting the monitoring results from each of the four measurement locations in proportion to the number of rows associated with each. Modeling was restricted to domestic smoking flights due to uncertainties concerning smoking rates in the business-class section of international flights.

Predicted and measured RSP concentrations for the two different methods are shown in Figure 5-3, together with the line of best fit for each. Predicted RSP values were 50 to 100 percent higher than measured values (a similar outcome was obtained in modeling results from the chamber tests used for calibration. The over-prediction may be due in part to the fact that a term for particle deposition was not included in the model due to uncertainty concerning an appropriate value for this parameter.

The correspondence between predicted and measured values was better for optical measurements (correlation coefficient of 0.65) than for Gravimetric measurements (correlation coefficient of 0.31). In addition, the average difference between predicted and measured values was lower for optical (55 percent) than Gravimetric (64 percent) measurements. The y-intercepts for regression of measured against predicted values indicate measurement results that can be expected in the absence of smoking. The larger intercept for Gravimetric results (40.2 ug/m3) than for the optical results (18.7 ug/m3) may reflect a higher sensitivity of the Gravimetric method to non-ETS sources of RSP. The intercept for the optical measurements is consistent with the optical results that were obtained during periods prior to smoking, which averaged near 18 ug/m3.

The cabin-average RSP measurements were also regressed against selected variables (smoking rate, cabin volume, fresh-air intake rate, and recirculation rate) to assess their relative predictability through an empirical model. The optical results had a stronger correlation with smoking rates ($r = 0.61$) than the Gravimetric results ($r = 0.33$). The following regression equation for the optical results included three predictor variables significant at the 0.05 level and explained 52 percent of the variance:

$$\text{Optical RSP} = \underset{(8.03)}{41.60} + \underset{(0.29)}{1.77} * \text{Cigarettes/h} - \underset{(0.16)}{0.55} * \text{Recirculation Rate} - \underset{(0.001)}{0.004} * \text{Fresh-air Rate}$$

Standard errors for the intercept and regression coefficients are given in parentheses in the above equation. For Gravimetric measurements, there was only one significant predictor (smoking rate), which explained 11 percent of the variance; the following regression equation was obtained:

$$\text{Gravimetric RSP} = \underset{(15.73)}{39.10} + \underset{(0.71)}{1.74} * \text{Cigarettes/h}$$

A final comparison was made between the two methods based on five Northwest Airlines nonsmoking flights that were monitored during the study. These flights were of relatively longer duration and should have had little or no residual ETS levels due to Northwest's no-smoking policy for all flights within the continental United States. Both the Gravimetric and optical results (Table 5-6) for this subset of flights were somewhat lower, based on the average of the two monitored locations, than for all nonsmoking flights as a whole. The Gravimetric results, however, were quite different at the two locations and had relatively high standard deviations, reflecting measurement uncertainty.

The above analysis and discussion indicate that the RSP results obtained by optical methods are more internally consistent and predictable than the results obtained by Gravimetric methods. Thus, there are indications that optical measurements may be more sensitive to ETS than Gravimetric measurements and the level of uncertainty associated with the Gravimetric measurements may be high for cases of low airborne RSP concentrations and short sampling durations, However, as stated previously, the average of the RSP measurement results from the two methods was used for risk assessment purposes.

TABLE 5-6. RSP MEASUREMENT RESULTS OBTAINED BY TWO DIFFERENT METHODS ON FIVE NONSMOKING FLIGHTS WITH NORTHWEST AIRLINES AS THE CARRIER

Monitoring Location	Measurement Result,* ug/m3	
	Gravimetric	Optical
Middle	70.7+/- 53.5	2.5+/-0.2
Rear	27.0 +/- 85.5	7.7 +/-7.5

*Average+/- standard deviation.

5.2.2 Ratios Between RSP and Nicotine

Based on a subset of 57 smoking flights with complete results for nicotine and RSP by both measurements methods, the average nicotine concentration in the smoking section was 13.0 ug/m3. Average RSP concentrations in this section were 181.7 ug/m3 by the optical method and 182.6 Ug/m3 by the Gravimetric method. These aggregate results imply an RSP-to-nicotine ratio near 14 for the smoking section. Netting out RSP levels not due to ETS (i.e., 19 ug/m3 for optical results and 40 ug/m3 for Gravimetric results) would result in a ratio between 11.0 and 12.5. This range of ratios is consistent, for example, with the 11:1 ratio assumed by Repace and Lowrey (1988) in developing an indoor concentration model for nicotine.

RSP-to-nicotine ratios calculated for each flight, and then averaged across flights, would be misleading because very large ratios would be obtained for flights with low nicotine levels. Instead, the nicotine results for the smoking section on each flight were regressed on RSP results for the same monitoring location. The following equations were obtained:

Nicotine = -2.38 + 0.084 * Optical RSP (R2 = 4.36)

Nicotine = 0.12 + 0.070 * Gravimetric RSP (R2 = 0.24)

The inverse of the regression coefficients imply an RSP-to-nicotine ratio between 11.9 and 14.3, consistent with the ratios based on aggregate data. The equations also imply that no nicotine would be detectable until the optical measurement reaches near 30 ug/m3, whereas some nicotine would be detectable for Gravimetric results near zero. As indicated by the R2 values shown above and the scatter about the regression lines shown in Figure 5-4, the nicotine measurements were more strongly correlated with optical than with Gravimetric measurements.

The RSP-to-nicotine ratios for the boundary section, calculated from aggregate data presented earlier in Table 5-1, were much higher (150 to 260). These much higher ratios for the boundary section indicate that nicotine is being preferentially removed (relative to RSP) before or as ETS leaves the smoking section. RSP is subject to some removal through deposition, whereas nicotine can react with various types of materials including clothing, seats, and carpeting on the cabin floor. Netting out RSP levels not due to ETS would result in RSP-to-nicotine ratios between 80 and 105 for the boundary section.

RSP-to-nicotine ratios higher than those observed in the smoking section have been measured by some researchers. Nicotine levels measured in this study were generally lower than those measured in the boundary section as part of a smaller field study reported by Mattson et al. (1989). However, in that study the higher nicotine values were obtained on a wide-body flight for passengers seated in aisle seats adjacent to the smoking section. Because the middle and side sections of wide-body aircraft are offset by about half the width of a seat, passengers in the boundary section sitting in outer seats could easily be exposed to ETS levels rivaling those in the smoking section. Thus, the RSP-to-nicotine ratios measured in the boundary section during this study, although relatively high, are not implausible.

5.2.3 Factors Related to Variations in ETS Concentrations

Nicotine measurement results for each monitoring location on smoking flights are summarized in Table 5-7 in relation to four factors -- type of aircraft, air recirculation, air exchange rate, and cigarette smoking rate. Compared to aircraft without recirculation, aircraft with recirculation had lower levels in the smoking section coupled with somewhat higher levels in the no-smoking section. Levels in all sections were lower on narrow-body than wide-body aircraft. Levels in the smoking section were strongly related to smoking rates. Air exchange rates appear to have had little impact.

TABLE 5-7. RELATIONSHIP OF NICOTINE MEASUREMENT RESULTS FOR DOMESTIC SMOKING FLIGHTS TO SELECTED FACTORS

Factor (Number of Flights)	Average+/- Standard Deviation, ug/m3			
	Smoking Row	Boundary Row	Middle Row	Remote Row
<u>Type of Aircraft</u>				
Wide Body (13)	20.4 +/- 19.5	0.42 +/- 0.93	0.04 +/- 0.07	0.08 +/- 0.12
Narrow Body (48)	11.3 +/-13.0	0.07 +/- 0.14	0.03 +/- 0.14	0.02 +/- 0.05
<u>Air Recirculation</u>				
No (36)	16.1 +/- 16.1	0.08 +/- 0.15	0.04 +/- 0.16	0.03 +/- 0.09
Yes (25)	9.1 +/- 12.4	0.22 +/- 0.69	0.02 +/- 0.06	0.03 +/- 0.06
<u>Air Exchange Rate (nominal)</u>				
<20 (31)	11.4 +/-14.2	0.21 +/- 0.62	0.02 +/- 0.05	0.04 +/- 0.09
Z 20 - (30)	15.1 +/- 15.8	0.07 +/-0.15	0.05+/- 0.18	0.02 +/- 0.06
<u>Cigarettes/Hour</u>				
< 10 (12)	1.7 +/-2.4	0.04 +/- 0.07	0.02 +/- 0.06	0.03 +/- 0.09
10 - 19.9 (23)	11.2 +/- 13.0	0.19 +/- 0.07	0.05 +/- 0.20	0.02 +/- 0.05
20 - 29.9 (17)	17.6 +/- 12.8	0.17 +/- 0.20	0.03+/- 0.07	0.05+/- 0.11
Z 30 (9)	25.2+/-21.3	0.11+/-0.15	0.01 +/- 0.04	0.03 +/- 0.06

RSP measurement results are summarized in relation to the same factors in Table 5-8 (for Gravimetric measurements) and in Table 5-9 (for optical measurements). The smoking rate had the greatest impact, in this case influencing levels in the boundary section in addition to those in the smoking section. The effects of aircraft type, air recirculation, and air exchange rate were less consistent, but levels in the smoking section were lower on narrow-body aircraft and on flights with air recirculation. More rapid removal of ETS contaminants from the smoking section, and some redistribution to other sections, could be occurring due to recirculation.

CO measurement results are summarized in relation to the same factors in Table 5-10. The only discernable pattern for CO was that of higher levels in the smoking section when smoking rates were higher, particularly at the upper extreme (i.e., 30 or more cigarettes per hour).

Measurement results for nicotine, RSP, and CO in the boundary section are summarized in Table 5-11 in relation to the technician's proximity to the smoking section. There was no discernable pattern for gas-phase tracers (nicotine and CO), but both average and peak RSP levels were highest when the technician was located in the row immediately bordering on the smoking section.

5.2.4 Modeling of CO2 Concentrations

A single-chamber steady-state model similar to that described previously for RSP was used to model average C02 concentrations for all study flights. Because the filters in aircraft with recirculation are not currently designed to remove C02, the equation previously used can be simplified to the following:

$$Cin = Cout + S/F$$

where Cin and Cout refer to indoor and outdoor C02 concentrations, S indicates the emission rate, and F indicates the fresh-air intake rate. Nominal air exchange rates were used for the model together with an

TABLE 5-8. RELATIONSHIP OF GRAVIMETRIC RSP MEASUREMENT RESULTS FOR DOMESTIC SMOKING FLIGHTS TO SELECTED FACTORS

Factor	Average+/- Standard Deviation, ug/m3			
	Smoking Row	Boundary Row	Middle Row	Remote Row
Type of Aircraft				
Wide Body	195.5+/-125.8	71.5+/-74.2	44.5+/-49.9	36.5+/-47.8
Narrow Body	176.5+/-102.1	69.2+/-60.4	42.0+/-68.7	58.9+/-66.7
Air Recirculation				
No	190.8+/-116.2	69.5+/-70.3	48.5+/-73.6	49.8+/-68.5
Yes	165.9+/-91.7	69.9+/-51.8	33.9+/-49.6	60.3+/-56.3
Air Exchange Rate (nominal)				
< 20	177.7+/-100.8	76.7+/-61.1	41.4+/-51.5	59.5+/-55.8
z 20	183.5+/-114.3	62.4+/-65.0	43.7+/-77.1	48.6+/-71.1
Cigarettes/Hour				
< 10	126.2+/-109.4	58.8+/-64.0	38.8+/-101.1	84.9+/-53.2
10 - 19.9	163.5+/-88.7	61.6+/-47.6	39.2+/-54.4	50.8+/-42.5
20 - 29.9	191.1+/-87.4	79.6+/-66.2	30.2+/-45.0	35.9+/-69.7
Z 30	276.7+/-127.2	86.1+/-90.5	79.3+/-57.9	55.9+/-97.4

TABLE 5-9. RELATIONSHIP OF OPTICAL RSP MEASUREMENT RESULTS DURING THE SMOKING PERIOD ON DOMESTIC SMOKING FLIGHTS TO SELECTED FACTORS

	Average+/- Standard Deviation, ug/m3			
Factor	Smoking Row	Boundary Row	Middle Row	Remote Row
Type of Aircraft				
Wide Body	212.0+/-137.1	66.5+/-47.6	17.2+/-9.2	15.9+/-9.4
Narrow Body	174.5+/-98.2	31.4+/-29.9	16.9+/-19.4	17.8+/-17.4
Air Recirculation				
No	200.9+/-106.5	43.8+/-39.6	17.0+/-21.3	17.7+/-19.0
Yes	153.4+/-102.2	31.4+/-31.7	16.8+/-10.4	17.0+/-10.6
Air Exchange Rate (nominal)				
< 20	171.5+/-118.0	43.6+/-43.3	17.3+/- 9.8	18.0+/-10.7
z 20	191.6+/- 95.1	34.3+/-29.3	16.5+/-23.5	16.8+/-19.9
Cigarettes/Hour				
< 10	105.8+/-47.9	23.8+/-17.9	13.1+/-10.0	26.2+/-33.2
10 - 19.9	150.9+/-83.5	24.1+/-19.4	21.0+/-25.5	15.9+/-9.9
20 - 29.9	189.7+/-64.0	52.3+/-39.2	14.2+/-11.5	15.3+/-10.2
z 30	355.1+/-105.7	71.8+/-56.7	16.7+/-9.4	16.3+/-11.7

TABLE 5-10. RELATIONSHIP OF CO MEASUREMENT RESULTS DURING THE SMOKING PERIOD ON DOMESTIC SMOKING FLIGHTS TO SELECTED FACTORS

	Average+/-Standard Deviation, ppm			
Factor	Smoking Row	Boundary Row	Middle Row	Remote Row
<u>Type of Aircraft</u>				
Wide Body	1.5+/-1.0	0.6+/-0.4	0.8+/-0.6	0.8+/-0.5
Narrow Body	1.5+/-0.9	0.6+/-0.4	0.7+/-0.5	0.8+/-0.4
<u>Air Recirculation</u>				
No	1.5+/-0.9	0.6+/-0.4	0.8+/-0.6	0.8+/-0.4
Yes	1.4+/-0.9	0.6+/-0.4	0.7+/-0.5	0.8+/-0.5
<u>Air Exchange Rate (nominal)</u>				
< 20	1.5+/-1.0	0.7+/-0.4	0.7+/-0.6	0.9+/-0.5
Z 20	1.4+/-0.9	0.6+/-0.4	0.7+/-0.5	0.8+/-0.4
<u>Cigarettes/Hour</u>				
< 10	1.1+/-0.6	0.5+/-0.3	0.8+/-0.7	0.9+/-0.4
10 - 19.9	1.3+/-0.8	0.7+/-0.5	0.6+/-0.3	0.7+/-0.3
20 - 29.9	1.3+/-0.9	0.5+/-0.3	0.7+/-0.4	0.8+/-0.4
z 30	2.4+/-1.1	0.7+/-0.4	1.1+/-0.8	1.1+/-0.7

TABLE 5-11. RELATIONSHIP OF ETS MEASUREMENTS IN THE BOUNDARY SECTION TO TECHNICIAN DISTANCE FROM SMOKING SECTION

	Average+/-Standard Deviation			
Type of Measurement	One Row Away	Two Rows Away	Three Rows Away	Four or More Rows Away
Nicotine, ug/m3	0.11+/-0.15	0.34+/-1.01	0.08+/-0.13	0.06+/-0.09
Gravimetric RSP, ug/m3	88.1+/-64.6	64.9+/-54.6	44.8+/-57.1	58.9+/- 77.0
Average Optical RSP,ug/m3	50.8+/-34.4	28.4+/-35.8	31.5+/-45.7	35.0+/-30.4
Peak Optical RSP, ug/m3	327.2+/-471.5	119.1+/-119.6	128.5+/-161.3	118.8+/-96.9
Average C0, ppm	0.6+/-0.4	0.8+/-0.4	0.6+/-0.4	0.5+/-0.3
Peak C0, ppm	1.5+/-0.8	1.5+/-0.6	1.2+/-0.6	1.0+/-0.3

assumed outdoor concentration of 330 ppm and an emission rate of 0.3 1/min (16,000 ml/h) per passenger (ASHRAE 1989). As illustrated in Figure 5-5, a reasonable association between predicted and measured values was obtained (r = 0.55). However, measured values (averaging 1,609 ppm) were nearly a factor of two higher than those predicted by the model (average of 841 ppm). The modeled values shown in the figure do not include emissions from the flight and cabin crew members, but adding emissions from 10 additional persons to account for the crew would increase the modeled values only to 888 ppm.

There are four possible explanations for the discrepancy between measured and modeled values: (1) the measurements may have a positive bias, due to proximity to the breathing zone or the measurement device used, (2) there may be short-circuiting between the supply and exhaust points within the aircraft, resulting in poor ventilation efficiency, (3) the nominal air exchange rates used for modeling may be higher than prevailing rates during the monitored flights, or (4) C02 emission rates may be higher than those used in the model. One study (Balvantz et al. 1982)has suggested that C02 exhalation rates in airliner cabins could be as high as 0.5 1/min per passenger due to factors such as environmental stress and food/alcohol consumption. With this higher emission rate, average measurement values still exceeded average modeled values (1,180 ppm) by a third. Further measurements at different heights in the aircraft, with more sophisticated monitoring devices, are needed to fully resolve the issue. However, even if the monitoring results were biased high by a factor of two, there would still be a substantial number of monitored flights (about 24 percent) exceeding 1,000 ppm C02.

5.2.5 Factors Related to Variations in C02 and Pollutant Concentrations

Average C02 levels measured at smoking and middle seats on all smoking flights (domestic plus international) are summarized in Table 5-12 in relation to type of aircraft, air recirculation, air exchange rate, and load factor (i.e., percent of seating capacity filled by passengers). Higher C02 levels were associated with narrow-body aircraft, aircraft with recirculation, lower air exchange rates, and higher load factors, with

TABLE 5-12. RELATIONSHIP OF C02 MEASUREMENT RESULTS FOR ALL SMOKING FLIGHTS TO SELECTED FACTORS

Factor (Number of Flights)	Average+/-Standard Deviation, ppm	
	Smoking Row	Middle Row
Type of Aircraft		
Wide Body (13)	1236.5+/-393.9	1211.6+/-359.5
Narrow Body (48)	1710.7+/-739.6	1723.6+/-456.4
Air Recirculation		
No (37)	1448.2+/-515.2	1545.3+/-449.9
Yes (32)	1694.4+/-829.8	1593.9+/-535.1
Air Exchange Rate (nominal)		
< 20 (37)	1609.5+/-804.3	1564.2+/-512.9
< 20 (32)	1507.0+/-521.0	1572.0+/-466.0
Load Factor		
< 50% (16)	1129.0+/-277.8	1183.0+/-275.6
50 to 69.9% (12)	1211.3+/-229.1	1153.1+/-603.3
70 to 89.9% (21)	1794.2+/-884.3	1699.9+/-584.5
z 90% (20)	1910.2+/-583.7	1745.9+/-212.4

load factor having the strongest association. The relationships with most of these factors were in opposite directions for bacteria versus fungi (Tables 5-13 and 5-14); bacteria levels were somewhat higher on wide-body aircraft, aircraft with recirculation, and flights with lower nominal air exchange rates, whereas fungi levels were somewhat lower in each of these cases. Bacteria and fungi levels both were generally higher in the presence of higher load factors"

5.3 REFERENCES

ASHRAE. 1989. Ventilation for Acceptable Indoor Air Quality . ASHRAE Standard 62-198 . American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA

Balvarz, Jr., S. Bowman, A. Fobelets, T. Lee, K. Papamichael, and R. Yoder. 1982. Examination of the Cabin Environment of Commercial Aircraft. Iowa State University, Ames, A

Ingebrethsen, B.J., 0. Heavner, A. Angel, J. Conner, T. Steichen and C. Green. 1988. "A Comparative Study of Environmental Tobacco Smoke Particulate Mass Measurements in an Environmental Chamber," JAPCA 38(4):413-417

Mattson, M., G. Boyd, D. Byar, C. Brown, J. Callahan, D. Corle, J. Cullen, J. Greenblatt, N. Haley, K. Hammond, J. Lewtas and W. Reeves. 1989. "Passive Smoking on Commercial Airline Flights," J. Amer. Med. Assoc., 261(6):867-872

National Research Council. 1986. Environmental Tobacco Smoke: Measuring Exposures and Assessing Health Effects. National Academy Press. Washington, D.C.

Repace, J.L. 1987. "Indoor Concentrations of Environmental Tobacco Smoke: Field Surveys," in Environmental Carcinogens Methods of Analysis and Exposure Measurement: Volume 9--Passive Smoking. Ed. I.K. O'Neil, K. Brunneman, B. Dodet, and D. Hoffman, International Agency for Research on Cancer, lyon, France.

Repace, J.L., and A. Lowrey. 1988. "Indoor Air Modeling of the Aerosol from Environmental Tobacco Smoke." Presented at the 1988 Annual Meeting of the American Association for Aerosol Research, Chapel Hill, NC

TABLE 5-13. RELATIONSHIP OF BACTERIA MEASUREMENT RESULTS FOR ALL SMOKING FLIGHTS TO SELECTED FACTORS

	Average+/-Standard Deviation, cfu/m3	
Factor	Smoking Row	Middle Row
<u>Type of Aircraft</u>		
Wide Body	169.0+/-89.0	164.8+/-118.0
Narrow Body	160.0+/-113.3	116.3+/-68.2
<u>Air Recirculation</u>		
No	146.5+/-89.9	130.0+/-81.3
Yes	181.0+/-120.1	132.4+/- 96.8
Air Exchange Rate (nominal)		
< 20	167.6+/-115.8	132.9+/-100.8
> 20	157.0+/-94.0	129.0+/-70.9
< 50%	131.0+/-76.8	100.4+/-80.7
50 to 69.9%	159.8+/-122.4	159.0+/-114.6
70 to 89.9%	178.8+/-136.9	122.5+/-65.2
Z 90%	173.8+/-78.4	147.4+/-97.9

TABLE 5-14. RELATIONSHIP OF FUNGI MEASUREMENT RESULTS FOR ALL SMOKING FLIGHTS TO SELECTED FACTORS

Factor	Average+/-Standard Deviation, cfu/m3	
	Smoking Row	Middle Row
Type of Aircraft		
Wide Body	3.9+/-3.4	4.2+/-5.1
Narrow Body	7.9+/-7.0	6.6+/-6.1
Air Recirculation		
No	7.6+/-6.4	5.9+/-6.8
Yes	5.7+/-6.4	5.7+/-4.7
Air Exchange Rate (nominal)		
< 20	5.8+/-6.2	5.0+/-3.5
> 20	7.7+/-6.6	6.9+/-7.9
Load Factor		
< 50%	2.8+/-2.1	2.9+/-2.8
50 to 69.9%	7.2+/-8.6	6.9+/-7.7
70 to 89.9%	10.4+/-7.8	7.1+/-7.7
Z 90%	5.5+-3.5	5.9+/-3.0

Section 6.0

GENERAL APPROACH TO RISK ASSESSMENT

The general approach to risk assessment in this investigation was that described by the National Research Council (1983) of the National Academy of Sciences. This report defines risk assessment as a systematic, multi-step process of data evaluation designed to characterize the nature and magnitude of health damage posed by an environmental agent under various conditions of exposure.

A comprehensive risk assessment contains four major steps:

* Hazard identification is the determination of whether exposure to a particular chemical is or is not causally linked to a particular health effect(s)

* Dose-response assessment is the determination of the relation between the magnitude of exposure and the probability of occurrence of the health effect(s) in question

* Exposure assessment is the determination of the extent of human exposure before or after application of regulatory controls

* Risk characterization is a description of the nature and often the magnitude of human risk, including attendant uncertainty.

The process of conducting a risk assessment involves integrating the information in each of these areas in a systematic fashion, first by identifying the health hazards, then deriving a quantitative expression of the dose-response relationship based on the identified health hazards of greatest concern, and then combining the derived dose-response algorithm with an independent quantitative exposure assessment to produce a characterization of risk. Prior to the collection and analysis of data for the quantitative estimation of risk, underlying decisions must be made about the population(s), pollutant(s), and health effect(s) of interest, so that the ensuing expression of risk targets those areas.

6.1 POLLUTANTS AND HEALTH EFFECTS OF INTEREST

The pollutants of concern in the airliner cabin environment and their attendant health effects (hazard identification) have previously been identified (National Research Council 1986), so that exposure assessment and dose-response assessment were the critical elements requiring definition for risk characterization. In this investigation, multiple procedures were required to characterize risk, depending on the health endpoint of interest, the chemical entity of interest, its mode of action, and the degree of scientific understanding about the chemical:

* Environmental tobacco smoke (ETS) was of interest as a chemical mixture because of its carcinogenic potential, and respiratory and cardiovascular effects. For carcinogenicity, it was necessary to select the most appropriate dose-response model(s) that correlate expected individual risk with degree of exposure to RSP as a surrogate for the ETS mixture.

* Nicotine, as a constituent of ETS, is an appropriate indicator for its acute respiratory effects. Human inhalation dose-response data exist for the irritant properties of ETS, using nicotine as a surrogate.

* Carbon monoxide, like nicotine, can be used as an ETS surrogate for acute respiratory effects.

* Universally applicable procedures for risk assessment of bioaerosols (both fungi and bacteria) hare not been established. As a result, conventional expressions of risk assessment cannot be used. For fungi, the 20 Genera that occur most frequently in highest concentrations on growth plates were identified. Their relative clinical significance was then ascertained using their ability to cause allergies and infections as benchmark clinical weight-of-evidence criteria. This relative significance is reported for the 20 identified genera. A similar procedure was used for bacteria to determine prevalence.

* Ozone presented a unique problem because the scientific community is divided on the lowest ambient air concentration causing an increase in lung infectivity. Concentrations aboard aircraft were compared with the current FAA regulatory 3-hour standard of 0.10 ppm.

* The risks from exposure to cosmic radiation were based on dose-response data provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (1986, 1988) and the Federal Aviation Administration (1989). Combining these data with plausible exposure levels and durations, risks were determined for cancer, fetal retardation, and birth defects.

6.2 POPULATIONS OF INTEREST AND FREQUENCY OF FLYING

In order to establish meaningful estimates of risk, it was necessary to subdivide the entire population of flyers according to frequency of flying (which would influence the amount of exposure to cabin air) and health and maturational status (which would influence the dose-response relationship between specific pollutants and their health effects).

The populations of interest in this investigation included cabin crewmembers, who are representative of occupational exposure, and all passengers. Children, fetuses, asthmatics, and individuals with preexisting cardiovascular disease constituted four passenger sub-populations of special interest. Flight crewmembers, whose environment on the flight deck is different from the aircraft cabin, were not considered in this investigation. The specific pollutants and associated health effects of concern varied among these populations and sub-populations:

* ETS was considered for cancer in all passenger populations without preexisting illness and cabin crew members, for chronic respiratory Illness in children, for acute respiratory effects in all individuals without preexisting illness and asthmatics, and for cardiovascular disease in cabin crew numbers and individuals with this preexisting illness.

* Bioaerosols (fungi and bacteria) were considered in all populations for their clinical significance as allergens and infectious agents.

* Ozone was considered in all passengers without preexisting illness and in cabin crew members, in accordance with the basis of the FAA ozone standard in aircraft.

* Cosmic radiation was considered for cancer in all passengers and cabin crewmembers, and for birth defects and retardation in fetuses.

The relationship among pollutants, populations, and health effects is presented in Figure 6-1.

Frequency of flying is important where exposure over a protracted time period (e.g., years) affects health, such as in case of development of cancer. Among passengers, frequency of flying was not distinguishable into apparent and justifiable categories since there were no universally applicable criteria for what constituted a frequent and non-frequent flyer. Accordingly, for this investigation classifications of frequency were set aside. Instead, in the case of cancer, frequency-variable risk tomograms were developed for ETS and cancer so that frequency-specific cancer risks can be developed.

Exposure to cosmic radiation is also dependent on frequency, as well as on altitude and latitude of flight. Greatest radiation occurs at high altitude over the earth's poles, gradually diminishing in intensity toward the equator. Exposure can be determined by adding individual doses received during individual flights. The cumulative dose is then applied to a dose-response curve for the health effect of interest.

Frequency of flying was not relevant for other health effects that were considered since they were a result of short-term episodic exposure.

Cabin crewmembers were estimated to log approximately 80 hours of flight time per month (Association of Flight Attendants 1988). This is based on the distribution of cabin crew flight frequencies contained in Table 6-1.

Table 6-1. AVERAGE NUMBER OF HOURS FLOWN BY MEMBERS OF THE ASSOCIATION OF FLIGHT ATTENDANTS (AFA). FIGURES REPRESENT COMBINED DOMESTIC AND INTERNATIONAL FLIGHTS.

Percentage of AFA Membership	Number of Hours Flown Per Month
3	64 or fewer
9	65-69
18	70-74
28	75-79
34	80-85
4	85-89
4	90 or more

Source: 1985 AFA Survey

6.3 REFERENCES

Association of Flight Attendants. 1988. Letter to Robert R. McMeekin. Federal Aviation Administration. October 3, 1988. Washington, D.C.

Federal Aviation Administration. 1989. Radiation Exposure of Air Carrier Crewmembers. AAM-624. Federal Aviation Administration, U.S. Department of Transportation.

National Research Council. 1983. Risk Assessment in the Federal Government. National Academy Press. Washington, D.C. .

National Research Council. 1986. The Airliner Cabin Environment: Air Quality and Safety. National Academy Press. Washington, D .C .

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1988. Sources Effects and Risks of Ionizing Radiation. Report to the General Assembly. Annex F: Radiation Carcinogen in Man. UN Publication Sales No. E.88.IX.9 United Nations, New York, NY

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1986. Genetic and Somatic Effects of Ionizing Radiation. Report to the General Assembly. Annex C: Biological Effects of Pre-natal Irradiation. UN publications Sales No. E.86.IX.9 United Nations. New York, NY.

Section 7.0
RISK ASSESSMENT FOR ENVIRONMENTAL TOBACCO SMOKE

7.1 REVIEW OF HEALTH EFFECTS

The health effects of ETS have been recently and extensively reviewed in several reports of the Surgeon General (1982, 1983, 1984, 1985, 1986, 1989), and in documents of the World Health Organization (WHO 1986), the Environmental Protection Agency (1987), the National Research Council (1986a, 1986b), the Fourth International Conference on Indoor Air Quality and Climate (1987), and in key research studies. These documents collectively represent critical evaluations of the complete body of scientific literature for its meaning and accuracy. The health effects are briefly summarized below.

7.1.1 Acute Effects

While odor in itself is not a health effect, it can be considered as a psychophysiological factor contributing to the development of an adverse health response and thus is important in considering the impact of ETS. This is particularly true for the nonsmoker, whose threshold for odor unacceptability is lower than the smoker who loses ETS odor detection sensitivity rapidly (Cain et al. 1983). While loss of sensitivity occurs in an experimentally controlled environment within four minutes after exposure begins, it is not meant to imply that it is directly applicable to the airliner cabin environment, where the number of individuals smoking at any given moment is highly variable. Odor, as the nonsmokers first sensory clue of ETS presence, is a major contributor to annoyance and is caused principally by the gas phase components of ETS.

While odor adaptation to ETS occurs over a short time frame, respiratory and ocular irritation increase proportionately over at least one hour at levels as low as 2 ppm CO (used as a surrogate for ETS concentration (Cain et at. 1987)). Ocular irritation begins at ETS levels lower than those causing respiratory irritation. Like odor, research suggested that eye irritation is caused predominantly by the gas-phase constituents of ETS (Weber 1986).

The evidence for acute respiratory and ocular irritation of ETS on the non-sensitive adult has been reported as equivocal and not scientifically conclusive (Lebowltz 1976; Schilling et al. 1977; Comstock et al. 1981; Schenker et al. 1982). Recent studies (Cain et al. 1987) have indicated that acute irritation is at least perceived to occur in individuals exposed to ETS and can be expressed as degree of dissatisfaction.

For individuals who are sensitive because they have preexisting conditions, such as asthma, that are provoked by ETS, or who, because of their stage in life, may be especially vulnerable, the acute effects can be more clinically significant and debilitating, leading to the notion that a smoking allergy may exist.

This is most apparent in infants and young children of smoking parents, who appear to be particularly susceptible to acute respiratory bronchitis and pneumonia from ETS exposure (U.S. Department of 'Health and Human Services 1986). While components of cigarette smoke are known to affect other preexisting conditions such as cardiovascular disease, the acute effects of ETS on these conditions is unclear. Recent studies (Health Effects Institute 1988) have demonstrated induction of angina at a carboxyhemoglobin level of 4 percent, while a series of studies have indicated that CoHb levels of nonsmokers in smoking environments to be 2 percent or less (National Research Council l986a). Endogenous levels of carboxyhemoglobin levels in the U.S. population are typically 0.5 percent. These circumstances indicate that the cardiovascular effects of ETS on individuals with preexisting conditions may occur at levels not much above background, at least for C0.

In addition, a significant segment of the U.S. population with high blood pressure accompanied by angina or coronary disease is known to be adversely affected by nicotine exposure (National Research Council 1986a). Several studies examined the potential for ETS impact on cardiovascular disease. However, the acute cardiovascular effects of ETS on individuals with this preexisting condition have not been examined.

7.1.2 Chronic Effects

Knowledge about the importance of ETS to chronic obstructive pulmonary disease and other respiratory effects, cardiovascular disease, and cancer (particularly lung cancer) has been greatly enhanced by the large volume of data on mainstream smoke and these diseases.

7.1.2.1 Chronic Obstructive Pulmonary Disease and Other Respiratory Effects

For acute respiratory effects, the literature on ETS as an etiologic agent of lower respiratory tract illnesses is derived principally from children of smoking parents (Colley 1974; Bland et al. 1978; Weiss et al. 1980; Schenker et al. 1983; Ware et al. 1984; Charlton 1984). while the evidence for ETS as an etiologic agent of childhood asthma is equivocal (Gortmaker et al. 1982; Burchfiel 1984; Leeder et al. 1976; Horwood et al. 1985; Tashkin et al. 1984), infants and young children of smoking parents are more likely than those of nonsmoking parents to contract lower respiratory diseases such as bronchitis and pneumonia (Ware et al. 1984; Schenker et al. 1983; U.S. Department of Health and Human Services 1986) and therefore likely to be affected by ETS exposure on aircraft. Three clinical manifestations that are seen consistently in studies of children include cough, reduced lung function measured as forced expiratory flow at the 25 percent to 75 percent level (FEF 25-75) (Tager et al. 1979), and impaired development of forced expiratory volume (FEV) with growth (Tager et al. 1983; Berkey et al. 1986).

Data on effects of ETS on the adult respiratory system are inconclusive. While reduced FEF 25-75 has been reported by several investigators (Kauffmann et al. 1983; White and Froeb 1980), other studies have not shown an effect on adult lung function (Burchfiel 1986; Kentner et al. 1984). Studies on both children and adults as sensitive populations with preexisting asthma are also inconclusive (U.S. Environmental Protection Agency 1987).

7.1.2.2 Cardiovascular Disease

Mainstream cigarette smoke has been implicated as a causative agent of arteriosclerosis, coronary heart disease, and cerebrovascular disease. The contribution of ETS to these diseases and its mechanisms of action are inconclusive, although it appears from animal studies that the predominant influence is being exerted by nicotine (Schievelbein and Richter 1984; Liu et al. 1979) and to a lesser degree CO (Astrup and Kjeldren 1979). Several epidemiological investigations (U. S. Environmental Protection Agency 1986; Hirayama 1984, 1985; Gillis et al. 1984; and Garland et al. 1985) indicate impacts of ETS but present methodological problems that preclude the drawing of firm conclusions. What is certain is that nonsmokers in a smoking environment do receive biological doses of nicotine at levels sufficient to produce significant amounts (40 ng) of cotinine in the urine (Hill and Marquardt 1980).

7.1.2.3 Cancer

The evidence for an association of environmental tobacco smoke with cancer is indisputable, as detailed in recent definitive reports of the Surgeon General (U.S. Department of Health and Human Services 1986), the World Health Organization (1986) and the National Research Council (1986a).

The great majority of epidemiological studies have indicated causal association between ETS and lung cancer that is exposure-dependent. While there are differences in cancer rates between men and women, they are not widely divergent. Misclassification is of concern among some of the studies, but does not negate the weight of evidence on the whole in favor of the dose-effect relationship.

Other cancers that investigators have correlated with ETS, typically derived from spousal studies, include brain, cervical, and endocrine cancers. In the aggregate, they do not provide consistent evidence for cancer at remote sites caused by ETS (National Research Council 1986a).

7.1.2.4 Other Chronic Impacts

There is evidence that smoking during pregnancy lowers birth weight, and a growing suggestion that exposure to ETS during pregnancy may impact birth weight. This may be of concern to female flight attendants who may receive occupational ETS exposures while flying during their first trimester of pregnancy. However, when considered with studies of birth weights at higher elevations such as in Denver (Martin and Bracken, 1986), it is conceivable that prolonged or frequent periods at high altitudes may be more strongly and etiologically related to low birth weights than ETS.

7.1.2.1 QUANTITATIVE ESTIMATION OF CANCER RISK

ETS is a mixture that has been implicated in cancer, respiratory effects (upper respiratory tract irritation, chronic respiratory tract illness), and cardiovascular disease. Since there is no peer-reviewed and widely used method for conducting a risk assessment for complex mixtures such as ETS, each individual constituent must be carefully examined for its potential use as a marker and a representative of the ETS mixture in the quantitative estimation of health risk.

The scientific literature presents evidence that exposure to particulate-bound polycyclic aromatic hydrocarbons, as ETS products of incomplete combustion, correlate with the carcinogenic potential of ETS (Wynder and Hoffmann 1967), and that inhalation of respirable suspended particulate (RSP) is an appropriate representative of this potential.

Data on active smokers are not valid quantitative predictors of effects on passive smokers and were not used in this investigation because:

* Concentrations of carcinogens in active smoke are different from concentrations in ETS. For example, given equal weights of smoke particles, sidestream smoke contains approximately three times the benzo(a)pyrene in mainstream smoke.

* Using data from active smoking to obtain risks from passive smoking involves several orders of magnitude in dose extrapolation.

* Active smokers experience actual tissue damage to the respiratory system (e.g., loss of mucociliary escalators from tracheal epithelium) which might either promote or inhibit tudor formation relative to passive smokers.

* Doses are so high in active smokers that some of the apparent dose may be "wasted" (i.e., received after a tudor has already been initiated).

Characterization of cancer risk from exposure to RSP requires information from three components: ambient air concentrations of RSP, exposure potential, and dose-response relationship for the health effect of interest, in this case cancer. The three components are related to one another as presented in Figure 7-1.

The appropriate parameters within each box in Figure 7-1 must be carefully selected from among the range of options so that the ultimate expression of risk approximates natural flight conditions and flying habits of interest as much as possible.

In this investigation, separate cancer risk determinations were conducted for domestic and international flights. This is because:

* Independent samples for the monitoring activity wore drown from the pool of domestic flights on U.S. carriers and the pool of international flights on U.S. carriers

* The sample from the pool of dos stic carriers was large and therefore could be drawn in a truly random fashion, whereas the sample drawn from the international pool was small due to prohibitive costs.

7.2.1 <u>Ambient RSP Concentrations</u>

RSP concentrations were obtained using optical and Gravimetric analytical methods. The relative merits of these two methods and the differences in results obtained from them are discussed in Section 5.0 of this report. Both methods were used for sampling because there was no clearly definable reason for favoring one over the other. The results of both methods of sampling were averaged for the determination of risk. RSP was measured at various seat locations on smoking and nonsmoking flights.

As a result, a number of RSP concentrations, representing various seat positions on smoking and nonsmoking flights, and using two methods of sample collection, were available for exposure assessment, as presented in Table 7-1. For estimation of exposure due exclusively to ETS, RSP concentrations on nonsmoking flights were subtracted as "baseline" values from RSP concentrations on smoking flights" On nonsmoking flights, the optical measurements of RSP may have been "Lower than actual and the Gravimetric measurements higher than actual. The difference between baseline" values obtained from the Gravimetric and optical methods of sampling ,whether averaged or used separately, did not change the outcome of the risk assessment. Therefore, the average of all values was used to represent the baseline concentration on nonsmoking flights. See Section 5.0 for more discussion on the monitoring results.

7.2.2 Exposure on Aircraft

The principal medium of exposure to RSP is via the air, so that inhalation is the primary exposure route of interest. Accordingly, the amount of RSP inhaled depends on respiratory rates, known to be variable for males and females, and for different states of physical activity. Respiratory rates have been determined for a range of conditions (U.S. Environmental Protection Agency 1989b). For this risk assessment, it is assumed that passengers are in a resting state throughout a flight, corresponding to an average respiratory rate of 0.5 m3/h (males 0.7; females 0.3). It is assumed that cabin crewmembers are engaged in moderate exercise, corresponding to an average respiratory rate of 2.1 m3/h (males 2.5; females 1.6).

Flying habits are also a critical determinant of exposure and risk. They include (a) the accumulated period of lifetime during which an individual flies, (b) the number of flights taken in that period, expressed as a yearly average, (c) the seat location chosen, and (d) the cumulative accounting of seat position over the course of the entire period of flying.

In determining exposures (and later risks), it is important to understand the terms of reference used to calculate quantitative estimates.

TABLE 7-1. RSP VALUES (ug/m3) USED IN THE RISK CALCULATIONS

	Nonsmoking Section		
	Smoking Section[1]	Boundary	Middle/ Remote[2]
NONSMOKING FLIGHTS			
Optical	10		11
Gravimetric	59		69
Average of all four values[3]	37		
SMOKING FLIGHTS			
Domestic			
Optical	182	39	17
Gravimetric	181	70	48
Average	181	54	33
Net (average RSP values on smoking flights minus nonsmoking flights)	144	17	--
International			
Optical	143	46	26
Gravimetric	129	51	39
Average	136	49	33
Net (average RSP values on smoking flights minus nonsmoking flights)	99	12	--

1 Rear of cabin for nonsmoking flights
2 Average value for middle and remote sections
3 The optical measurements for RSP may be lower than actual. The Gravimetric measurements for RSP may be higher than actual. The results of both were averaged. See Section 5.0 for further discussion on the results of RSP sampling.

Proportion of space in each section of the aircraft is a unitless dimension. It is the fraction of the total cabin space that is dedicated to each of the smoking, boundary, and nonsmoking sections. Proportion of time in each section of the aircraft is similarly unitless. It is, by definition, identical to proportion of space on the assumption that as the space dedicated to one section varies, so does the time spent in that section by the equivalent of one individual. Flight hour is the time spent in flight during which smoking is permitted. Flight hours per year is the time spent in flight, during the course of one calendar year, during which smoking is permitted. RSP concentration is the amount of RSP, in ug, contained in one m3 of air. Duration of exposure is the number of years which one flies on smoking flights. For example, an individual who takes his or her first flight on an aircraft where smoking is permitted at age 20 and whose most recent flight on an aircraft where smoking is permitted occurred at age 40, has been flying for 20 years. An exposure coefficient,. in the context of this investigation, is the average amount of RSP (generated by ETS and used as a surrogate for ETS), in ug, inhaled by an individual during one hour of time in an airline cabin when smoking is permitted, and annualized over the period of a calendar year. (Further explanation of this term is described later in this section). A person-year is the equivalent of one year's worth of time (365 days, not necessarily consecutive) for the equivalent of one person. Ten people, each exposed to ETS for 36.5 days, are equivalent to one person exposed for 365 days. A risk coefficient, in the context of this investigation, is the incremental number of premature deaths due to lung cancer among 100,000 nonsmokers exposed to ETS on flights where smoking is permitted.

Relative proportions of size among the smoking section, the nonsmoking section, and the boundary section between them were calculated for the 61 domestic flights on which smoking was permitted and the 8 international flights in this investigation. The proportions of space in each of the smoking, boundary and nonsmoking sections for each flight were averaged across all 61 domestic flights as the proportions of space in each of the smoking, boundary, and nonsmoking sections. Similar averages were calculated among all 8 international flights. These size proportions were assumed to be directly applicable as proportions of relative time that passengers and cabin crew members spend in each section throughout the period of lifetime that they are in aircraft cabins, as presented in Table 7-2.

By consolidating the ambient air concentrations of RSP, the appropriate respiratory rates, and the proportion of time spent in each section of the aircraft cabin, exposures can be estimated, as presented in Table 7-3 for domestic flights and Table 7-4 for international flights. The values in these tables are expressed as one-hour exposures during which time smoking in the aircraft cabin is permitted.

To produce the exposure values, first each proportion of time in a particular cabin section (from Table 7-2) is multiplied by the RSP concentration corresponding to the same section (from Table 7-1). The three multiplied values, each representing exposure in one of the three aircraft sections, are added together to produce a cumulative value, as illustrated in the footnotes to Tables 7-3 and 7-4. The cumulative value is then multiplied by the appropriate respiratory rate (cabin crew member or passenger) to produce a cabin-crew-specific or passenger-specific exposure (micrograms of RSP) inhaled during each flight hour that smoking is permitted.

Cancer risks are usually associated with long periods of time, i.e., several years of exposure to a carcinogen. The reasons for this are embedded in the prevailing theories of the mechanism of carcinogenesis. While this exposure may be greater or lesser at various times throughout the exposure interval, it is averaged out over a long time span to accommodate brief periods of higher or lower exposure, and the intervals during which no exposure may occur. Accordingly, cancer risk is usually expressed as the risk per unit of average daily exposure to a carcinogen, day after day and year after year (i.e., an annualized average). In this investigation, the unit of exposure per flight hour, as presented in Tables 7-3 and 7-4, must be made compatible with the "annualized daily

TABLE 7-2. PROPORTION OF TIME SPENT IN DIFFERENT SECTIONS OF CABIN[1]

	Domestic		International	
	Passenger	Cabin Crew	Passenger	Cabin Crew
Nonsmoking Section				
Middle and Remote Rows	0.84	0.75	0.82	0.65
Boundary Rows	0.11	0.10	0.13	0.10
Smoking Section	0.05	0.15	0.05	0.25

1 based on the average of actual numbers of rows in each section of all monitored flights.

2 Nonsmokers seated in the smoking section of the aircraft.

TABLE 7-3. CALCULATION OF EXPOSURE FOR DOMESTIC FLIGHTS
(ug/person/flight hour)

	Passenger	Cabin Crew
RSP concentration aggregated by time spent in each aircraft section (ug/m3)	9.01	23.32
Respiratory rate (m3/hr)	0.5	2.1
Exposure (ug/flight hour)	4.53	48.94

1 (0.84 x 0) + (0.11 x 17) + (0.05 x 144)

2 (0.75 x 0) + (0.10 x 17) + (0.15 x 144)

3 9.0 x 0.5

4 23.3 x 2:1

TABLE 7-4. CALCULATION OF EXPOSURE FOR INTERNATIONAL FLIGHTS (ug/person/flight hour)

	Passenger	Cabin Crew
RSP concentration aggregated by time spent in each aircraft section (ug/m3)	6.5 1	26.0 2
Respiratory rate (m3/hr)	0.5	2.1
Exposure (ug/flight hour)	3.3 3	54.6 4

1 (0.82 x 0) + (0.13 x 12) + (0.05 x 99)

2 (0.65 x 0) + (0.10 x 12) + (0.25 x 99)

3 6.5 x 0.5

4 26.0 x 2.1

averaging" concept that is used to construct cancer dose-response graphs and which is used to express cancer risk. This is accomplished by dividing the RSP exposure in one flight hour by 365 days per year to provide a value that represents an average exposure, during one hour when smoking is permitted on an aircraft, for any given day of the year. The result is an expression of an exposure coefficient. An exposure coefficient in this investigation is defined as the average daily amount of RSP inhaled by one individual during one flight hour, averaged over the course of a year. This is a conceptual construct that is necessary in order to make the exposure unit consistent with the dose-response unit in the calculation of risk.

Accordingly, the exposure values presented in Tables 7-3 and 7-4 must be annualized into an average daily exposure by dividing them by the 365 days in one year. Therefore, the exposure coefficients in this investigation, expressed as annual averages, are:

* For passengers on domestic flights: 4.5 ug/flight hour divided by 365 or 0.00001233 mg/h/exposure day

* For cabin crew members on domestic flights: 48.9 ug/flight hour divided by 365 or 0.00013400 mg/h/exposure day

* For passengers on international flights: 3.3 ug/flight hour divided by 365 or 0.00000904 mg/h/exposure day

* For cabin crew members on international flights: 54.6 ug/flight hour divided by 365 or 0.00015000 mg/h/exposure day.

These values are used in combination with cancer risk coefficients, derived from cancer dose-response graphs described below in Section 7.2.3, to produce exposure-specific expressions of risk.

It should be noted that the proportions of time spent in various sections of the aircraft cabin by cabin crewmembers, as indicated in Table 7-2, do not include time spent in galleys. Galleys have their own sources of ventilation. Consequently, those galleys located adjacent to the smoking sections of aircraft cabins may contain ambient air concentrations of ETS constituents that are different from concentrations measured in the smoking sections. The exposure of cabin crew members in the galley, therefore, may be different than in other sections of the aircraft, but this exposure could not, be estimated because aircraft galleys could not monitored for ambient air concentrations of ETS in this investigation.

7.2.3 Determination of Dose-Response Relationships and Risk Coefficients

A prominent feature of risk assessment is characterization of the toxicologic dose-response relationship. In the context of this investigation, it is the relationship between the amount of RSP inhaled and the number of lung cancer deaths that the inhaled RSP produces. The greater the RSP inhalation, the greater the amount of response in the form of increased number of lung cancer deaths. Graphically, the relationship is represented by a line, which can be expressed as a mathematical constant known as the coefficient of risk:

Risk coefficient = Number of lung cancer deaths per 100,000 persons at risk per milligram of RSP (annual average) per day

Risk coefficients are frequently referred to as unit cancer risks in these analyses. The level of risk corresponding to a particular level of exposure can be determined by using the appropriate risk coefficient.

For this investigation, a number of dose-response models for the relationship of ETS to lung cancer deaths were considered, each having its own characteristic risk coefficient.
These are described in Table 7-5.

The advantages and disadvantages of each model were weighed according to three criteria:

* Strength of each model as determined by the quality of the design and data used in its construction. The following characteristics are used to define model strength:

    - The size of the study population used in model construction and validation

- The scientific soundness of the dose information used to construct the model

- The ease of model adaptation for intermittent exposure

- The size of the study subpopulation having the health endpoint of concern (e.g., cancer)

- the unique statistical design features of each model applicable to this study

* Whether the assumptions used in the model are reasonable

* Amount of peer review and scientific acceptance.

Two models were selected for this investigation because they most closely approximated the desirable traits embodied in the selection criteria: the Phenomenological Model (Repace and Lowrey, 1985) and the Armitage and Doll Model (Armitage and Doll, 1961), modified for less-than-lifetime exposure (Ginevan and Mills; 1986), and known as LesLife.

Repace and Lowrey estimate that the excess exposure of 1 mg/day increases lifetime lung cancer risk by 5 deaths per 100,000 person-years (PY) exposure. The Phenomenological model, though simple, is based on a fairly sizable body of data, and if it is inaccurate, would likely understate risk. These arguments have been fully developed by Repace and Lowrey (1985) and are briefly reviewed below.

The general Phenomenological Model is based on observed differences in lung cancer mortality between groups of never-smokers who were members of the Seventh Day Adventist Church and those who were not (Phillips et al. 1980 a,b). Because of their religion, which proscribes smoking, Seventh Day Adventists are less likely to encounter ETS, and 40 percent of the Seventh Day Adventist cohort worked for church-run organizations. The non-Seventh Day Adventists were a demographically comparable group of lifelong nonsmokers, among the general population, who resided in the same geographical area as the Seventh Day Adventists. The difference in lung cancer rates between Seventh Day Adventists and non-Seventh Day Adventists was taken to be due to their differential

exposure to ETS, and the ratio of mortality differential to exposure differential was taken as the risk coefficient. The mortality rates among Seventh Day Adventists were based on 109 lung cancer deaths, and were therefore quite well determined. Moreover, Repace and Lowrey assumed that ETS exposure in Seventh Day Adventists was zero and thus based their dose-response coefficient on the maximum possible exposure. Since some Seventh Day Adventists were undoubtedly exposed to ETS in the workplace, this assumption is conservative in that it overstates the differential exposure and thus understates the actual dose-response.

The Modified Armitage and Doll Model is based on consideration of what the multistage theory of carcinogenesis predicts about age-specific risks of exposure to a fixed concentration of a carcinogen for a fixed duration of time. This risk assessment approach converts the ambient air data to a risk-equivalent dose. There are several underlying assumptions to this approach:

* RSP is a reliable indicator for estimating the relationship between exposure to cigarette smoke and health risks.

* Data on wives of smoking husbands indicate that their relative risk is approximately 1.3, based on case-control studies.

* Spousal exposure can be inferred from measurements of an individual smoker's impact on indoor air quality in the home, together with empirical statistics on the duration of marriages.

* For the multistage model of carcinogenesis the following question can be posed: If X years of exposure at level Y cause a relative risk of 1.3, what is the dose-response coefficient?

* The dose-response coefficient, a five-stage multi-stage model of carcinogenesis, and dose estimates derived from airliner monitoring data, are used to calculate risks to the selected populations of interest. A five-stage model assumes that a number of events or "stages" must occur before a normal cell can become a cancer cell. The first stage is generally equated to a mutational event. Subsequent stages might include further mutations, as well as other biochemical changes in the cell. After all stages have occurred, the transformed cell proliferates until it becomes a clinically diagnosable tumor.

A detailed discussion of this methodology, including a sensitivity analysis of the model, is presented in Appendix A. The principal advantage of this modeling approach is that it permits the user to explicitly specify such important factors as age at commencement of exposure and duration of exposure. At the same time, as demonstrated in the sensitivity analysis contained in Appendix A, the lung cancer risk data for ETS exposure are sufficiently abundant and consistent that altering parameters of this modeling approach does not alter the conclusions about risk in any significant way.

A comparison of the basic features of the two models is contained in Table 7-6. Both models have undergone peer review. The risk coefficients presented by these two models are:

* For the Phenomenological Model, 5 excess lifetime lung cancer deaths/100,000 person-years exposure/mg RSP/exposure-day, ascribable to ETS assuming a constant exposure. The lung cancer rate is an average value based on lifetable statistics.

* for the Modified Armitage and Doll Model, 6.45 excess lung cancer deaths per 100,000 persons at risk/mg RSP/exposure-day, ascribable to ETS.

Using these risk coefficients, the risk of death from lung cancer as a result of exposure to ETS in airliner cabins was determined as a function of number of years flown. For the Modified Armitage and Doll Model, the risk of death from cancer is dependent on the age of first exposure to ETS as a potential carcinogen. Therefore, each commencement age warrants its own unique exposure-response relationship, as depicted in Figure 7-2 for the Modified Armitage and Doll Model. The exposure-response relationship for the Phenomenological Model is presented in Figure 7-3. The graphs in these figures serve as risk nomograms, allowing an individual to determine his or her appropriate unit of risk according to the number of years of flight (i.e., the number of years of exposure).
In the case of the age-dependent Modified Armitage and 'Doll Model, the

TABLE 7-6. .COMPARISON OF THE PHENOMENOLOGICAL MODEL AND THE MODIFIED ARMITAGE AND DOLL MODEL

Parameter	Phenomenological Model	Modified Armitage and Doll Model
Age of first exposure	Fixed at age 20	Adaptable to any age
Duration of exposure	45 years	Variable
Linearity	Linear at low doses	Linear at low doses
Stages of carcinogenesis	None assumed	5
Concurrence of risk coefficients	5 lung cancer deaths /100,000 exposed/mg exposure-day	6.45 lung cancer deaths /100,000 exposed/mg /exposure-day

appropriate curve representing the age at which flying commences is selected prior to determination of the risk coefficient.

7.2.4 Risk Characterization

7.2.4.1 Individual Risk

Once the risk coefficient is determined, it is multiplied by the appropriate exposure coefficient presented in Section 7.2.2 (on domestic flights -- 0.00001233-mg/h/exposure day for passengers and 0.00013400 mg/h/exposure day for cabin crewmembers; on international flights--0.00000904 mg/h/exposure day for passengers and 0.00015000 mg/h/exposure day for cabin crew members) to determine exposure-specific risk. The final expression is the incremental risk due to premature lung cancer deaths among nonsmokers, ascribable to ETS on smoking flights.

The procedure for determining risk can be illustrated in the following three examples, the parameters and results of which are summarized in Table 7-7. These examples are intended to represent occupational and non-occupational profiles of flying habits. Typical flight frequency and duration for cabin crewmembers were used for one example in the occupational setting. Flight frequencies and durations for passengers (representing profiles of a frequent flyer and a non frequent flyer) used for the two examples in the non-occupational setting are likely to be at the high end of the range. Risks for a range of other scenarios are presented in Appendix B. Data on the number of cabin crewmembers who smoke were not available. However, it is known that approximately 29 percent of U.S. adults aged 20 or older smoke (U.S. Department of Health and Human Services, 1989).

Example 1. Risk determination for a cabin crewmember who flies ours per month or 960 hours per year (see Table 6-1) on domestic flights: The total number of hours is reduced by 6.25. percent as an approximation of the flight time during which the no-smoking light is illuminated, resulting in 900 flight hours when smoking is permitted. The period of flying is 20 years, commencing at age 25. These values were chosen because they represent the career length and career commencement for a large percentage of cabin crewmembers (Association of Flight

TABLE 7-7. SUMMARY OF DATA CONTAINED IN THE EXAMPLE CALCULATIONS OF RISK

	Example 1	Example 2	Example 3
Cabin occupant	Crew Member	Business Passenger	Casual Passenger
Hours per year in flight 1	900	450	45
Number of years flown	20	30	40
Age at start of flying2	25	35	25
Exposure coefficients (mg/h/exposure day)			

Domestic	0.00013400	0.00001233	0.00001233
International	0.00015000	0.00000904	0.00000904
Risk coefficients3			
Phenomenological Model	100	150	200
Modified Armitage and Doll Model	123	49	150
Risk4			
Domestic			
Phenomenological Model	12.06	0.83	0.11
Modified Armitage and Doll Model	14.86	0.27	0.08
International			
Phenomenological Model	13.46	0.61	0.08
Modified Armitage and Doll Model	16.59	0.20	0.06

1reduced by 6.25% to account for periods of flying when no-smoking light is illuminated.

2Applicable to risks determined using the Modified Armitage and Doll Model. Risks determined using the Phenomenological Model are based on an assumed 35 years of exposure.

3 Premature lung cancer deaths/mg RSP/day/100,000 exposed nonsmokers.

4Premature lung cancer deaths ascribable to ETS/100,000 nonsmoking individuals on smoking flights.

Attendants 1988). The exposure coefficient for cabin crewmembers on domestic flights is 0.00013400 mg/h/day. Referral to Figure 7-3 produces a unit cancer risk, for a 20-year duration of exposure, of 100-lung cancer deaths/mg RSP/day/100,000 exposed nonsmokers (who, in this case, are exposed nonsmoking cabin crewmembers on smoking flights). A final multiplication of the exposure coefficient (0.00013400 mg/h/day) by the unit cancer risk (100 lung cancer deaths/mg RSP/day/100,000 individuals) yields a risk of lung cancer deaths amounting to 0.0134/100,000 for every hour flown in a smoking environment. Since cabin crew members are estimated to fly 900 hours per year during smoking periods, the incremental risk of premature death from lung cancer ascribable to ETS on smoking flights is 12.06/100,000 exposed cabin crew members, or 1 in every 8,292 cabin crew members according to the Phenomenological Model of cancer deaths, as presented in Table 7-7. A similar calculation using the Modified Armitage and Doll Model in Figure 7-2 produces an incremental risk of premature death from lung cancer amounting to 14.86/100,000 nonsmoking cabin crew members on smoking flights, as presented in Table 7-7,or 1 lung cancer death per 6,729 nonsmoking cabin crew members.

Example 2. Risk determination for a passenger who is representative of a frequent flyer: This individual logs 480 hours per year (reduced to 450 hours per year for the 6.25 percent of time when the no-smoking light is assumed to be illuminated). This is approximately covalent to an average of four round-trip coast-to-coast flights per month. The individual is assumed to continue this pattern of flying for 30 years commencing at age 35, to constitute what is likely an upper limit on the amount of time spent in an airliner cabin environment during a lifetime. The exposure coefficient for passengers on domestic flights is 0.00001233 mg/h/exposure day. The unit cancer risk for this individual, according to the Phenomenological Model in Figure 7-3, is 150 lung cancer deaths/mg RSP/day/100,008 exposed non-smokers. Taking into account the exposure coefficient and period of flying, the incremental risk is 150 x 0.00001233 x 450, or 0.83 premature lung cancer deaths ascribable to ETS for every
100,000 exposed nonsmoking passengers on smoking flights, according to the conditions in this example, or 1 in 120,482 nonsmoking passengers. The Modified Armitage and Doll Model produces a risk of 49 x 0.00001233 x 450, equal to an incremental risk of premature lung cancer death of 0.27104,000 nonsmoking passengers on smoking flights as presented in Table 7-7, or lung cancer death per 370,370 nonsmoking passengers.

Example 3. Risk determination for a passenger who is representative of a non-frequent flyer: Flight time of 48 hours per year, adjusted for no-smoking periods, is assumed to be 45 hours per year for 40 years, commencing at age 25. The annual flight frequency was assumed to be one-tenth that of the frequent flyer in

example 2, occurring on a casual basis throughout adult life. The exposure coefficient is 0.00001233 mg/h/exposure day and the Phenomenological Model unit cancer risk is 200 lung cancer deaths/mg RSP/day/100,000 exposed nonsmokers. The incremental risk is therefore 200 x 0.00001233 x 45, or 0.11 lung cancer deaths ascribable to ETS for every 100,000 exposed nonsmoking passengers on smoking flights, according to the conditions in this example, or 1 in 900,091 nonsmoking passengers. The Modified Armitage and Doll Model produces an incremental risk of 150 x 0.00001233 x 45, equal to an incremental risk of premature lung cancer death of 0.08 as presented in Table 7-7, or 1 premature lung cancer death per 1,250,000 nonsmoking passengers.

7.2.4.2 Population-Based Risk

For passengers, the risk of premature lung cancer death can be expressed on a population basis. In 1987, 418 million domestic enplanements occurred (U.S. Department of Transportation, 1987), the average flight time was 1.84 hours (based on analysis of data provided by the Federal Aviation Administration) and smoking was permitted on 54.3 percent of all flight hours. It follows that, for current conditions under which a ban on smoking exists for flights with durations of two hours or less, estimates for passengers on domestic flights are:

Passenger hours flown/year	= 418 million x 1.84 = 769 million
Passenger hours flown/year on smoking flights	= 769 million x 54.3 % = 418 million
Reduced 6.25% for the time that the no-smoking light is assumed to be illuminated on a flight	= 391 million hours per year
Number of individuals flying 45 hours per year (from Example 3 above)	= 391 million / 45 = 8.7 million
Number of "lifetimes" of flying 40 years (from Example 3 above)	= 8.7 million / 40 = 0.217 million passengers/yr.
Expected population-based risk (based on a risk of 0.11 lung cancer deaths per 100,000 exposed nonsmokers according to the Phenomenological Model in Example 3 above, or 1.1/million)	= 0.217 million x 1.1 /million = 0.238 premature lung cancer deaths per year.

A similar calculation for passengers on international flights, using 62 million enplanements per year (U.S. Department of Transportation

1987), an average flight time of 4.75 hours per flight (based on analysis of data provided by the Federal Aviation Administration), a flight frequency of 45 hours per year, a duration of flying of 40 years, and a risk of 0.08 premature lung cancer deaths per 100,000 exposed nonsmokers (from Example 3 above) results in a population-based risk of 0.122 premature lung cancer deaths per year. (In this calculation, all flights are presumed to be smoking flights, so that the fraction of flight hours on which smoking is permitted is reduced only by the time that the no-smoking light is illuminated -- assumed to be 6.25 percent.)

For cabin crew members on domestic flights, the calculation is somewhat different, based on the number of individuals logging approximately 960 hours per year (80,000; see Table 6-1), and the proportion who fly on domestic (0.7) and international (0.3) flights. Using 54.3 percent as the percent of flight hours during which smoking is permitted under the two-hour ban enacted in 1988, then:

Number of cabin crewmembers flying on domestic

flights = 80,000 x 0.7
= 56 , 000

Of these, number of cabin crewmembers flying on smoking flights = 56,000 x 0.583
= 30,408

Number of "lifetimes" flying 20 years (from Example 1 above) = 30,408 / 20
= 1520

Expected population-based risk (based on a risk of 12.06 lung cancer deaths per 100,000 exposed nonsmokers in Example 1 above) = 1520 x 12.06/100,000
= 0.183 premature lung cancer deaths per year.

For cabin crew members on international flights the calculation is:

Number of cabin crew members flying on international flights
= 80,000 x 0.3
= 24,000

Number of "lifetimes" flying 20 years (from Example 1 above)
= 24,000 / 20
= 1200

Expected population-based risk (based on a risk of 13.46 lung cancer deaths per 100,000 exposed nonsmokers according to the Phenomenological Model in Example 1 above)
= 1200 x 13.46/100,000
= 0.162 premature lung cancer deaths per year.

All international flights in this case are presumed to be smoking flights, so that no reduction in the number of flights to account for those that are nonsmoking is necessary.

7.2.5 Discussion

The cancer risk coefficient for 45 years of exposure to RSP as a surrogate for ETS is 5 premature lung cancer deaths per 100,000 (5 X 10-5) nonsmokers per mg RSP, ascribable to ETS, as derived from the Phenomenological Model by Repace and Lowrey (1985). The counterpart age-dependent risk coefficients using the Modified Armitage and Doll Model range from 40 premature lung cancer deaths per 100,000 (4 x 10-4) nonsmokers, for exposure commencing at 35 years of age, to 600 premature lung cancer deaths per 100,000 (6 x 10-3) nonsmokers for exposure commencing at 5 years of age. For comparison, risk coefficients for other chemicals that present a potential for inhalation exposure are presented in Table 7-8. All of the substances listed in this table are regulated by the EPA under its various statutes.

The risks calculated here are well within the spectrum of risks from other carcinogen exposures. The risks derived from the Phenomenological Model and the Modified Armitage and Doll Model suggest that two approaches which differ in both design and database give nearly the same result. The major divergence is for the case of exposure early

TABLE 7-8. RISK COEFFICIENTS FOR A RANGE OF CHEMICALS IN COMPARISON WITH ETS IN AIRCRAFT CABINS

	Risk Coefficient (Cancer Potency Factor)	and Cancer Classification 1
ETS (Phenomenological Model)	5 x 10-5	
ETS (Modified Armitage and Doll Model)	6 x 10-3 commencing at 5 years 4 x 10-4 commencing at 35 years	
Acrylonitrile	2.4 x 10-1	B1
Arsenic and compounds	5 x 101	A
Benzene	2.6 x 10-2	A

B1s(chloromethyl)ether	9.3 x 103	A
1,2-Dichloroethane	3.5 x 10-2	B
Ethylene oxide	3.5 x 10-1	B1/B
Nickel and compounds	1.19	A
Tetrachloroethylene	1.7 x 10-3	B
Trichloroethylene	4.6 x 10-3	B
Polynuclear aromatic compounds	6.11	-
Vinyl chloride	2.5 x 10-2	A

1 As determined by the U.S. Environmental Protection Agency. Classifications A and B (human carcinogen and animal carcinogen, respectively) usually result in regulatory action.

in life using the Modified Armitage and Doll Model where risk is elevated by an order of magnitude, relative to risks from exposure commencing later in life. This is because exposure to first-stage carcinogens is especially damaging to the young. While making other assumptions regarding stage of action would generally reduce these risks, it would generally elevate risks in older travelers, who constitute the majority of the traveling public (Murdoch and Krewski 1988). Thus the fundamental results obtained here are not "conservative" in the sense that they overstate actual risk. Rather, they are the best estimates implied by the database and the models selected. Worst-case, upper bound, estimates such as are often used in a regulatory context could well be a factor of five higher.

7.3 QUANTITATIVE ESTIMATION OF ACUTE RESPIRATORY EFFECTS

The most common complaint from exposure to ETS-based carbon monoxide and nicotine is upper respiratory tract and ocular irritation, as verified by the descriptions of prior investigations in Section 7.1.1. Two studies provide empirical dose-response measures of respiratory and ocular irritation from exposure to various levels of carbon monoxide (Cain et al.

1987) and nicotine (Mattson et al. 1989). These dose-response relationships were applied to the carbon monoxide and nicotine levels obtained in this investigation to determine whether these pollutants, at their observed concentrations, constitute sources for health effects.

7.3.1 Carbon Monoxide

Carbon monoxide (CO) was measured continuously during all flights. This presented an opportunity to disclose peak concentrations that might have appeared at various times throughout flight. Short-term CO concentrations have been tested as surrogates for the acute respiratory irritant properties of ETS in smoking environments. Therefore, peak concentrations of CO as a surrogate for ETS as a short-term respiratory irritant are of interest in the aircraft cabin environment. Accordingly, continuous 30-minute averages of CO concentrations were plotted as a function of their cumulative frequency in the smoking, boundary, and nonsmoking sections, as presented in Figure 7-4. Thresholds for discom-

fort as described by Cain et al. (1987) for 2 ppm and 5 ppm CO were superimposed over the concentration-frequency plots as an indication of the levels of CO and frequencies with which discomfort to eyes, nose, and throat might occur from exposure to these levels. These researchers determined that the 2 ppm level of CO produced dissatisfaction among 12 percent of individuals exposed for 60 minutes, while the 5 ppm of CO produced dissatisfaction among 18 to 30 percent of individuals exposed for 60 minutes (this range includes eye, nose, and throat irritation). It is apparent from Figure 7-4 that approximately 32 percent of the 30-minute CO averages exceeded 2 ppm in the smoking section of the aircraft cabin. Applying the data of Cain et al., this implies that on 32 percent of the flights where CO levels exceeded 2 ppm, 12 percent of the occupants sitting in the smoking section would experience respiratory discomfort after 60 minutes of exposure to CO from ETS. Similarly, on 5 percent of all flights tested, the 30-minute CO averages exceeded 2 ppm in the boundary and nonsmoking sections. This implies that on 5 percent of the flights, 12 percent of the nonsmokers in these sections would be dissatisfied. It should be noted that in the Cain et al. study, 25 percent of the individuals tested were smokers. In addition, odor perception, over a 60-minute time period, for occupants of a space containing 2 ppm or 5 ppm CO as a surrogate for ETS (e.g., passengers or cabin crew members in an aircraft cabin containing ETS would be less sensitive than for visitors to that space (e.g., the flight engineer who leaves the flight deck to visit the cabin.

7.3.2 Nicotine

Integrated samples of nicotine were taken on 61 domestic smoking and 8 international smoking flights. The results of sample analysis for domestic flights are presented in Figure 7-5, as the percentages of flights with nicotine concentrations at or below the plotted values. For domestic flights, nicotine was below the detection limit in the smoking section on 5 percent of flights, lower than detectable in the boundary section on 62 percent of flights and lower than detectable in the nonsmoking section an 75 percent of flights. Recognizing that integrated

samples do not reveal peak short-term concentrations during flight, average concentrations of nicotine never exceeded 2 ug/m3 in the nonsmoking section and 5 ug/m3 in the boundary section. Nicotine concentrations obtained on international flights and in a recent study by Mattson et al. (1989) presented too few data points to construct valid plots.

The level of discomfort from ETS measured as ETS-generated nicotine aboard aircraft, observed by Mattson et al. (1989), was superimposed over the concentration data in Figure 7-5. These researchers determined that no subjects reported moderate or mild sensory response of the nose and eye at a concentration of 4 ug/m3. Using this value as a threshold for response in the present study, nicotine in the boundary and nonsmoking sections did not reach concentrations that would provoke nose and eye irritation on any flights. Nicotine concentrations did exceed this threshold concentration in the smoking section on 65 percent of the domestic flights that were monitored. Subjects in the Mattson et al. study reported marked sensory response at nicotine concentrations of approximately 16 Ug/m3. This value significantly exceeded nicotine levels in the boundary and nonsmoking sections of all domestic flights that were monitored, so that marked sensory responses from nicotine would not be expected. However, nicotine concentrations in the smoking sections of 35 percent of all domestic flights monitored reached levels that would evoke a marked sensory response in the eye and nose.

7.4 ESTIMATION OF CARDIOVASCULAR EFFECTS

While ETS has been shown as an etiologic agent of cardiovascular disease (Wells, 1988), no definitive data exist on the quantitative relationship between ETS and ischaemic heart disease, particularly for individuals with preexisting cardiovascular illness, as acknowledged by the National Research Council (1986a) and the U.S. Department of Health and Human Services (1983). Simply put, not enough is known about the physiology and etiology of ETS-induced cardiovascular disease to postulate a dose-response model.

Scientific evidence suggests that CO impacts the cardiovascular system (causing angina and cardiac ischemia) and implies that nicotine also has an effect. In the case of C0, a recent multi-center investigation has demonstrated that 3 percent carboxyhemoglobin contributes to the expression of angina (Health Effects Institute, 1988), which is a symptom of cardiac effect but not necessarily indicative of coronary heart disease. In that study, an exposure chamber CO concentration of 9 ppm for up to 50 minutes produced 3 percent carboxyhemoglobin. The EPA has estimated that in the ambient air environment, 2.7 percent (at rest) or 2.9 percent (with moderate exercise) carboxyhemoglobin is equivalent to breathing an ambient air CO concentration of 20 ppm for 8 hours, based on the Coburn equation (Federal Register, 1985). Similarly, 2 percent carboxyhemoglobin is equivalent to breathing 35 ppm CO for one hour (with moderate exercise) or 15 ppm CO for 8 hours (at rest). This is the basis of an EPA 8-hour standard of 9 ppm for CO (Federal Register 1985). However, the contribution of CO in ETS to nonsmoker carboxyhemoglobin is unknown. Smokers self-dose with ETS-derived CO to a level of 3 to 8 percent carboxyhemoglobin; the nonsmokers' ETS-induced carboxyhemoglobin levels are presumably less. Endogenous carboxyhemoglobin levels (in the absence of ambient air CO) in the U.S. population are approximately 0.5 percent. The CO levels measured aboard aircraft in this study, including the peak concentrations, were considerably less than 9 ppm.

7.5 EFFECTS OF ETS ON SPECIAL POPULATIONS

Children, asthmatics, and individuals with preexisting cardiovascular disease constitute populations of special concern for the health effects of ETS.

Although there is evidence to suggest that the respiratory system of children is affected by chronic exposure to ETS (based on studies of children in homes of smoking parents), given the small number of hours that children fly, the risk from exposure to ETS in aircraft cabins is likely to be small.

Currently available data are insufficient to quantify the impact of carbon monoxide on asthmatics. A recent review by the EPA (U.S.

Environmental Protection Agency 1989a) on the current status of knowledge regarding the health effects of CO demonstrates a lack of information in this area. There are indications in individual research papers of what conceptually may be the effects of exposure to CO by asthmatics (e.g., decrease in lung cell function and degradation of epithelial cell integrity). Any quantitative observations as to where the threshold for acute respiratory effects of CO on asthmatics lies, and whether it is likely to be lower and the symptomatic response larger than for non-asthmatics, are currently considered to be speculative. Similarly, the quantitative impact of CO on preexisting ischaemic heart disease or other cardiovascular illness at the levels observed in airliner cabins' currently cannot be estimated because health data are insufficient.

The impact of nicotine on the respiratory system of asthmatics is even more poorly understood than for carbon monoxide. No empirical quantitative data are available to determine the level of nicotine that would provoke an asthmatic response, or whether the level causing respiratory irritation in non-asthmatics is different from that causing irritation in asthmatics.

7.6 REFERENCES

Armitage, P. and R. Poll. 1961. "Stochastic models for carcinogenesis." Proceedings of the Fourth Berkekey Symposium on Mathematical Statistics and Probability. University of California Press, Berkekey, California. 4:19-38 .

Astrup, P. and K. Kjeldsen. 1979. "Model studies linking carbon monoxide and/or nicotine to arteriosclerosis and cardiovascular disease." Prevent. Med. 8:295-302.

Berkey, C.S., J.H. Ware, D.W. Dockery, B.G. Ferris Jr. and F.E. Speizer. 1986. "Indoor air pollution and pulmonary function growth in preadolescent children." Am. J. Epidemiol 123:250-260.

Bland, M., B.R. Bewley, V. Pollard, and M.H. Banks. 1978. "Effect of children's and parents' smoking on respiratory symptoms." Arch. Dis. Child. 53:100-105.

Burchfiel, C.M., M.W. Higgins, J.B. Keller, N.J. Butler, W.F. Howatt, and I.T.T. Higgins. 1986. "Passive smoking, respiratory symptoms and pulmonary function: a longitudinal study in children." Am. Rev. Respir.Dis. 133:A157.

Cain, W.S., B.P. Leaderer, R. Isseroff, L.G. Berglund, R.J. Huey, E.D. Lipsitt and D. Perlman. 1983. "Ventilation requirements in buildings. Control of occupancy odor and tobacco smoke odor." Atmos. Environ. 17:1182-1197.

Cain, W.S., T. Tarik, L. See, and B. Leaderer. 1987. "Environmental tobacco smoke: sensory reactions of occupants." Atmos. Environ. 21(2):347-353.

Charlton, A. 1984. "Children's coughs related to parental smoking." Brit. Med. J. 288:1647-1649.

Colley, J.R.T. 1974. "Respiratory symptoms in children and parental smoking and phlegm production." Brit. Med. J. 2:201-204.

Comstock, G.W., M.B. Meyer, K.H. Helsing, and M.S. Tockman. 1981. "Respiratory effects of household exposures to tobacco smoke and gas cooking." Am. Rev. Respir. Dis. 124:143-148.

Federal Register. 1985. U.S. Environmental Protection Agency carbon monoxide standard. 50 FR 37491. September 13, 1985.

Fourth International Conference on Indoor Air Quality and Climate. 1987. Proceedings of the Conference, August 17-21, Berlin (West).

Garland, C., E. Barrett-Connor, L. Suarez, M.H. Criqui, and D.L. Wingard. 1985. "Effects of passive smoking on ischaemic heart disease mortality of nonsmokers." Am. J. Epidemiol. 121:645-650.

Gillis, C.R., D.J. Hole, V.M. Hawthorne, and P. Boyle. 1984. "The effects of environmental tobacco smoke in two urban communities in the west of Scotland." Europ. J. Respir. Dis. 65(Suppl. 133):121-126.

Ginevan, M.E. and W.A. Mills. 1986. "Assessing the risks of radon exposure: the influence of cigarette smoking." Health Physics 51:163-174.

Gortmaker, S.L., D.K. Walker, F.H. Jacobs, and H. Ruch-Ross. 1982. "Parental smoking and the risk of childhood asthma.: Am. J. Public Health 72:574-579.

Health Effects Institute. 1988. The multicenter study on the acute effects of carbon monoxide on individuals with coronary artery disease. Cambridge, MA.

Hill, P. and H. Morquardt. 1980. "Plasma and urine changes after smoking different brands of cigarettes." Clin. Pharm. and Ther. 27(5):652-658.

Hirayama, T. 1984. "Cancer mortality in nonsmoking women with smoking husbands based on a large-scale cohort study in Japan." Prevent. Med. 13:680-690.

Horwood, L.J., D.M. Fergusson, and F.T. Shannon. 1985. 'Social and familial factors in the development of early childhood asthma." Pediatrics 75:859-868.

Kauffmann, F., J.F. Tessier, and P. 0riol. 1983. "Adult passive smoking in the home environment. a risk factor for chronic airflow limitation." Am. J. Epidemiol. 117:269-280.

Kenter, M., G. Triebig, and D. Weltle. 1984. "The influence of passive smoking on pulmonary function - a study of 1,351 office workers." Prevent. Med. 13:656-669.

Lebowitz, M.D., G. Corman, M.K. 0'Rourke and C.J. Holberg. 1984. 'Indoor-outdoor air pollution, allergen and meteorological monitoring in an arid Southwest area. J. Air Pollut. Control Assoc. 34:1035-1038.

Leeder, S.R., R. Corkhill, L.M. Irwig, W.W. Holland, and J.R.T. Colley. 1976. "Influence of family factors on the incidence of lower respiratory illness during the first year of life." Brit. J. Prev. Soe. Med. 30:203-212.

Liu, L.B., C.B. Taylor, S.K. Peng and B. Mikkelson. 1979. "Experimental arteriosclerosis on Rhesus monkeys induced by multiple risk factors: Cholesterol, vitamin D. and nicotine." Arterial wall 5:25-3B.

Martin, T.R. and M.B. Bracken. 1986. "Association of low birth weight with passive smoke exposure in pregnancy." Am. J. Epidemiol. 124:633-42.

Mattson, M., G. Boyd, D. Byar, C. Brorn, J. Callahan, D. Corle, J. Cullen, J. Greenblatt, N. Haley, K. Hammond, J. Lewtas and N. Reeves. 1989. "Passive smoking on commercial airline flights." J. Amer. Med. Assoc. 261:867-872.

Murdoch, D.J. and D. Krewski. 1988. "Carcinogenic risk assessment with time-dependent exposure patterns." Risk Anal. 8:509-530.

National Research Council. 1986a. Environmental Tobacco Smoke: Exposures and Assessing Health Effects. National Academy Press. Washington, D .C .

National Research Council. 1986b. The Airliner Cabin Air Environment. Air Quality and Safety . National Academy Press, Washington, D .C.

Phillips, R.L, J.w. Kuano, N.L. Beeson, and T. Lotz. 1980a. "Influence of selection versus lifestyle on risk of fatal cancer and cardiovascular disease among Seventh Day Adventists." Am. J. Epidemiol. 112:296:.314.

Phillips, R.L, L. Garfinkel J.W. Kuzma, W.L. Beeson, T. Lotz. and B. Brin. 1980b. "Mortallty among California Seventh Day Adventists for selected cancer sites." J. Nat. Cancer Inst. 65:1097-1107.

Repace, J.L. and A.H. Lowrey. 1985. 'A quantitative estimate of nonsmokers lung cancer risk from passive smoking." Environ. Internat. 11:3-22.

Schenker, M.B., S.T. Weiss, and B.J. Murawski. I982. "Health effects of residents in homes with urea formaldehyde foam insulation: a pilot study." Environ. Int. 8:359-363.

Schenker. M.B., J.M. Samet, and F.E. Spelzer. 1983. 'Risk factors for childhood respiratory disease: the effect of host factors and home environmental exposures." Am. Rev. Respir. Dis. 128:1038-l043.

Schievelbein, H. and F. Richter. 1986. 'The influence of passive smoking on the cardiovascular system.' Prevent. Med. 13:626-644.

Schllling, R.S.F., A.D. Litai, S.L. Hiu, G.J. Beck, J. B. Schoanburg, and A. Bouhuys. 1977. "Lung function, respiratory disease and smoking in families." Am. J. Epidemiol. 106:274-283.

Tager, I.B., S.T. Wefss, B. Rossner, and F.E. Spaizer. 1979. 'Effect of parental cigarette smoking on the pulmonary function of children.' Am J. Epidemlol. 110:15-26.

Tager, I.B., S.T. Weiss, A. Nunoz, B. Rosner, and F. Speizer. 1983. "Longitudinal study of the affects of parental smoking on pulmonary function in children.' New Eng. J. Med. 309:699-703.

Tashkin, D.P., V.A. Clark, M. Simnons, C. Reams, A.H. Coulson, L.B. Bourque, J. W. Sayre, R. 0ntels, and S. Roknw. 1988. "The UCLA population studies of chronic obstructive respiratory disease relationship between parental smoking and children's lung function.' Am. Rev. Respir. Dis. 129:891-897.

U.S. Department of Health and Human Services. 1982. The Consequence of Smoking: Cancer. Report of the Surgeon General. Rockville, Md.

U.S. Department of Health and Human Services. 1983. The Health Consequences of Smoking : Cardiovascular Disease. Report of the Surgeon General. Rockville, Md.

U.S. Department of Health and Human Services. 1984. The Health Consequences of Smoking: Chronic Obstructive Lung Disease. Report of the Surgeon General. Rockville, Md.

U.S. Department of Health and Human Services. 1985. Consequences of Smoking : Cancer and Chronic Lung Disease in the workplace. Rockville, Md.

U.S. Department of Health and Human Services. 1986. The Health Consequences of Involuntary Smoking . Report of the Surgeon General . Rockville, Md.

U.S. Department of Health and Human Services. 1989. Reducing the Health Consequences of Smoking : Twenty -five Years of Progress. Report of the Surgeon general . Rockville, Md.

U.S. Department of Transportation. Federal Aviation Administration. 1987. Airport Activity Statistics of Certified Route Air Carriers: Twelve Months Ending December 31,1987 U.S. Department of Transportation, Washington, D.C.

U.S. Environmental Protection Agency. 1986. Air Quality Criteria for Ozone and other photochemical oxidants. Volumes 4 and 5 EPA/600/8-84/0206F. Environmental Criteria Assessment Office, Research Triangle Park, N.C.

U.S. Environmental Protection Agency. 1987. EPA Indoor Air Quality Plan: Appendix A. Preliminary Indoor Air Pollution Information Assessment. EPA/600/8-87/014. Office of Health and Environmental Assessment, Washington, D.C.

U.S. Environmental Protection Agency. 1989a. Air Quality Criteria for Carbon Monoxide. Addendum. In draft preparation. Environmental Criteria and Assessment Office. Research Triangle Park. N.C.

U.S. Environmental Protection Agency. 1989b. Exposure Factors Handbook, Office of Health and Environmental Assessment. EPA/600/8-89/043.U.S. EPA Washington, D.C.

Ware, J.H., D.N. Doekery, A. Spiro III, F.E. Speizer, B.G. Ferris Jr. 1984. "Passive smoking, gas cooking and respiratory health of children living is six cities." Am. Rev. Resplr. Dis. 129:336-374.

Weber, A. 1984. "Acute effects of environmental tobacco smoke." Europ. J. Respir. Dis. 68(Supp. 133):98-108.

Weiss, S.T., I.B. Teger, F.E. Speizer, B. Rosner. 1980. "Persistent wheeze: its relation to respiratory illness, cigarette smoking and level of pulmonary function in a population sample of children." Am. Rev. Respir. Dis. 122:697-707.

Wells, J. 1988. "An estimate of adult mortality in the United States from passive smoking." Environ. Internat. 14:249-265.

White, J.R., H.F. Froeb. 1980. "small-airways dysfunction in non-smokers chronically exposed to tobacco smoke." New England J. Med. 302:720-723.

World Health Organization, International Agency for Research on Cancer. 1986. IARC Monograph on the Evaluation of the Carcinogenic Risk of Chemicals to humans, Tobacco Smoking. World Health Organization Vol. 38

Wynder, E. and D. Hoffmann. 1967. Tobacco and Tobacco Smoke: Studies in Experimental Carcinogenesis. Academic Press. New York, N.Y.

Section 8.0
RISK ASSESSMENT FOR OTHER CONTAMINANTS

8.1 BIOAEROSOLS

In general, illnesses associated with indoor air exposure to bioaerosols include two major categories: infections (e.g., measles, influenza, legionnaires disease), and hypersensitivities (e.g., humidifier fever, hypersensitivity pneumonitis, asthma, and allergic rhinitis). Although infectious diseases can be transmitted via indoor air (Bloch et al. 1985; Robinson et al. 1983; Bitton, 1980; Benenson 1985; Richardson and Barkley 1984), indoor bioaerosol investigations are most often only appropriate for assessing microorganisms potentially responsible for hypersensitivity diseases. This is because the sampling methodology and sampling efficiency for infectious agents (e.g., viruses that are known to be infective via the airborne route such as rhinovirus, influenza virus, coxsackievirus, adenovirus, and measles virus) are usually inadequate. Consequently, outbreaks of hypersensitivity diseases, such as interstitial lung disease and febrile syndromes are among the best-documented indoor air-related diseases. Numerous case reports have described exposure to microbial allergens from a variety of sources including home humidifiers, HVAC systems, car air conditioners, saunas, carpet, cooling towers, bathroom fixtures, and cooling process sprays (Morey and Feeley 1988; Burge et al. 1987; U.S. National Institute of Occupational Safety and Health 1987). In addition to the pulmonary diseases, recurrent outbreaks of fever, leucocytosis, chills, muscle aches, and malaise are part of the hypersensitivity disease spectrum. Attack rates have varied from 1 percent to 70 percent (Kreiss and Hodgson 1983). Various bacteria, fungi, and protozoans have been implicated in outbreaks and case reports, including Micropolyspora faeni, Bacillus subtilis, Flavobacteria, thermophilic Actinomyces, Penicillium species, and Amoebae species. The most specific clinical test for hypersensitivity pneumonitis is bronchial challenge with either antigen or the implicated source media (e.g., water); however, this test is restricted to clinical facilities because of the severity of reactions which may be possible.

Other tests of clinical or scientific interest include erythrocyte sedimentation rate, HLA-haplotpy, atopic status, rheumatoid factor, bronchoaveolar lavage, gallium scan, lymphocyte blast transformation, antigen in lung tissue at biopsy, electron micrographic findings, and nasopharyngeal swabs. Convincing demonstration of the specific microbial etiology of hypersensitivities (and infections) requires culture of air and water samples taken from plausible sources, as well as clinical evidence (e.g., body fluid cultures, medical evaluations, serum antibody levels).

Other hypersensitivity disorders, such as asthma and allergic rhinitis, are less clearly documented in the medical literature to be associated with saprophytic bioaerosols in indoor environments. Symptoms may occur within an hour of exposure or may be delayed for up to 6 to 12 hours. A pattern of exacerbation of asthma or rhinitis in relation to occupancy in indoor environments will usually be present when the issue of bioaerosols is raised, since these conditions are common in the general population.

Aircraft cabins present unique indoor air conditions and few indoor environments can serve to adequately predict potential health risks aboard aircraft. Submarine and spacecraft indoor environments are comparable, with the exception of their complete air recirculation systems (no outdoor air is available). Studies which have measured submarine and spacecraft indoor bioaerosols (Brockett and Ferguson 1975; Brockett et al. 1978; Watkins 1970) suggest that these environments generally do not have unusually high microbe concentrations (i.e., below 20 Colony Forming Units (CFU) per m3 of air sampled). However, the potential risk of contracting a contagious disease on an aircraft is exemplified by a
report of an influenza epidemic on a grounded aircraft. The aircraft was grounded for four hours in Alaska and 72 percent of the passengers became ill (National Research Council 1986). This incident emphasizes the importance of adequate ventilation both during flights and particularly while on the ground.

The following sections discuss potential types and sources of bioaersols in aircraft, environmental factors associated with their growth, amplification, survivability, and transport. In addition, the results of this investigation with respect to measured bioaerosol concentrations in aircraft cabin air are presented, including their health significance and general recommendations for minimizing the risk of indoor air-related diseases for airliner passengers and cabin crew members.

8.1.1 Types and sources of Potential Bioaerosols in Aircraft Associated with Human Health Effects

At cruising altitudes, outside air contains relatively few particle-associated microbiological organisms (National Research Council 1986b). However, outside air which enters the aircraft while on the ground carries a considerable spectrum of microorganisms including viruses, bacteria, actinomycetes, fungal spores and hyphae, animal and human dander, and arthropod-associated particles (Burge 1985).

As mentioned previously, many viral diseases can be transmitted by the aerosol route (e.g., influenza, measles, chicken pox, smallpox, colds, rabies, Venezuelan Equine Encephalitis, Newcastle disease , Infectious Mononucleosis, Yellow Fever, Rift Valley Fever, Foot and Mouth Disease, Swine Vesicular Disease, and Poliomyelitis). The primary source of indoor viral and bacterial aerosols are humans and animals (Spendlove and Fannin 1983). Airliner passengers can create these aerosols by processes such as coughing, sneezing, talking, and singing (Letts and Doermer 1983). A sneeze, for example, produces large droplets which upon desiccation remain airborne. These particle-associated microorganisms can remain infective for hours and even days depending upon the environmental conditions. Bacterial species are usually not found in infectious concentrations in the outdoor air, with the exception of several species (e.g., soil organisms such as Legionella). However, bacteria have been well recognized in indoor environments, particularly in hospitals (e.g., nosocomial infections), as the etiological agents responsible for infections of the human respiratory tract (e.g., group A Streptococcus). Human dispersion (via skin desquamation, talking, coughing, and sneezing) of both Streptococcus and Staphylococcus species (e.g., Staphylococcus aureus) have also been studied as nosocomial infection risks (Benenson, 1985).

Fungal spores, some of which are of pathogenic significance (e.g., soil-associated Coccidioides immitis in the southwestern United States), are present in the outside air, and passengers and cabin crew members boarded on an aircraft could be exposed when the aircraft is grounded and the doors are opened for unloading passengers, baggage, and other materials. Many fungi can grow and reproduce on man-made surfaces, given appropriate organic substrates and moisture conditions. When disturbed, they can produce dense aerosols that can accumulate within enclosed environments. A wide variety of fungi have been isolated from air and many fungal diseases (e.g., aspergillosis, coccidiomycosis, histoplasmosis, blastomycosis, and cryptococcoses) are known to be transmitted via the transport of spores or spore-bearing soil particles. Sufficient exposure to fungal aerosols can result in hypersensitivity diseases, such as hypersensitivity pneumonitis, allergic rhinitis, and allergic asthma in susceptible persons (Burge 1985).

Other sources of bioaerosols could include cargo compartments transporting animals. Animal dander, feces, urine, arthropods, contaminated baggage, and microorganisms transported in culture could all potentially contribute to aerosols within aircraft. Aerosol transport to passenger sections could occur depending upon the airflow patterns for a given aircraft.

8.1.2 Environmental Factors Associated with Bioaerosol Emission, Transportation and Fate

Assessment of the risks associated with respiratory infection and hypersensitivity diseases resulting from exposure to indoor air bioaerosols involves many complex and interrelated environmental, host-specific, and microbe-specific factors. Factors involved in the experimental evaluation of respiratory risk include:

- source strength
- concentration of viable units
- spray factor
- biological behaviour
- type of environmental release
- influence of air volume
- ventilation rate
- host-specific factors (e.g., immune status)
- microbe-specific factors (e.g. pathogenicity)
- relative humidity
- temperature
- organism half-life in air.

The source strength on an aircraft would include variables such as the number of people (load factor), the number of people with respiratory or skin infections, and the ability of microbes to bioamplify, which depends upon substrate availability, nutrients, water, temperature, and pH. The source strength is also influenced by the degree of sporulation and spore-celt availability. These depend on relative humidity, temperature, light, viability, and colony morphology (National Research Council 1986). Host-specific factors such as immunological status, existing antibody titers, pre-existing illness, vulnerability of specific cells in the nasal and respiratory tracts to colonization and infection, and exposure duration could be highly variable for people on a given flight. Further microbe-specific factors such as inhalation dose-response relationships, are unknown for most organisms. For example, the number of fungal spores required for a given species to induce hypersensitivity diseases remains largely unknown and most likely varies considerably with the susceptibility of the host (Platts-Mills et al. 1985; Burge 1985).

As mentioned previously, disease transmission through the air is known to occur both by droplets and droplet nuclei (Spendlove and Fannin 1983; National Research Council 1986). Methods of aerosolization include dispersal by coughing, sneezing, talking, air movement, water splashing, and turbulence. Talking can produce as many as 2,000 particles per explosive sound and a sneeze can produce approximately 2 million viable particles (Spendlove and Fannin 1983). Usually, these particles do not remain airborne for long periods, but are respirable and highly infective.

The persistence of viruses, bacteria, and fungi in the airborne state (and consequently the risk of health effects) depends on numerous environmental factors, the most important of which are relative humidity, desiccation, solar radiation, and temperature. The decline of microbes in the airborne state proceeds at two stages. First, there is a rapid die-off of the microbe following initial shock due to desiccation. This stage lasts seconds and it has been estimated that 0.5 log10 of microbes undergo inactivation (Bitton 1980). The second stage is slower and is influenced by the variables of relative humidity, temperature, and solar radiation.

Relative humidity appears to have an inverse relationship with the viability of some viruses (Loosli et al. 1943), whereas for some bacteria this relationship is reversed; the higher the humidity, the longer the survival of bacterial aerosols. It is generally recommended that the relative humidity in indoor spaces be maintained at levels less than 70 percent and less than 50 percent where cold surfaces are in contact with room air (Burge et al. 1987). In most aircraft, the relative humidity is low, which would greatly inhibit bacterial survival. However, viruses could plausibly remain viable for longer time periods. Extreme temperatures (hot or cold) are limiting factors for bioamplification of most bacteria and fungi (viruses are intracellular parasites and require host cells for replication). However, the temperature ranges (i.e., average of approximately 75 oF) found on aircraft are not likely to have substantial limiting effects because of the need to maintain comfort.

8.1.3 Bioaerosol Concentrations in Airliner Cabins:Empirical Data, Health Significance. and Risk Characterization

Bacterial and fungal aerosol concentrations measured as part of this investigation were presented previously in Tables 4-24 and 4-25, respectively. These tables list the average Colony Forming Units per cubic meter (CFU/m3) of air sampled for total bacteria and fungi on smoking and nonsmoking flights. In addition, Table 4-24 lists the concentrations of Staphylococcus species on smoking and nonsmoking flights. Tables 4-26 and 4-27 list the frequency of detection for predominant bacterial and fungal species, respectively, for both smoking and nonsmoking flights.

Interpretation of the health significance of these data is most appropriately approached by initially determining if aircraft bioaerosol concentrations could reasonably be anticipated to pose risks to "healthy" passengers and cabin crew members. If this evaluation suggests that measured bioaerosol concentrations do not pose significant risks, quantitative investigation of microbe-and host-specific factors (e.g., infectious dose, pathogenicity, organism survivability, susceptible subpopulation distribution on aircraft, epidemiological circumstances) are not necessary and successful recommendations can likely be made in general terms with respect to environmental (e.g., ventilation rates, relative humidity, temperature) and operational factors (e.g., time spent on the ground without ventilation, air filtration methods) which are necessary to minimize the possibility for bioamplification and exposure to pathogenic microorganisms in aircraft.

It is acknowledged that "nonhealthy" individuals, such as immuno-compromised persons, may be at risk for infection or hypersensitivity diseases in densely populated, enclosed indoor spaces. Further, it is assumed that these individuals do not represent the "average" airliner passenger population and that reductions in their risk of acquiring bioaerosol-related diseases would require isolation from such environments. Thus, for "healthy" passengers and cabin crew members qualitative risk assessment methods can be used to determine the health significance of the data presented in Tables 4-24 and 4-25 and whether these data justify further analyses and research. These qualitative risk assessment methods include: 1) "rank order assessment" and 2) assessment of the relationship of bioaerosol concentrations to critical environmental factors ("environmental factors assessment"), including source strength as expressed by passenger load factor, air recirculation conditions, air exchange rate, type of aircraft, smoking versus nonsmoking flights, temperature, and relative humidity.

8.1.3.1 Rank Order Assessment

As applied in most indoor air evaluations for bioaerosols, the rank order assessment involves comparison of the prevalence of taxa measured in the indoor environment to the prevalence of taxa simultaneously measured outdoors (Burge et al. 1987). In general, indoor levels of microorganisms, particularly fungal spores, should be approximately less than one-third of outdoor levels (Burge et al. 1987). It is important to note that the outdoor air should be the most predominant source of the organisms being evaluated and, thus, should be qualitatively similar to the indoor air. Higher concentrations of a given taxa indoors versus outdoors suggests bioamplification and the potential for adverse health effects given that the taxa is pathogenic for humans and there are susceptible persons being exposed. These ranked populations can be compared qualitatively or quantitatively using Spearman Rank Order Correlation (Dixon and Massey 1969). This statistical procedure is used because bioaerosols rarely follow a normal distribution which precludes the use of parametric statistical methods.

Measured (average) bacteria concentrations (Table 4-24) were somewhat higher in the smoking (163 CFU/m3) than nonsmoking sections (131 CFU/m3) of monitored smoking flights, and the average level in the nonsmoking sections on these flights was identical to that on nonsmoking flights (131 CFU/m3). Measured (average) fungi levels (Table 4-25) were somewhat higher on nonsmoking flights (9.0 CFU/m3) than smoking flights (5.5 CfU/m3). It is important to note the standard deviations for these mean values and the general observation that microorganism concentrations were very low in all cases.

Since outdoor air at cruising altitudes is likely to have few biological particles of any kind, the rank order assessment comparison is best performed using data from other bioaerosol studies where no significant health risks were found to exist. Several studies offer such comparison to the ranked cabin air bioaerosol data presented previously in Tables 4-26 and 4-27. Table 8-1 presents "normal background" airborne concentrations of various microflora measured in 240 homes (Tyndall et al. 1987). Tables 8-2 (Solomon 1976) and 8-3 (Kozak and Gallup 1984; Kozak 1979) present similar data from a study of the prevalence of fungi encountered indoors. With respect to bacterial taxa prevalence in cabin air, Micrococcus, Staphylococcus, Anthrobactor, Corynebacterium, and Bacillus were the most frequently identified taxa. These taxa are commonly found in indoor environments, such as homes, as suggested in Table 8-1 and most importantly, the concentrations measured in the airliner cabins in this study (Table 4-24) were low and not indicative of indoor bioaerosol problems. The presence of Staphylococcus aureus is probably an indication of the density of human occupancy because this organism is normally shed by humans on skin scales. No conclusion on risk of infection due to this organism should or can be made because it is associated with infections only with immunocompromised individuals or persons in critical care facilities.

With respect to the ranked order of fungi measured in cabin air (Table 4-25), Cladosporium, Alternaria, Aspergillus, Penicillium, and Epicoccum were the revalent taxa. As shown in Tables 8-2 and 8-3, fungal prevalence indoors during the winter is very similar to that found in airliner cabin air. Further, the fungal concentrations found in cabin air (Table 4-25) are low and not indicative of an indoor bioaerosol problem.

In summary, the bacteria and fungi present in the airliner cabin air of flights measured in this study do not appear to be present at concentrations generally thought to pose risk of illness. The taxa normally encountered in indoor environments characterized as "normal" are also found in cabin air environments with similar prevalence and at similar air concentrations.

TABLE 8-1. AIRBORNE CONCENTRATIONS OF VARIOUS BACTERIA AND FUNGI MEASURED IN 240 HOMES[1]

	Summer (CFU/m3)		Winter (CFU/m3)	
	Indoor	Outdoor	Indoor	Outdoor
Bacillus				
Average	1273	603	818	260
Range	0-6000	0-6200	33-3300	1716
Micrococcus				
Average	71	16	68	26
Range	0-633	0-333	0-383	0-583
Staphylococcus				
Average	143	28	250	18
Range	0-5466	0-466	0-1450	0-283
Penicillium				
Average	870	1166	80	26
Range	0-6200	0-8066	0-3033	0-350
Aspergillus				
Average	482	342	45	17
Range	0-3000	0-5400	0-450	0-267
Other Fungi and Yeast (Mucor, Fusarium, Candida)				
Average	135	101	90	23
Range	0-1350	0-733	0-1266	0-216

1 Tyndall et al. (1987)

TABLE 8-2. PREVALENCE PARAMETERS FOR FUNGI ENCOUNTERED INDOORS IN WINTER[1]

Type	Recovered in Homes		Mean Indoor Levels Where Recovered	
	No.	%	Xmean	Range
Penicillium	138	92.0	71.3	1-2,260
Cladosporium	122	81.2	3.7	1-43
Rhodotorula	114	75.9	173.0	1-8,412
Nonpigmented yeasts	62	70.7	39.1	2-1,485
Aspergillus	47	31.3	24.4	1-946
Alternaria	37	24.6	1.1	1-6
Geotrichum	28	18.6	110.7	1-2,614
Aureobasidium	26	17.3	4.2	1-36
Cephalosporium	17	11.3	189.1	2-3,760
Sporobolomyces	14	9.3	576.2	9-8,113
Candida	14	9.3	1.7	1-7
Eppicoccum	14	9.3	1.6	1-10
"Paecilomyces - like"	10	6.7	3,817.2	6-18,436
Verticillium	10	6.7	313.9	1-2,064
Sporothrix	9	6.0	307.6	4-886
Sphaeropsidales	8	5.3	2.7	1-6
Fusarium	8	5.3	197.4	3-624
Trichosporon	4	2.7	88.2	2-341
Scopulariopsis	3	2.0	104.6	1-310
Bullera	2	1.3	289.5	13-566
Miscellaneous identified	42	28.0	3.3	1-21
Unidentified sporulating	5	3.3	3.0	1-6
Unidentified nonsporulating	21	14.0	5.7	1-28

[1]Solomon (1976)

TABLE 8-3. ISOLATION, FREQUENCY, AND CONCENTRATION OF VIABLE MOLDS IDENTIFIED IN A SURVEY OF 68 HOMES IN SOUTHERN CALIFORNIA[1]

Mold Genera	Percent of Homes in which Genera Isolated	Range of Spores/m3	Mean of Spores/m3
Cladosporium	100	12-4673	437.7
Penicillium species	91·2	0-4737	168.9
Nonsporulating mycellia[2]	89.7	0-494	44.3
Alternaria	87·0	0-282	30.7
Streptomyces	58.8	0-212	28.1
Epicoccum	52.9	0-153	9.6
Aspergillum species	48.5	0-306	15.0
Aureobasidium	44.1	0.294	8.0
Drechslera (Helminthosporium)	38.2	0-94	6.9
Cephalosporium	36.7	0-59	5.3
Acrenomium	35.3	0-188	3.6
Fusarium	25.0	0-47	4.5
Botrytis	23.5	0-54	2.9
Aspergillus niger	19.1	0-59	2.9
Rhizopus	13.2	0-29	1.4
Rhodotorula	11.8	0-29	1.5
Beauveria	10.3	0-12	0.7
Chaetomium	8.8	0-47	1.2
Unknown	8.8	0-34	1.2
Scopulariopsis	8.8	0-25	0.9
Mucor	7.4	0-14	1.4
Curvularia	7·4	0-12	1.1
Rhinocladiella	4.4	0-12	0.5
Verticillium	4.4	0-12	0.4
Plenozythia	4.4	0-6	0.3
Pithomyces	2·9	0-25	0.4
Zygosporium	2·9	0-18	0.4
Paecilomyces	2·9	0-12	0.3
Stachybotrys	2·9	0-12	0.3
Aspergillis fumigatus	2·9	0-5	0.2

1Koznk and Gallup (1984)
2Subcultures of nonsporulating mycelia from one home (grown on Moyer's multiple media) subsequently produced Torula herbarum colonies.

(Continued)

TABLE 8-3. ISOLATION, FREQUENCY, AND CONCENTRATION OF VIABLE MOLDS IDENTIFIED IN A SURVEY OF 68 HOMES IN SOUTHERN CALIFORNIA1
(Concluded)

Mold Genera	Percent of Homes in which Genera Isolated	Range of Spores/m3	Mean of Spores/m3
Nigrospora	2.9	0-5	0.1
Stysanus	2.9	0-6	0.1
Leptosphaerulina	1.5	0-18	0.3
Botryosporium	1.5	0-6	0.1
Trichoderma	1.5	0-12	0.2
Chrysosporium	1.5	0-6	0.1
Phoma	1.5	0-6	0.1
Sporobolomyces	1.5	0-6	0.1
Tricothesium	1.5	0-6	0.1
Ulocladium	1.5	0-5	0.1
Yeast	1.5	0-5	0.1
Geotrichum	1.5	0-3	0.04

1Koznk and Gallup (1984)

8.1.3.2 Environmental Factors Assessment

Tables 5-13 and 5-14 describe the relationship of bacterial and fungal measurements, respectively, to selected aircraft factors (i.e., type of aircraft, air recirculation, air exchange rate, and passenger loading factor) for smoking flights. The type of aircraft (wide or narrow body) did not appear to have a dramatic effect on average bacterial or fungal air concentrations (CFU/m3). The presence of air recirculation appeared to slightly increase bacterial and fungal concentrations. However, this effect was not significant. Increased air exchange rate appeared to lower the average bacterial concentrations, with little effect apparent for average fungal concentrations. The passenger load factor appeared to increase average bacterial and fungal concentrations when comparing <50 percent loading to >90 percent loading. Finally, the temperatures in the cabins of monitored aircraft averaged 75 oF for both smoking and nonsmoking flights and the relative humidity levels were quite low, averaging below 25 percent on both smoking and nonsmoking flights. The measured humidity levels were somewhat lower on smoking than nonsmoking flights.

The results of this investigation suggest that airliner cabin air concentrations of bacteria and fungi, and the prevalence of their respective taxa, are not indicative of significant potential for illnesses (e.g., hypersensitivities) associated with some indoor environments. It is recognized that this conclusion is appropriate for "healthy" passengers and not necessarily for immunocompromised persons. Consistent with recommendations made by the National Research Council (1986), if the risk of illness, whether due to an infection or a hypersensitivity disease; is to be reduced, the amount of outside air supplied to each passenger should be maximized because of the low levels of contaminants associated with this air. Further, if ventilation systems are not operating, passengers should not stay aboard the plane for long time periods (i.e., greater than 30 minutes). Consistent with general indoor hygiene, efforts should be made to maintain dry surfaces to prevent structural contamination. Based on this investigation, temperature and relative humidity ranges present on monitored flights were consistent with acceptable levels for discouraging the survival and growth of microorganisms. Cargo compartments in aircraft should be kept free of animal excrement and arthropods. Pathogenic microorganisms should not be transported on aircraft carrying passengers (National Research Council, 1986).

This study does not address the role of viruses as infectious agents in the cabin air environment. The relative importance of viruses as sources of indoor-related illnesses (e.g., influenza) can be seasonally related (Joklik 1985). Additionally, in the case of influenza viruses, the periodicity of epidemics and pandemics is related to the genetic stability of the virus and the appearance of a new virus with altered surface antigens (Joklik 1985). The monitoring conducted for this investigation occurred during the spring/summer season and not the winter season, which is associated with an increase in virus-related illnesses (Joklik 1985). Monitoring of viruses in aircraft cabins was not undertaken because of contractual constraints. To meet the contract schedule, monitoring had to be conducted during April through June when seasonal prevalence of viruses would have been low. Thus no monitoring for viruses was conducted. Nonetheless, viruses are recognized as the predominant etiologic agent for respiratory infections, estimated to cause 50 to 60 percent of all community-acquired illnesses (Feeley 1985).

8.2 COSMIC RADIATION

8.2.1 Exposure to Cosmic Radiation

The major source of radiation exposure to humans is natural in origin. This includes external sources such as cosmic radiation and terrestrial radiation from radioactive substances in the ground and building materials, and internal sources such as naturally occurring radionuclides in the body inhaled or ingested from air and diet. Natural radiation exposes virtually the world population at a relatively constant rate throughout time and is virtually independent of human activity.

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the mean annual effective dose equivalent is estimated to be 2.4 millisieverts (mSv) per year or 240 millirem (mr) per year[1] (UNSCEAR, 1988).

For airline passengers and cabin crew members, the major contributing factor to any increase in the overall radiation dose is cosmic radiation, high energy radiation that enters the atmosphere from cosmic space originating usually at either the sun or in deep space. Primary cosmic rays enter the atmosphere and interact with the nuclei of atoms present in the air, resulting in the formation of secondary cosmic rays such as neutrons, protons, pions, and kaons, and a variety of reaction products (cosmogonic nuclides) such as 3H, 7Be, 10Be, 14C, 22Na, and 24Na. The high-energy secondary cosmic rays thus formed react further with nuclei in the air to form additional secondary particles (electrons and muons).

In the lower atmosphere, dose rates from the ionizing component vary little with latitude but significantly with altitude, doubling approximately every 1,500 meters (4,875 feet). Measures of absorbed dose rates in air, derived from ionization chamber measurements on aircraft, yield dose rates of 30 nGy/hr (one Gray, Gy, is equal to 100 RAD) at sea level for any latitude and from there increase to about 4 uGy/hr at an altitude of 12 km (39,600 feet) closer to the poles. At sea level, the absorbed dose rate in outdoor air from the ionizing component of cosmic rays was reported to be 32 nGy/hr (UNSCEAR 1982). This value was taken to be numerically equivalent to the effective dose equivalent. The doses are somewhat lower indoors due to the shielding effect of building structures. A shielding factor of 0.8 has been used to yield an average indoor absorbed dose index rate (at sea level) of 26 nGy/hr (UNSCEAR 1988). Using a value of 1 for the quality factor and an indoor occupancy factor of 0.8, the annual effective dose equivalent is estimated to be about 240 uSv per year at sea level.

---

1 1 millisievert is equal to 100 millirem.

Variation of the neutron component with altitude and latitude is similar to that of the ionizing component. At sea level, the neutron flux rate is approximately 0.008 cm-2s-1. Using an estimate of 2.4 nSv/hr for the average dose equivalent rate, and neglecting the shielding effect of building structures, the annual effective dose equivalent for the neutron component is estimated to be about 20 uSv at sea level (UNSCEAR 1982).

When the data are transformed to a cumulative effective dose equivalent as a function of altitude, a per capita effective dose equivalent for the world population is found to be 355 uSv (not time dependent), with the ionizing component accounting for 300 uSv and the neutron component accounting for 55 uSv. This increased dose equivalent estimate is due to the range of altitudes and latitudes in which people live. It is important to note that the dose equivalent from the neutron component, which is small at sea level, increases more rapidly than the dose from the ionizing component and becomes more important at altitudes above 6 km (19,800 feet).

Elevated exposures result from prolonged presence at high altitudes. Populations living in such high altitude cites as Bogota, Lhasn, or Quito receive annual effective dose equivalents from cosmic radiation in excess of 1 mSv. It follows that commercial airliner passengers and cabin crew members will be exposed to higher dose rates than the general nonflying population. These dose rates will vary according to flight altitude, flight latitude, and the amount of solar activity.

With decreasing altitude from the top of the atmosphere, the dose equivalent rate from galactic radiation first increases, then decreases. The increase is a consequence of the multiplicity and characteristics of the secondary particles produced after collision of high energy cosmic particles with the atomic nuclei of gases in the atmosphere. Many of the impacting and generated particles maintain enough energy to form additional secondary particles. The altitude at which the dose equivalent rate is maximum depends on the geomagnetic latitude. With decreasing altitude below 21.2 km (70,000 feet) at all latitudes, continued energy degradation and cannibalization of particles results in a decreasing dose equivalent rate. In the contiguous United States, the dose equivalent rate at 12.1 km (40,000 feet) is about 40 percent of the rate at 21.2 km (70,000 feet) (Federal Aviation Administration 1989).

The geomagnetic field of the earth deflects many charged particles of solar and galactic origin that would otherwise enter the atmosphere. Shielding is most effective at the geomagnetic equator, where the geomagnetic lines of force are nearly perpendicular to the surface of the earth. At airliner cruise altitudes, the cosmic radiation dose equivalent rate over the geomagnetic poles is approximately twice that over the geomagnetic equator. Most high-altitude flights of U.S. commercial aircraft occur with scheduled flights between the United States and Europe or Asia (Federal Aviation Administration 1989).

The cycle of rise and decline in the intensity of the cosmic radiation incident on the atmosphere lasts approximately 11 years, with the intensity inversely related to solar activity. Charged particles are continuously ejected from the sun but are generally too low to contribute to the radiation level at airliner flight altitudes. On infrequent occasions, the energy levels and quantities of ejected solar particles are high enough to substantially increase the dose equivalent rate at typical cruise altitudes. During the period from 1956 to 1972, there were four solar particle events during which the dose equivalent rate on polar routes at 12.4 km (41,000 feet) probably exceeded 100 uSv/hr (Federal Aviation Administration 1989).

Dose equivalents for flights typical of continental U.S. latitudes and circumpolar transoceanic routes are presented in Table 8-4. Since total radiation dose is the simple sum of individual exposures, this table enables any individual to ascertain cumulative radiation dose by adding appropriate flights (as actually listed or as representatives of similar flights) according to their specific frequencies of occurrence. The summed value represents the relevant individual exposure in the determination of risk, as described in Section 8.2.3.

TABLE 8-4. DOSE EQUIVALENTS FROM GALACTIC COSMIC RADIATION RECEIVED ON AIRLINER FLIGHTS

	Single Nonstop One-way Flight				
Origin - Destination	Highest Altitude KM	(feet, thousands)	Air Time (in hrs)	Block Time1 (in hrs)	Dose2 (in microsieverts)
Houston - Austin	6.1	(20)	0.5	0.6	0.1
Seattle - Portland	6.4	(21)	0.4	0.6	0.1
Miami - Tampa	7.3	(24)	0.6	0.9	0.4
St. Louis - Tulsa	10.7	(35)	0.9	1.1	2.0
Tampa - St. Louis	9.4	(31)	2.0	2.2	5.4
San Juan, PR - Miami	10.7	(35)	2.2	2.5	7.2
New Orleans - San Antonio	11.9	(39)	1.2	1.4	4.3
Denver - Minniapolis	10.1	(33)	1.2	1.5	4.7
New York - San Juan, PR	11.3	(37)	3.0	3.5	13.0
Los Angeles - Honolulu	10.7	(35)	5.2	5.6	22.0
Chicago - New York	11.3	(37)	1.6	2.0	8.5
Honolulu - Los Angeles	12.2	(40)	5.1	5.6	25.0
Washington, DC - Los Angeles	10.7	(35)	4.7	5.0	24.0
Tokyo, Japan - Los Angeles	11.3	(37)	8.8	9.2	46.0
Los Angeles - Tokyo, Japan	12.2	(40)	11.7	12.0	62.0
New York - Chicago	11.9	(39)	1.8	2.3	12.0
Minniapolis - New York	11.3	(37)	1.8	2.1	11.0
London - Dallas/Ft. Worth	11.9	(39)	9.7	10.1	53.0
Dallas/Ft.Worth - London	11.3	(37)	8.5	8.8	49.0
Seattle - Anchorage	10.7	(35)	3.4	3.7	21.0
Lisbon - New York	11.9	(39)	6.5	6.9	41.0
Chicago - San Francisco	11.9	(39)	3.8	4.1	26.0
Seattle - Washington, DC	11.3	(37)	4.1	4.4	29.0
London - New York	11.3	(37)	6.8	7.3	9.0
New York - Seattle	11.9	(39)	4.9	5.3	36.0
San Francisco - Chicago	12.5	(41)	3.8	4.1	29.0
Tokyo - New York	12.5	(41)	12.2	12.6	91.0
London - Los Angeles	11.9	(39)	10.5	11.0	80.0
Chicago - London	11.3	(37)	7.3	7.7	
New York - Tokyo, Japan	13.1	(43)	13.0	13.4	93.0

London - Chicago	11.9	(39)	7.8	8.3	62.0
Athens, Greece - New York	12.5	(41)	9.4	9.7	93.0

1 The block hours of a flight begin when the aircraft leaves the blocks before takeoff and when it reaches the blocks after landing.
2For each flight, estimates of dose-equivalent were made using one flight plan, taking into account changes in altitude and geomagnetic latitude from takeoff to touchdown.

8.2.2 <u>Health Effects from Exposure to Cosmic Radiation</u>

There are two types of effects from exposure to radiation: nonstochastic and stochastic. Nonstochastic effects are those for which the probability and severity of the effect vary with dose and a threshold for the effect exists. Examples of nonstochastic effects include pancytopenia following irradiation of bone marrow, and pneumonitis and pulmonary fibrosis following irradiation of the lung. Stochastic effects are those for which the probability of the occurrence of effect, and not its severity, varies as a function of dose in the absence of a threshold. The major stochastic effects are heritable genetic effects and cancer.

Early to intermediate effects of exposure to radiation can be taken to include the somatic effects of exposure to irradiation, excluding carcinogenesis and shortening of life span which are late somatic effects. Genetic effects of irradiation include gene mutation and chromosome aberrations.

Tumors caused by radiation are indistinguishable from tumors caused by other sources (e.g., chemicals), and health effects other than cancer are also very similar to those occurring spontaneously or induced by exposure to other agents. The health effects of radiation are often augmented by other factors that tend to increase overall risk; these include tobacco smoking and dietary factors (UNSCEAR 1988).

8.2.3 <u>Quantitative Estimation of Risk</u>

Risk was determined for cancer, fetal retardation, and birth defects using an algebraic combination of the exposure assessment and dose-response risk coefficients. Radiation risk coefficients used in this investigation were based on UNSCEAR dose-response relationships and modeling protocols (UNSCEAR 1986; 1988). The Fourth Report of the Committee on Biologic Effects of Ionizing Radiation, National Research Council (BIER IV for cosmic radiation) was not complete at the time analyses were conducted.

Risk coefficients for cosmic radiation exposure in utero leading to birth defects, mental retardation, and childhood cancer, as presented in Table 8-5, were derived from epidemiological studies of children exposed in utero during the bombing of Hiroshima and Nagasaki. The risk coefficient for childhood cancer was assumed to be constant during prenatal development, although there is evidence suggesting that risk is higher in the first trimester (UNSCEAR 1986).

Risk coefficients for adult cancer (solid tumors and leukemia) were derived from epidemiological studies of atom bomb survivors, patients with ankylosing spondylitis (spinal arthritis), and patients with cervical cancer. Estimates were computed using an assumed exposure of 1 Gy and linear dose-response relationship for solid tumors. Additive and multiplicative projection extrapolation models were used to determine risks. Minimum latency for leukemia was set at 2 years and for all other sites at 10 years. The plateau was 40 years for leukemia and lifetime for all other sites. Cancer mortalities in Japan and the United Kingdom were used as baseline mortality rates. The risk coefficients assumed a quality factor of 1. This value is the sum of the relative risk for leukemia and the relative risk for other malignancies (UNSCEAR 1988).

Dose-response plots presented in Figures 8-1, 8-2, and 8-3 for adult cancer, childhood cancer, and fetal retardation and birth defects, respectively, were constructed using the risk coefficients contained in Table 8-5. The procedure for determining risk can be illustrated using the same three example flying profiles presented in Section 7.0 of this report to illustrate cancer risks from exposure to ETS. The parameters of these examples are summarized in Table 7-7. For purposes of illustration, an additional assumption is made here that half of the total flying time indicated for the individuals in the three examples is between New York and Seattle (representing a constant latitude in the continental U.S.) and the other half is between New York and Tokyo (representing a circumpolar flight at high altitude). Additional flights, and their associated cumulative doses and cancer risks, are presented in Tables 8-6 and 8-7 for domestic and international flights, respectively. In each case, flights of varying duration, latitude, and direction were chosen as examples. It

TABLE 8-5. RISK COEFFICIENTS FOR A RANGE OF HEALTH EFFECTS ASSOCIATED WITH EXPOSURE TO COSMIC RADIATION

Health Effect	Risk Coefficient	Period of Vulnerability
Fetal structural abnormalities	500/1million/mSv	Weeks 2-8 of pregnancy
Mental retardation in fetus	800/1million/mSv	Weeks 8-15 of pregnancy
	100/1 million/mSv	Weeks 16-26 of pregnancy
Childhood cancer	20/1million/mSv	Full term of pregnancy
Adult cancer (leukemia and solid tumors)	70/1million/mSv	

.

should be noted that the cancer risks or cosmic radiation and ETS are additive.

Example 1. The individual is a cabin crew member who flies 960 hours per year for 20 years. Assuming that 10 years are spent flying from New York to Seattle (dose equivalent of 36 uSv for 5.3 hours from Table 8-4), the dose Equivalent for this segment is 65 mSv. Assuming that the next 10 years are spent flying from New York to Tokyo (dose equivalent of 99 uSv for 13.4 hours from Table 8-4), the dose equivalent for this period is 71 mSv. The total dose equivalent for 20 years of flying is 136 mSv (65 + 71). Referring to Figure 8-1 for adult cancer risk, a lifetime exposure of 136 mSv in flight results in a lifetime cancer risk of 952 cancer deaths per 100,000 or a risk of 1 in 105.

Example 2. This individual is a frequent flyer who logs 480 our year for 30 years. Assuming that the first 15 years are spent flying from New York to Seattle, the dose equivalent for this period is 49 mSv. Similarly, the dose equivalent for 15 years of flying from New York to Tokyo is 53 mSv. The combined dose equivalent for 30 years of flying is 102 mSv. From Figure 8-1, the risk is 714 cancer deaths per 100;000 or a risk of 1 in140.

Example 3. This individual flies 48 hours/year for 40 years. For the last 20 years, Flights between New York and Seattle result in a dose equivalent of 6.5 mSv. For the next 20 years, flights between New York and Tokyo result in a dose equivalent of7.1 mSv. With a lifetime dose of 13.6 mSv acquired in flight, the risk is 95 cancer deaths per 100,000 or a risk of 1 in 1,053.

Risks for childhood cancer, fetal retardation, and birth defects can be determined in a similar fashion, using the risk coefficients in Table 8-5. For a single transcontinental flight such as Washington to Los Angeles, the dose equivalent is 24 uSv. The risks for any of the childhood health effects are very small (about 1 per 100,000) according to Figures 8-2 and 8-3. For even a high exposure flight such as New York to Tokyo with a dose equivalent of 99 uSv, the risks are still small (about 5 per 100,000).

8.3 OZONE

Ozone levels in airliner cabins were measured on domestic and international flights to determine compliance with current federal stan-

dards and to ascertain if observed concentrations pose a health hazard to cabin crew members and passengers.

8.3.1 The FAA Standard for Ozone in Airliner Cabins and its Basis

In 1980, the Federal Aviation Administration (FAA) promulgated an ozone standard for aircraft cabins that included transport category airplanes of commercial air carriers (Federal Register 1980). The standard was prompted by research of the FAA Civil Aeromedical Institute (Federal Aviation Administration 1979, 1980) that demonstrated no significant health effects attributable to ozone at a sea level equivalent of 0.2 ppm for 4 hours, but which did demonstrate respiratory effects in exercising individuals at a sea level equivalent of 0.3 ppm. This suggested a threshold for effect between 0.2 and 0.3 ppm. At a cabin pressure altitude of 1.8 km (6,000 ft), where there is less air for a given volume, 0.3 ppm equates to a sea level equivalent of 0.25 ppm. Accordingly, the FAA established an instantaneous standard of 0.25 ppm (sea level equivalent) and a time-weighted three-hour standard of 0.1 ppm (sea level equivalent).1

Other regulatory agencies have established similar standards. The Occupational Safety and Health Administration's Threshold Limit Value (TLV)2 for the workplace environment is 0.1 ppm. The Environmental Protection Agency's one-hour ambient air standard remains at 0.12 ppm, although recent research on humans under conditions of controlled exposure has suggested the possibility of respiratory effects (i.e., lung infectivity) at ozone levels as low as 0.08 ppm (see below). In addition, there is scientific and regulatory debate over the need for an 8-hour ambient air standard lower than 0.12 ppm. The FAA's standard of 0.1 ppm appears to be in the protective range.

---

1 While the actual time-weighted average was 0.08 ppm, the FAA wished to have its standard in harmony with OSHA's standard of 0.1 ppm.

2 A TLV is the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which workers may be exposed, day after day, without adverse health effect.

8.3.2 Health Effects of Ozone

Extensive investigations of ambient air ozone in humans and experimental animals have been described in several definitive scientific reviews (National Research Council 1977; U.S. Environmental Protection Agency 1986; Lippmann 1989). The health effects are briefly summarized below.

Ozone in the ambient air, in sufficiently high concentrations, irritates the upper respiratory tract, causes measurable degradation of pulmonary function, enhances lung infectivity, and causes alterations in blood biochemistry related to immune response. Most of the reported effects were observed after administration of doses considerably higher than those to which humans are routinely exposed. Under these conditions, morphological effects of ozone on the respiratory tract include damage to ciliated cells, proliferation of bronchiolar cells, cellular inflammation, and thickening of pulmonary arteriolar walls. Short-term exposure to ozone affects pulmonary function by increasing the breathing frequency, various physiological measures of breathing volume, airway resistance, and airway reactivity. Tidal volume, lung compliance, and diffusion capacity are decreased. Long-term exposure to ozone causes increased lung volume and airway resistance, and decreased lung compliance, respiratory flow, and lung function indicators (e.g., FEV1). Biochemically, ozone causes increases in metabolic enzymes in lung and blood, permeability changes in the lung, and increased oxygen consumption. Finally, ozone affects host defense mechanisms by delaying mucociliary clearance, accelerating alveolar clearance, inhibiting bacterial activity, altering lung macrophages causing a decrease in function, altering the number of defense cells, increasing susceptibility to bacterial infection, and altering immune activity.

Currently at issue is whether exposure to low levels of ozone manifests any of these effects. Recent work was conducted by Horstman et al. (1989), who exposed humans to 0.08 ppm in six 50-minute cycles during exercise representative of a day of moderate or heavy work. At this

level, often found in ambient air, clinically meaningful alterations in lung function were observed.

The Clean Air Scientific Advisory Board of the EPA is divided on the implications of these findings for regulation. Nevertheless, this and other recent research is lending to a reexamination of the bases for current regulatory standards and the durations of exposure prescribed in those standards. One of the more prominent issues is the need for an 8-hour ambient air standard for ozone. Such reconsideration are applicable to the airliner cabin environment, particularly for cabin crew members engaged in the equivalent of moderate exercise at altitude for extended periods of time.

8.3.3 Comparison of Ozone Levels Measured in Airliner Cabins with Existing Standards

A summary of ozone levels measured on all flights in this investigation was presented in Table 4-28. Average concentrations, obtained by integrated sampling, were 0.010 ppm on smoking flights and 0.022 ppm on nonsmoking flights; the maximum concentrations measured among all flights sampled was 0.078 ppm. Concentrations appeared to be uniformly distributed throughout the cabin, precluding the need to consider weighted exposures of cabin crew members and passengers by cabin section. All values were consistently below flight, occupational, and environmental standards established by the Federal government, as indicated in Section 8.3.2. This and current scientific knowledge lead to the conclusion that ozone does not pose a health hazard to cabin crew members or passengers.

8.4 REFERENCES

Benenson, A.S. 1985. Control of Communicable Diseases in Man. Fourteenth Edition. American Public Health Association. Washington, D.C.

Bitton, G. 1980. Introduction to Environmental Virology. John Wiley & Sons, Inc. New York, N.Y.

Bloch, A.B., W.A. Orenstein, W.M. Ewing, W.H. Spaln, G.F. Mallison, K. . Herrman and A.R. Hinman. 1985. "Measles outbreak in a pediatric practice: airborne transmission in an office setting." Pediatrics 75:676-683.

Brockett, R.M. and J.K. Ferguson. 1975. "Microbiological sampling of the spacecraft atmosphere during a simulated Skylab mission." Aviat. Space Environ. Med. 46:30-32.

Brockett, R.M., J.K. Ferguson and M.R. Henney. 1978. "Prevalence of fungi during Skylab missions." Appl. Environ. Microbiol. 36:243-246.

Burge, H.A. 1985. "Indoor sources for airborne microbes in indoor air and human health." In: Indoor Air and Human Health. Gammage, R.B. and S.V. Kaye, eds. Lewis Publishers,Inc. Chelsa, MI

Burge, H.A., M. Chatigny, J. Feeley, K. Kreiss, P. Morey, J. Otten and K. Peterson. 1987. "Guidelines for assessment and sampling of saprophytic bioaerosols in the indoor environment." Appl. Indust. Hyg. 2(5):R10.

Dixon, W.J. and F.J. Massey, Jr. 1969. Introduction to Statistical Analysis, 3rd edition. McGraw-Hill Book Company, NY .

Federal Aviation Administration. 1979. Effects of Ozone on Exercising and Sedentary Adult Men and Women Representative of the Flight Attendant Population. Report of the Civil Aeromedical Institute, Oklahoma City,. October 1979. National Technical Information Service, Springfield, Va. FAA-AM-79-20

Federal Aviation Administration. I980. Effects of Ozone (0.30 part per million, ~600 ug/m3 on Sedentary Men Representative of Airline Passengers· and Cockpit Crewmembers. Report of the Civil Aeromedical Institute, Oklahoma City March 1980. National Technical Information Service, Springfield, Va. FAA-AM-80-9.

Federal Aviation Administration. 1989. Radiation Exposure of Air Carrier Crewmembers. AAM-624. Federal Aviation Administration, US Department of Transportation.

Federal Register. 1980. Airplane Cabin Ozone Contamination. 45 FR 3880. January 21, 1980.

Feeley, J.C. 1985. "Impact of indoor air pathogens on human health." In: Indoor Air and Human Health. Gammage, R.B. and S.V. Kaye, eds. Levis publishers, Inc. Chelsa, Mich.

Horstman, 0., W. McDonnell, L. Folinsbee, S. Abdul-Salaam, and P. Ivas. 1989. Changes in pulmonary function and airway reactivity due to prolonged exposure to typical ambient ozone (03) levels. In: Atmospheric Ozone Research and its Policy Implications. Pages 755-762. T. Schneider et al. (eds). Elseiver Science Publishers B.V.. Amsterdam.

Joklik, W.K. 1985. Virology. Second Edition. Appleton-Century-Crofts. Norwalk, Conn.

Kozak, P.P., J, Gallup, L.H. Cunmlns and S.A. Gillman. 1979. "Factors of importance in determining prevalence of indoor molds." Ann. Allergy 43:88-94.

Kozak, P.P. and J. Gallup. 1984. "Endogenous mold exposure: environmental risk to atopic and nonatopic patients." In: Indoor Air and Human Health. Gammage, R.B. and S.Y. Kaye, eds. Lewis Publishers, Inc. Chelsa, Mich.

Kreiss, K. and M.J. Hodgson. 1984. "Building-associated epidemics." In: Indoor Air Quality. Pages 87-106. Walsh, P.J., C.S. Dudney and E.D. Copenhaver, eds. CRC Press. Boca Raton, Fla.

Letts, R.M. and E. Doermer. 1983. "Conversation in the operating theatre as a cause of airborne bacterial contamination." J. Bone Joint Surg. 65:357-362.

Lippmann, M. 1989. Health effects of ozone. A critical review." J. Air Pollut. Control Assoc." 39:672-692.

Loosli, C.G., H.M. Lanon, O.H. Robertson and E. Appel. 1943. "Experimental airborne influenza Infection: I. Influence of humidity on survival of virus in air." Proc. Soc. Exp. Biol. Med. 53:205-206.22

Morey, P.R. and J.C. Feeley. 1988. "Microbiological aerosols indoors." ASTM Standardization News (December).

National Research Council. 1986. The Airliner Cabin Air Environment. Air Quality and Safety. National Academy Press. Washington, D.C.

National Research Council. 1977. Ozone and Other Photochemical Oxidants. National Academy Press. Washington, D.C.

Platts-Mills, T.A., F. Rawle and M.O. Chapman. "Problems in allergen standardization." Clin. Rev. Allergy 3:271-290.

Richardson, J.H. and W.E. Barkley. 1984. Biosafety in Microbiological Laboratories. Centers for Disease Control and National Institutes of Health. U.S. Department of Health and Human Services. HHS Publication No. (CDC) 84-8395. Washington, D.C.

Robinson, P.A., R.V. Tauxe, W.G. Winkler and M.E. Levy. 1983. "Respiratory illness in conference participants following exposure to rug shampoo." Infection Control. 4:158-160.

Solomon, W.R. 1976. "A volumetric study of winter fungus prevalence in the air of Midwestern homes." J. Allergy Clin. Immunol. 57:46-55.

Spendlove, J.C. and K.F. Fannln. 1983. "Source, significance and control of Indoor microbial aerosols: human health aspects." Public Health Rep. 98:229-244.

Tyndall, R.L., C.S. Dudney, A.R. Hawthorne, R. Jernigan, K. Ironside and P. Metler. 1987.

"Microflora of the typical home.' In: Proceedings of the 4th International Conference on Indoor Air quality and Climate Seifert, B. H Esdorn, M. Fisher, H. Rueden. and J. Wegner, eds. Institute for Water, Soil and Air Hygiene. Berlin (West), August 17-21. Volume 1. Pages 617-621.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1988. Sources Effects and Risks of Ionizing Radiation. Report to the General Assembly. Annex A: Exposures from natural sources of radiation. UN Publication Sales No. E.8B.IX.7. United Nations. New York, N.Y.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1986. Genetic and Somatic Effects of Ionizing Radiation. Report to the General Assembly. Annex C: Biological effects of pre-natal irradiation. UN Publication Sales No. E.B6.IX.9. United Nations. New York, N.Y.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1982. Ionizing Radiation: Sources and Biological Effects. Report to the General Assembly Annex B . Paragraph 10. UN Publication Sales No. E.B2.IX.B. United Nations. New York, N.Y. As cited in United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR): 1988. Sources, effects and risks of ionizing radiation. Report to the General Assembly.

U.S. Environmental Protection Agency. 1986. Air Quality Criteria for Ozone and Other Photochemical Oxidants. Volumes 4 and 5. EPA/600/8-84/0206F. Environmental Criteria and Assessment Office, Research Triangle Park, N.C.

U.S. National Institute for Occupational Safety and Health. 1987. Guidance for Indoor Air Quality Investigations. Hazards Evaluations and Technical Assistance Branch, Division of Surveillance, Hazard Evaluations and Field Studies. Cincinnati, Oh.

Watkins, H.M.S. 1970. "Epidemiologic investigations in Polaris submarines." In: Aerobiology: Proceedings of the Third International Symposium on Aerobiology, Silver, I.H.(ed.). University of Sussex, England. September 1969. Academic Press. New York, N.Y.

Section " G."

MITIGATION

As identified through the risk assessment given in preceding sections, the pollutants that pose the highest risks of mortality and morbidity to airliner flight attendants and passengers are ETS contaminants and cosmic radiation. The measurement results also indicated that carbon dioxide levels on flights monitored during this study were frequently above the level thought to satisfy comfort criteria. A general framework for identifying and assessing alternative mitigation strategies for these pollutants is presented in Section 9.1. Application of this framework to strategies for reducing ETS levels in aircraft is described in Section 9.2, and application of the framework to other pollutants (cosmic radiation and carbon dioxide) is described in Section 9.3.

9.1 GENERAL FRAMEWORK FOR ASSESSING MITIGATION OPTIONS

A general framework for evaluating alternative mitigation strategies for a contaminant in an airliner cabin is depicted in Figure 9-1.

The first step in this process is to identify candidate mitigation strategies. Such strategies could include potential technological or procedural solutions to apparent problems; the technological solutions generally involve some type of change in aircraft design or equipment, whereas procedural solutions involve changes in the activities of people aboard the aircraft. Although it may be possible to identify many types of candidate strategies, only a limited number will be feasible from technological or procedural standpoints. As a simple example, addition of lead shielding could be contemplated to reduce cosmic radiation exposure, but such a procedure would be technologically impractical because of the resultant increase in aircraft mass. Some qualitative judgments obviously are required in this feasibility assessment process.

In the second step of the overall framework, strategies that survive the feasibility assessment are subjected to a more quantitative process of modeling and estimation. If performing this evaluation, it must

be recognized that certain options will have practical upper limits (e.g., extent to which ventilation rates or filter efficiencies can be increased). Some aspects of cost estimation will require detailed pricing or econometric models that cannot be developed within the scope of this effort. In addition to the types of costs (e.g., fuel penalties, new equipment) that can be addressed quantitatively, practical considerations such as anticipated acceptability by airline management, flight crews, or passengers need to be addressed qualitatively. The cost and practical aspects are juxtaposed with the estimated benefits of each strategy. Benefits accrue from presumed decreases in contaminant concentrations and associated health or discomfort risks. The contaminant concentrations expected to prevail when a specific strategy is applied are estimated through cabin air quality modeling, discussed later. The risk reduction associated with reduced concentrations 1s estimated through the framework used to assess risks for currently prevailing concentrations (see Section 6.0). The benefits of reduced risk can be placed in monetary terms using estimates of an individual s willingness to pay for reduced mortality or morbidity. Such estimates, which are discussed in more detail later, can be taken from other studies.

The third step of the overall framework 1s to determine the strategy or strategies of choice. Generally speaking, the optimal strategy would be the one with the highest net benefit (i.e., benefit minus tost), given cost and distrlbutional constraints. However, if two candidate strategies have similar estimates for risk reduction, then a cost-effectiveness analysis can be performed, with a focus on the costs and practical aspects of each alternative.

9.2 APPLICATION OF FRAMEWORK TO ETS CONTAMINANTS

The framework described above is first applied to ETS contaminants. Alternative mitigation options that are considered, and the subset retained for further analysis, are discussed in Section 9.2.1. Modeling efforts and estimated costs and benefits for each strategy are described in Section 9.2.2. Discussion of the relative costs and benefits of the alternative strategies is provided in Section 9.2.3.

9.2.1 Identification of Options

Eight candidate options for reducing the exposure of flight attendants or passengers are identified 1n Table 9-1. Half the options require a technological approach and the other half require a procedural approach. The options are also classified according to three general types of strategies for mltignting potential exposures:

(1) Preventing or minimizing the emission of ETS contaminants from cigarettes (i.e., emissions reduction)

(2) Removing the ETS contaminants from the cabin environment after they have been introduced (i.e., contaminant removal)

(3) Reducing the exposure of cabin occupants to ETS contaminants that have been introduced (i.e., exposure arrangement).

Although some of these options could obviously be used 1n combination with others, the general feasibility of each option has been assessed separately, as discussed below.

For the strategy involving emissions reduction, an obvious option is an outright ban of smoking on all flights. This procedural option would be quite feasible to implement and, in fact, has been implemented in partial form on domestic flights (i.e., smoking not allowed for flights of two hours duration or less under Public Law 100-202)1. Consideration would need to be given to possibilities such as smokers experiencing withdrawal symptoms, becoming unruly, or attempting to smoke in the lavatory, thereby creating additional hazards for other passengers.

A different type of procedural option would involve curtailment of smoking by restricting the periods when it is allowed. For example, smoking could be allowed for a period of 10 minutes after every two hours of flight time, consistent with the earlier ban for flights shorter than

All of the work described in the report preceded passage of PL101-16d, which w111 ban smoking on all domestic commercial flights under six hours in duration.

TABLE 9-1. MAJOR OPTIONS CONSIDERED FOR MITIGATION OF ETS CONTAMINANTS

	Approach Required	
General Strategy	Technological	Procedural
1. Reduction of emissions		
- ban on smoking (total or partial)		X
- curtailment of smoking period		X
2. Contaminant removal/confinement		
- increased ventilation	X	
- local exhaust (smoking section)	X	
- smoking lounge	X	
- tiltrntionlsorption	X	
3. Exposure n nganent		
- separate smoking/nonsmoking flights		X
- stationing of flight attendants		X

two hours. In this case, consideration would need to be given to the possibility of substantially elevated ETS levels during the smoking period, since most smokers would probably smoke during this time.

The next set of options to be evaluated involves the notion of removal of ETS contaminants, rather than reduction of emissions. The rate of removal could be increased, for example, by increasing the amount of fresh-air intake to the airliner cabin. The extent to which fresh air could be added has n practical upper limit, however, related to the need to maintain a prescribed cabin pressure. An added benefit of this approach would be reduction of levels of some other pollutants (e.g., carbon dioxide) having sources within the cabin environment. Potential disadvantages could include the added fuel penalty associated with increased fresh-air intake, the need for increased thermal treatment of incoming air, potential increases in ozone levels, and potential decreases in relative humidity levels. The extent of contaminant removal due to increased ventilation can be modeled, and the associated fuel penalty can be estimated. Because both the strategy and the modeling of consequences are feasible, this option can be subjected to a quantitative assessment.

Local exhaust can be thought of as a special case of increased ventilation. This strategy would be most effective 1f combined with the concept of a smoking lounge, discussed below. Under the current configuration of smoking and no-smoking sections, the notion of local exhaust would essentially be tantamount to increasing the fresh-a1r supply to the smoking section only. Although there are some uncertainties related to technological feasibility and costs, the strategy is feasible and its potential consequences can be modeled.

Another special case of increased ventilation would involve the creation of a smoking lounge, which would also serve to confine ETS emissions. In a simplified form, this option would involve creating smoking sections of fixed size with physical barriers (e.g., walls/door or curtains) separating such compartments from nonsmoking sections. This option, while technologically feasible, would be inefficient (1) because of the need to create smoking/nonsmoking sections of fixed size, as opposed to the concept of a "sliding' boundary that is currently used to accommodate varying numbers of nonsmokers on smoking flights, and (2) because it would do little to reduce the risks of flight attendants assigned to or passing through the smoking section (as shown in Section 7.0, risks related to ETS exposures are estimated to be highest for flight attendants).

A truer version of the smoking-lounge concept would be construction of an actual lounge on one side of the plane toward the rear. This lounge could be "visited' by smokers wishing to smoke, much in the same sense as lavatories are currently visited by cabin occupants. The size of the lounge (and maximum occupancy) would obviously need to be limited, and emissions could be effectively contained by providing an independent exhaust system for the lounge. Flight attendants would not need to enter the lounge, thereby minimizing their exposures. Some challen9es in design and financing of the lounge, however, would be likely. Some of the costs could be recovered by charging a per-visit fee for the lounge. However, this approach would add some administrative burden, and the extent of costs recovered (both the cost of building the lounge and the cost of reduced seating capacity) would be somewhat difficult to predict. Thus, while potentially attractive, concepts for emissions confinement should be dismissed at this time as impractical to implement.

A third type of contaminant-removal option involves improved filtration of particle-phase ETS constituents or sorption of gas-phase constituents. Such an option obviously would be viable only for aircraft with recirculation capabilities, but the percent of aircraft with recirculation 1s expected to steadily increase in the future. Most aircraft with recirculation are currently equipped with some type of filter in the recirculation loop, and the efficiency of these filters can presumably be improved. Some potential drawbacks of filtration are (1) that filtration of only particle-phase constituents would not remove the gas-phase constituents that can cause odor and irritation, and (2) some gas-phase constituents, following removal by sorption, could conceivably volatilize and subsequently cause odor/irritation problems throughout the aircraft. Although some uncertainties are involved, modeling can be performed with assumptions involving efficiencies of currently installed filters and the extent of improvement that may be technologically feasible. Like the option of increased fresh-air intake, filtration may also achieve some reduction of pollutants other than ETS contaminants.

The last set of options involves the notion of exposure management rather than emissions reduction or contaminant removal. An extreme example would be to have separate smoking and no-smoking flights. Although such an approach would reduce exposures for nonsmoking passengers, it would not necessarily reduce flight attendants' overall exposures. The model required to assess the economic consequences of separate smoking and nonsmoking flights would be difficult to construct and would involve a number of assumptions. Even without such a model, it seams unlikely that such an approach would be economically viable. Thus, it should be dismissed at this time as impractical and having questionable benefits that cannot easily be modeled.

Another approach to exposure management would involve rotating flight attendants so that each is assigned to the smoking section only for some fraction of flights. This approach, however, would merely r distribute risk; the aggregate risk for flight attendants would not be reduced, and risks for nonsmoking passengers would be unaffected. Thus, the strategy would have no apparent benefits. A variation of this theme would involve recognition rather than reduction of risk. For example, flight attendants stationed in the smoking section could be offered "hazardous duty pay." The costs of increased risk could be estimated, translated into salary differentials, and the costs recovered through differential pricing for smoking and no-smoking seats. Such an approach, however, could affect passenger behavior (e.g., more smoking passengers opting for no-smoking seats, which would reduce ETS levels and associated risks for attendants), thereby adding a layer of assumptions and uncertainties to the assessment. Like the other options for exposure management, no benefits would accrue to nonsmoking passengers (unless ETS levels would actually decrease through this approach). Thus, approaches involving exposure management can be dismissed as having very limited benefits and posing some difficulties in econometric modeling needed to help determine the extent of any potential benefits.

Based on the above discussion, the following candidate approaches to ETS mitigation have been retained for further, quantitative analysis:

- Ban on smoking (total or partial)
- Curtailment of smoking period
- Increased intake of fresh air (including special case targeted at smoking section)
- Filtration/sorption of ETS contaminants.

9.2.2 Modeling of Cabin Air Quality

Model Description. Air quality modeling was performed to assess the potential impacts of alternative mitigation strategies on ETS concentrations in cabin environments. The focus of the modeling effort was on RSP, which was used as the ETS tracer 1n performing the risk assessment for chronic effects due to ETS exposure. A two-chamber model, depicted in Figure 9-2, was developed; this model, similar in concept to that described by Rynn et. al (1988), treats the smoking and no-smoking sections as separate compartments with communicating airflows. The model also allows contaminant emission rates to be specified for each compartment and incorporates supply airflow rates from fresh (makeup) air and recirculated air (where applicable) as well as return airflow from each compartment that is exhausted from the aircraft or recirculated.

The model can actually be thought of as a three-chamber model, with the supply airstream representing the third chamber. Under steady-state conditions (appropriate for predicting average concentrations chamber is as follows (the terms used below are defined in Figure 9-2):

$$Cs \cdot SA = CD \cdot MA + (1 - e) \cdot (C1\ RA1 + C2\ RA2)/(RA1 + RA2) \cdot (RAl + RA2 - E)$$

$$Cs \cdot SA1 + CZ \cdot F21 + S1 = C1\ (L1 + \ 1 + F12)$$

$$Cs \cdot SA2 + C1 \cdot F12 + S2 = C2\ CL2 + \ 2 + F21)$$

The above mass-balance description yields a system of three equations and three unknowns (Cs, C1, and C2) which can be obtained by solving the equations simultaneously. In solving he equations, fresh-air supply rates and interchamber airflow rates were based on PFT measurements.

Leakage rates were assumed to equal zero because no quantitative guidance was available for specifying these rates; thus, any leakage is captured in the term for exhaust flow rate, equal to the fresh-a1r intake rate by assumption. The return airflow rate incorporates recirculation airflow rates based on aircraft specifications (Lorengo and Porter, 1985). A filter efficiency of 90 percent for RSP removal was assumed for baseline modeling, based on information reported by Lorengo and Porter (1985). An emission factor of 26 mg/cigarette (NRC, 1986) was combined with technician observations of smoking rates to develop an hourly emission rate for each flight that was modeled. Supply airflow rates for each section of the aircraft were apportioned by volume, using the number of rows 1n each section as a proxy for volume. Return airflow rates were determined by flow-balance considerations, given supply and lnterchamber airflow rates.

Although PFTs were deployed to estimate airflow rates on study flights, practical limitations (i.e., the need for unobtrusive measurements) precluded obtaining meaningful measurement results in a number of cases. Ideally, PFT sources and samplers would have been distributed throughout each section (smoking and no-smoking) of the aircraft; however, logistical constraints restricted the approach to one release location and one sampling location per section. PFT measurement results were reviewed to determine cases for which results were most plausible, according to the following criteria:

(1) Measured ventilation rates for the aircraft determined by
two different PFT methods (single tracer common to both sections and trenchers unique to each section) were consistent
with one another and with maximum ventilation rates indicated by aircraft specifications.

(2) Interzonal airflow rates were positive but not excessively large.

The three flights chosen for modeling involved two types of narrow body aircraft (B-727 with no recirculation and ! -80 aircraft with recirculation) that collectively accounted for more than 50 percent of the flights monitored during the study. Selected characteristics of the aircraft and the i9hts used for RSP modeling are given in Table 9-2. The flights collectively provide a tan-to-twenty-told range in smoking rates and measured ETS concentrations 1n the smoking section.

The model described previously was chosen over the one developed by Rynn et al. (1988) because of the ability to include a filtration factor for recirculated air (important to the analysis of mitigation options related to filtration/sorption). However, the software for the Ryan et al. (1988) model was obtained from the principal author and applied to the case without recirculation that was listed in Table 9-2. The published model and the model developed specifically for the mitigation assessment yielded identical results when applied to this case.

nl Application. Results of baseline modeling for the three study flights, to be used as a benchmark for assessing various mitigation alternatives, are compared with measured RSP concentrations 1n Table 9-3. Although the modeling results are 9enerally lower than measured values, the general patterns of results are consistent. For example, both measured and modeled values indicate somewhat greater mitigation of RSP from the smoking to the no-smoking section for the 1-80 than for the B-727 aircraft, presumably due to air recirculation.

TABLE 9-2. SELECTED CHARACTERISTICS OF FLIGHTS/AIRCRAFT USED FOR RSP MODELING

	Flight		
Characteristic Model Input	1	2	3
Type of Aircraft	B-727	MD-80	MD-80
Number of Passenger Rows	21	33	38
(Number assigned to coach smoking)	(2)	(7)	(8)
Passenger Capacity	108	142	142
Observed Smoking Rate (cigarettes/h)	3	1	15
Measured Fresh-air Intake Rate, nr3/h	3,579	3,125	3,964
Percent Recirculation Air*	0	21	21
Chamber Airflow Rates, nr3/h			
- SA1	3238.0	3116.9	3960.9
- SA2	340.8	839.2	1056.2
- RA1	3058.5	3636.5	4036.6
- 2	520.3	319.6	980.5
F12	308.1	434.0	859.8
F21	128.6	953.6	935.5

* Per aircraft specifications

TABLE 9-3. MEASURED AND MODELED* RSP CONCENTRATIONS FOR THREE STUDY FLIGHTS

Flight/Section	RSP Concentrations, ug/m3	
	Measured	Modeled
Flight 1 (B-727)		
- no-smoking section**	31,g	4.7
- smoking section	233.5	122.4
Flight 2 (MD-80)		
- no-smoking section**	11.0	5.3
- smoking section	7.3	22.3
Flight 3 (MD-80)		
- no-smoking section**	86.3	44.2
- smoking section	302.0	224.3

* Baseline model, derived from measurements together with assumed recirculation rate of 21 percent and filter efficiency of 90 percent for MD-80 aircraft.

** Volume-weighted average of Gravimetric and optical measurements in boundary, middle, and remote locations.

Both the measured and modeled values also have sane uncertainties; 1n the case of modeled values, sources of uncertainty include emission, mixing, and deposition rates, fresh-a1r supply and lnterchamber airflow rates, the prevailing recirculation rate during a flight, and the filter efficiency for RSP removal.

As noted in Section 9.2.1, four alternatives for ETS mitigation were retained for further analysis:

- Ban on smoking (total or partial
- Curtailment of the smoking period
- Increased ventilation (including special case targeted at smoking section)
- Filtration/sorption of ETS contaminants.

The total ban on snaking requires no modeling; 1f this option were exercised, then RSP levels on current smoking flights would be reduced to those prevailing on non-smoking flights, and the incremental exposure and incremental risk would be zero. 51mllnrly, modeling is not required to assess the impact of partial bans; population exposures to ETS-related RSP would be reduced essentially in proportion to the reduction 1n number of flight hours during which smoking would be permitted (the reduction would not be exactly proportional because longer flights generally have larger aircraft capacities, greater percentages of time when the no-smoking light is not illuminated, and possibly different smoking rates than shorter flights).

A data file supplied by DOT, containing information on a11 flights scheduled for departure from U.S. airports during January 1989, was analyzed to determine the relative frequency: for domestic flights of different durations. The analysis was based on jet flights departing from 70 airports associated with large amounts of air traffic hubs, consistent with the sampling frame used for the study (see Section 2.4). The relative frequencies of flights and flight hours represented by flights of different durations (classified into hourly duration intervals) are summarized in Table 9-4. Flights under two hours in duration account for 44.5 percent of all flight hours. Thus, under the two-hour ban enacted in April 1988 under PL 100-202, smoking would be allowed during 55.5 percent of all flight hours. (A more detailed analysis, factoring in the specific policies of Northwest Airlines and United Airlines, indicated a revised figure of 54.3 percent.) A four-hour ban would limit smoking to 14 percent of all flight hours, and a six-hour ban would restrict smoking to 2 percent of all flight hours, as illustrated in Figure 9-3.

Two hypothetical scenarios were examined for curtailment of the smoking period:

- Restriction of smoking to a 10-minute period after every two hours of flight time

- Restriction of smoking to a 10-minute period after every hour of flight time

The impact of each scenario on the smoking rate (cigarettes per flight) was estimated for each domestic smoking flight monitored during the study by assigning that each passenger seated in the smoking section would smoke one cigarette during each period when smoking was allowed. On the average, the first scenario would lower total smoking per flight by about 70 percent (i.e., from 51.9 to 15.2 cigarettes/flight) and the second scenario would reduce total smoking by about 25 percent (from 51.9 to 39.8 cigarettes/flight). Each of the flights previously chosen for modeling was modeled with these reductions in the smoking rate. As shown in Table 9-5, the reduction in average RSP concentrations in both the no-smoking and the smoking sections was proportional to the reduction in smoking rate in all three cases. However, as noted earlier, short-term peaks in RSP and gas-phase ETS constituents could rise sharply if smoking periods were restricted, thereby increasing irritation and discomfort for flight attendants and passengers.

The impact of the increased fresh-air intake rates was first examined for the flight with the highest smoking rate (flight 3).

TABLE 9-4. RELATIVE FREQUENCIES FOR DOMESTIC FLIGHTS OF DIFFERENT DURATIONS

Flight Duration	Percentage of Flights	Percentage of Flight Hours
C 1 hour	17.6	7.4
1-1.99 hours	48.7	37.1
2-2.99 hours	21.3	28.1
3-3.99 hours	7.2	13.4
4-4.99 hours	3.2	7.6
5-5.99 hours	1.5	4.3
) 6 hours	0.6	2.1
Total, all durations	100.0	100.0

TABLE 9-5. PREDICTED RSP CONCENTRATIONS FOR THREE STUDY FLIGHTS WITH HYPOTHETICAL REDUCTIONS IN SMOKING DUE TO CURTAILMENT OF SMOKING PERIODS

Case Modeled	RSP Concentration, uglm3 No-smoking Section	Smoking Section
Flight 1		
- no curtailment (base case)	4.7	122.4
- ten-minute smoking period every hour (total smoking reduced by 25 percent)	3.5 (25X)*	91.8 (25X)
- ten-minute smoking period every two hours (total smoking reduced by 70 percent)	1.4 (70X)	36.7 (70X)
Flight 2		
- no curtailment (base case)	5.3	22.3
- ten-minute smoking period every hour (total smoking reduced by 25 percent)	4.0 (25X)	16.8 (25X)
- ten-minute smoking period every two hours (total smoking reduced by 70 percent)	1.6 (70X)	6.7 (70X)
Flight 3		
- no curtailment (base case)	44.2	224.3
- ten-minute smoking period every hour (total smoking reduced by 25 percent)	33.2 (25X)	168.2 (25X)
- ten-minute smoking period every two hours (total smoking reduced by 70 percent)	13.3 (70X)	67.3 (70X)

* Numbers in parentheses indicate percent reduction in concentration from the base case.

Hypothetical increases of 25, 50, 75 and 100 percent in fresh-air intake were modeled. The results displayed in Figure 9-4 indicate a curvilinear relationship between increase in fresh-air intake and RSP concentration in either section; however, the relationship is more direct than indicated -- when the intake rate is doubled, the concentrations are halved. Thus, for example, to reduce concentrations by an order of magnitude, a tenfold increase in fresh-air intake would be required. However, such an increase is not likely achievable, and resultant airflows in the cabin would cause intolerable drafts for passengers. In addition, as noted earlier, ozone concentrations in the cabin could increase and relative humidity levels could decrease.

The impact of a more likely achievable 50-percent Increase in the fresh-a1r intake rate is shown for each of the three modeled flights in Table 9-6. In each case, concentrations 1n both the no-smoking and smoking sections are reduced by one-third; that is, the concentrations with a 50-percent increase 1n fresh-a1r intake are two-thirds of their original values, consistent with the ratio of the old-to-new intake rate (i.e., 1/1.5 or 0.67).

A special case of increased fresh air is increasing the amount supplied to the smoking section only. If the fresh air supplied to the smoking section is increased by 50 percent, the overall increase is only 10.5 percent (because the smoking section accounts for only 21 percent of the total airflow). Although the reduction in RSP concentrations (23 percent, as shown in the bottom portion of Table 9-6) is less than that achieved with a 50-percent increase in fresh air to the entire cabin, the relative effectiveness is greater; the ratio of concentrations is 0.77 (i.e., 34.2/44.2 for the no-smoking section and 172.6/224.3 for the smoking section) whereas the ratio of 1nflltrntion rates for the aircraft is 0.9 (1/1.105). An assumption 1n modeling this case was that increased air supply to the smoking section would be compensated by increased exhaust from that section; otherwise, the smoking section would be over- supplied, increasing the flow rate from the smoking to the no-smoking

TABLE 9-6. PREDICTED RSP CONCENTRATIONS FOR THREE STUDY FLIGHTS WITH A HYPOTHETICAL INCREASE IN THE FRESH-AIR INTAKE RATE

Case Modeled	RSP Concentration, ug/m3 No-Smoking Section	Smoking Section
Flight 1		
- no increase (base case)	4.7	122.4
- 50-percent increase	3.1	81.6
	C3)*	(33X)*
Flight 2		
- no increase (base case)	5.3	22.3
- 50-percent increase	3.6	14.8
	(33X)	(33X)
Flight 3		
- no increase (base case)	44.2	224.3
- 50-percent Increase	29.5	149.5
	(33X)	(33X)
- 50-percent increase for smoking section only	34.2 (23X)	172.6 (2)

* Numbers in parentheses indicate percent reduction in concentration from the base case.

section. As a result, RSP levels 1n the smoking section would decrease even further, but levels in the no-smoking section would increase.

The impact of filtration was examined in greatest detail for the flight with the highest smoking rate. The MO-80 aircraft for this flight has a specified air circulation rate of 21 percent (i.e., 21 percent of the air supplied to the cabin is recirculated air). RSP concentrations were modeled with hypothetical filter efficiencies of 0 (i.e., no filter), 0.3, 0.6, 0.8, 0.9, 0.95 and 0.99 (filters currently in use on aircraft are thought to have RSP removal efficiencies in the neighborhood of 0.9). As illustrated in Figure 9-5, overall RSP reductions are less than proportional to filter efficiency, because filtration competes with fresh air for RSP removal and only a fraction of the cabin air 1s recirculated through the filter. A change in filter efficiency from 0 to 0.99 would reduce RSP concentrations for this flight by 33 percent in the no-smoking section (from 63.2 to 42.7 ug/m3) and by 8 to 9 percent in the smoking section (from 243.3 to 222.8 ug/m3).

Increased filter efficiency would provide no benefit for aircraft with no recirculation capability, such as the B-727 for flight 1. For flights 2 and 3 (MD-80 aircraft), the effect of increasing filter efficiency from 90 to 99 percent was modeled. As shown in Table 9-7, minor reductions in RSP (less than 5 percent) would be achieved with more efficient filters. Because some aircraft have higher recirculation rates (up to 50 percent), flight 3 was also modeled with an MD-80 aircraft having a hypothetical recirculation rate of 50 percent. As shown in the lower portion of Table 9-7, RSP concentrations for the base case (90-percent filter efficiency) were slightly higher with 50-percent recirculation than with 21-percent recirculation. The RSP reductions due to improved filter efficiency are projected to be somewhat greater 1f the aircraft had 50 - percent recirculation, but the reductions are still less than 10 percent.

Similarly, the RSP reductions due to improved filtration will be somewhat greater if the current filter efficiency is below 90 percent; however, as shown previously in Figure 9-5, the percent reduction due to filtration is relatively insensitive to filter efficiency.

TABLE 9-7. PREDICTED RSP CONCENTRATIONS FOR TWO STUDY FLIGHTS WITH A HYPOTHETICAL INCREASE IN FILTER EFFICIENCY

Case Modeled	RSP Concentration, ug/m3 No-smoking Section	Smoking Section
Flight 2 (MD-80 with 21 percent recirculation)		
- 90-percent filter efficiency (base case)	5.9	22.3
- 99-percent filter efficiency	5.2	22.2
	( )*	((IX)
Flight 3 (MP-80 with 21 percent recirculation)		
- 90-percent filter efficiency (base case)	44.2	224.3
- 99-percent filter efficiency	42.7	222.8
	)	(1X)
Flight 3 (MD-80 with hypothetical recirculation of 50 percent)		
- 90-percent filter efficiency	46.6	226.7
- 99-percent filter efficiency	42.9	223.0
	(8X)	(2X)

* Numbers in parentheses indicate percent reduction in concentration from the base case.

9.2.3 Cost-Benefit Analysis

A correlate cost-benefit analysis of alternative mitigation strategies would include a full accounting of all categories of costs and benefits. Mitigation costs include not only the cost of the technical approach, but the losses (1f any) to smokers required to modify their behavior, and, if appropriate, losses in profits to airlines to the extent that smokers fly less often. Economists would measure losses to smokers as their willingness to pay (WTP) to avoid having their behavior modified. This type of measure has been applied with reasonably high replicability of results in other contexts, but not to the issue of valuing smokers' WTP.

In the analysis below, only technical costs are considered, because of lack of information on thc other cost categories. This limitation means that procedural approaches are given zero cost, clearly an underestimate.

On the benefit side, mortality, morbidity, and comfort considerations dominate. Mortality reductions and their associated economic benefits (measured in terms of the WTP for a reduction 1n the risk of death divided by the given risk reduction) are estimated below. The linkages between passive ETS exposure and morbidity (acute effects, such as eye irritation, exacerbation of chronic conditions, say by helping initiate an asthma attack, and increase in the probability of developing chronic conditions) are not well enough understood to include these effects (although estimates of the WTP for these effects exist in the economics literature).

Comfort effects related to odor or other effects that might be part of the WTP of nonsmokers to have their ETS exposure reduced also cannot be included because of data limitations. Because a ban on smoking has to have the largest quantifiable benefit but a zero (quantifiable) cost, it must appear as the best approach, subject to the incomplete analysis.

Benefit calculations for the mitigation analysis focused on reductions in risk of lung cancer mortality due to ETS exposure, using RSP as a tracer. To treat mortality risks in monetary terms, estimates are needed either for the w>llingness to pay to avoid specific risks of death or an assumed value of a statistical life (VSL).2 The most recent valuation and wage-risk studies provide YSL estimates in the range of 2 to 5 million (Viscusi, 1986). A value of 3.75 million was chosen for this analysis, consistent with recent EPA assessments (Fisher et al. 1987).

Use of the VSL approach requires that the results of the risk assessment be translated into annual expected premature lung cancer deaths due to ETS exposure for the flying population, including both passengers and flight attendants. Based on the estimated cancer risks per 100,000 cabin occupants provided in Section 7.0, estimated annual deaths to be expected in the absence of any ban on smoking for domestic flights are 0.44 for passengers and 0.34 for flight attendants (see Table 9-8). The estimated annual deaths given here are higher than those given in Section 7.0 because the estimates in Table 9-8 assume that smoking would be allowed on all domestic flights, whereas the estimates in Section 7.0 assume that smoking would be allowed only on flights of two-hour or longer durations. Given a YSL of 53.75 million, the expected deaths in Table 9-8 translate into annual economic values of 1.65 million and 51.28 million, respectively. There are also increments in morbidity due to ETS exposure that have not been taken into account.

Projected annual benefits and costs of alternative mitigation options are given 1n Table 9-9. The greatest benefit (2.93 million) would result from a total ban on smoking; benefits other than reduced mortality risk could accrue, for example, from reduced maintenance (e.g., changing of filters) or cleaning costs in the absence of smoking. There are no direct costs of implementing such a ban, although dollar values could conceivably be attached to smokers inconvenience and discomfort.

2 The VSL can be thought of as the average willingness to pay for a given reduction in mortality risk, divided by the risk reduction. Thus, if 1,000 individuals are willing to pay an average of 2,000 for a 11,000 reduction in mortality risk, than the average VSL is 2 million.

TABLE 9-8. ESTIMATION OF ANNUAL EXPECTED DEATHS DUE TO PASSENGER AND FLIGHT ATTENDANT EXPOSURES TO ETS WITH UNRESTRICTED SMOKING ON DOMESTIC FLIGHTS

Passengers

418 million enplanements per year for domestic flights*
x 1.84 (hours per flight)**
million passenger-hours per year
x .9375 (fraction of time smoking allowed)***
'fl million passenger-hours per year with smoking permitted
= 45 (hours per year per flying passenger used in risk assessment)
million people flying 45 hours per year
= 40 (average lifetime for flying used in risk assessment)
million lifetimes of flying 45 per hours per year
x 1.1 (deaths per million flying lifetimes)
expected deaths per year due to ETS exposure

Flight Attendants

56 thousand flight attendants flying 900 hours/year on domestic flights
= 20 (average lifetime for flying used in risk assessment)
thousand lifetimes of flying 900 hours per year
x 0.12 (deaths per thousand flying lifetimes)
expected deaths per year due to ETS exposure

* Source: NRC (1986)
** Based on analysis of data file provided by FAA
*** Assuming no-smoking light is illuminated 6.25 percent of the time

TABLE 9-9. PROJECTED ANNUAL BENEFITS AND COSTS FOR ALTERNATIVE MITIGATION STRATEGIES TO REDUCE ETS EXPOSURES

Strategy	Exposure Reduction	Annual Benefits (million) Passengers	Attendants	Annual Costs (million)
Total ban on smoking	l00X	1.65	1.28	0*
Partial ban on smoking				
-flights under two hours	45X	0.74	0.58	0
-flights under six hours	98X	1.62	1.25	0
Curtailment of smoking				
- 10 minutes every 2 hours	70X	1.16	0.90	0
- 10 minutes every hour	25X	0.41	0.32	0
Increased fresh-air intake				
- 50 percent for entire cabin	33X	0.54	0.42	30.8 to 51.5
- 50 percent for each smoking	237G	0.38	0.29	6.2 to 10.3
Increased filter efficiency** (from 90 to 99 percent)	4-5X***	0.08	0.06	****

* Assuming that a value can be placed on smokers inconvenience and discomfort (e.g., willingness to pay for the right to smoke on aircraft), some costs could be estimated; however, no studies to provide such inputs have been identified. Costs could conceivably be estimated for losses in ridership due to smokers opting for other modes of transportation.

** Assuming that all aircraft have recirculation and filters

*** 4.8 percent for passengers, 4.5 percent for attendants

**** Cost information could not be obtained.

However, there are currently no studies of smokers' willingness to pay for the right to smoke on aircraft. There could be losses in airline ridership due to smokers opting for other modes of transportation, but such losses could not be estimated in this study. In addition to partial smoking bans, options to curtail smoking also provide significant benefits at no apparent cost, particularly the option of a 10-minute smoking period every two hours. Such an option would, however, substantially raise short-term ETS levels and thereby increase acute health responses. For example, application of a steady-state model to the third flight (MD-80 - with 25 smoking passengers) indicates that CO levels in the smoking section could be as high as 5 ppm if all passengers smoked during the 10-minute smoking period. The data from Cain et al. (1987) indicate that 10 percent of nonsmokers exposed to 5-ppm CO (due exclusively to tobacco smoking) for 10 minutes would express dissatisfaction due to eye irritation.

The other options listed in Table 9-9 either have costs that substantially exceed benefits (increased fresh-air intake) or very limited benefits (increased filter efficiency). Several manufacturers were contacted in an attempt to obtain estimates of filter costs, but the manufacturers were reluctant to divulge this information. Although the fuel penalty for increased fresh-air intake is quite small on a per-flight basis (10 to 20), the aggregate costs are substantial. The fuel cost penalty was estimated from the relationship shown in Figure 9-6, which was derived from data provided in an NRC report (1986). The incremental fuel cost for a 50-percent increase in fresh-air intake ranges from 0.04 per passenger-hour for OC-10-10 aircraft to 0.067 for a B-727 aircraft. Multiplication by 769 million passenger-hours per year (see Table 9-8) yields an estimated cost range of 30.8 to 51.5 million for added fuel requirements.

9.3 APPLICATION OF FRAMEWORK TO POLLUTANTS

9.3.1 Cosmic Radiation

As noted earlier in this section, there are no practical approaches for reducing cosmic radiation levels on aircraft. Thus, the

only potential mitigation route involves the notion of exposure management. Through this strategy, excessive exposures could be reduced by avoiding extreme northern or southern latitudes and high altitudes where possible. Exposure management could also focus on specific types of personnel facing higher risks, such as female flight attendants in different stages of pregnancy, particularly the first trimester. This type of mitigation strategy applies equally to flight crew members, cabin crew members, and passengers.

9.3.2 Carbon Dioxide

Risk assessment was not performed for carbon dioxide (C02) because health effects of C02 exposure (other than those above occupational guidelines) have not been documented. Nonetheless, C02 levels exceeding 1,000 ppm, the level recommended by ASHRAE for satisfaction of comfort criteria, were measured on a substantial fraction of the monitored flights. Consequently, alternatives for reducing C02 levels in airline cabins were investigated but no cost-benefit analysis could be performed.

There are three types of options for reducing C02 levels -- emissions reduction, increased ventilation, and removal by sorption. C02 removal could be achieved, for example, by passing air through an adsorbent bed mounted on a rotating drum or revolving belt (White 1989). Regeneration of the adsorbent would permit hlgh capacity with low bed volume and weight. Continuous regeneration of the adsorbent would be accomplished by passing a small amount of purified air through a heated portion of the bed, then exhausting overboard the heated air containing high concentrations of C02. Alrcraft waste heat from the lubrication oil system or englne exhaust gas would be used as the heat source for regeneration.

Emlssions could be lowered by reduction of seating capacity, but this approach is not likely to be economically attractive to the airline industry. The potential effectiveness of remaining options, involving ventilation or removal, was investigated through modeling. Because the C02 sourccs (passengers and crew) are spread throughout the cabin, a single-chamber model can be used. Using similar terminology to that used for the two-chamber model described earlier in this section (see Figure 9-2), the model for C02 in the cabin (Cin) can be stated as follows:

$$\text{Cin} = \frac{\text{Cout}' \quad + S}{(RA + L) - (1 - e) \cdot (SA \cdot\cdot \quad MA)}$$

The flights used previously for RSP modeling were also used for this modeling exercise. An emission rate of Q.3 1/min (18,000 ml/h) per passenger and an outdoor concentration of 330 ppm were assumed in making the calculations. The aircraft were assumed to be at full capacity--108 passengers for B-727 aircraft and 142 passengers for MD-80 aircraft.

C02 concentrations related to ventilation rates (currently measured levels and hypothetical increases up to 100 percent) are shown in Table 9-10. Concentrations are projected to decrease by about a third if the fresh-air intake rate were to be doubled. Thus, some flights with C02 levels above 1,000 ppm would likely remain under this scenario. As discussed earlier, this mitigation option would carry a fuel penalty and could also increase ozone levels and decrease humidity levels.

C02 concentrations related to filter removal efficiencies (zero assumed as current efficiency) are given in able 9-11. (Discussions with a filter manufacturer indicated that removal efficiencies in the neighborhood of 50 to 75 percent may be attainable.) At a 50 percent removal efficiency, C02 levels could be reduced by 12 percent for current MD-80 aircraft (21 percent recirculation) air by 33 percent 1f the recirculation rate were as high as 50 percent).

9.4 REFERENCES

Cain, W.S., T. Tarik, L. See, and B. Leaderer. 1987. "Environmental Tobacco Smoke: Sensory Reactions of Occupants." Atmos. Environ. 21(2):347-353.

Fisher, A., D. Violette, and L. Chestnut. 1987. The Value of Reducing Risks of Death: A Note on New Evidence. Draft report, U. . Environmental Protection Agency.

TABLE 9-10. PREDICTED C02 CONCENTRATIONS FOR THREE STUDY FLIGHTS WITH HYPOTHETICAL INCREASES IN THE FRESH-AIR INTAKE RATE

Ventilation Rate	C02 Concentration, ppm Flight 1	Flight 2	Flight 3
Current level (base case)	873.2	1147.8	g74,g
Increase of 25 percent	764.6 (12.4X)*	984.3 (14.2X)	845.9 (13.2X)
Increase of 50 percent	692.1 (20.7X)	875.2 (23.7X)	75g,g (22.1X)
Increase of 75 percent	640.4 (26.7X)	797.3 (30.5X)	698.5 (28.4X)
Increase of 100 percent	601.6 (31.1X)	738.9 (35.6X)	652.4 (33.1X)

* Numbers in parentheses indicate percent reduction in concentration from the base case.

TABLE 9-11. PREDICTED C02 CONCENTRATIONS FOR TWO STUDY FLIGHTS WITH HYPOTHETICAL INCREASES IN FILTER EFFICIENCY

	C02 Concentration, ppm		
Filter Efficiency	Flight 2 (21X recirc.)	Flight 3 (21X recirc.)	Flight 3 (50X recirc.)*
Zero (base case)	1147.0	974.9	1348.9
25 percent	1076.3 (6.2X)**	914.1 (6.2X)	1079:1 (2O.OX)
50 percent	1013.2 (11.7X)	860.5 (11.7X)	89g,3 (33.3X)
75 percent	957.0 (16.6X)	812.8 (16.6X)	770.8 (42.9X)

* Hypothetical recirculation rate for MD-80 aircraft.
** Numbers in parentheses indicate percent reduction in concentration from the base case.

Lorengo, D.G., and A. Porter. 1985. Aircraft Ventilation 5 stems Stud . Final Report DTFA-03-84-C-0084. Atlantic City, NJ: U. . Federal Aviation Administration Technical Center.

National Research Council. 1986. Environmental Tobacco Smoke: Measuring Exposures and Assessing Health Effects. National academy Press. Washington, D.C.

Ryan, P.B., J. Spengler, and P. Halfpenny. 1988. "Sequential Box Models for Indoor Air Quality: Application to Airliner Cabin Air Quality". Atmos. Environ. 22(6):1031-1038.

U.S. Department of Transportation, Federal Aviation Administration. 1987. Airport Activity Statistics of Certificated Route Air Carriers: Twelve Months Ending December 1, 19 7. U. . department of transportation, Washington, 0. .

Viscusi, W.K. 1986. "The Valuation of Risks to Life and Health." In Bentkover et al., Benefit Assessment: The State of the Art. Dordrecht, Holland, Reidel Publishers.

Whlte, O.H. 1989. "Modern Aircraft Cabin Air Purification Including Carbon Dioxide Removal." Pall Corporation, Glen Cove, NY.

Section 10.0
CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

10.1.1 Measurement Methods and Results

The flights that were randomly chosen for monitoring in this study proved to be representative of the population of flights departing from major U.S. airports. Distributions of the monitored flights by airline and type of aircraft were very similar to those for all scheduled commercial jet aircraft flights.

Levels of particle-phase ETS contaminants monitored during the study were substantially higher in smoking sections of the aircraft than in nonsmoking areas. Respirable suspended particle (RSP) concentrations in the coach smoking section averaged about 175 ug/m3. The average RSP concentration in the no-smoking section near coach smoking (i.e., boundary region) was near 55 ug/m3, and RSP concentrations averaged about 35 ug/m3 in other no-smoking areas and on nonsmoking flights. These averages are based on combined results from two measurement methods -- optical and Gravimetric. One-minute peak RSP concentrations measured with optical sensors were more than ten times higher in the smoking section, and three times higher in the boundary region, than in the no-smoking areas on smoking flights. Measured RSP levels in the boundary region were most strongly correlated with observed smoking rates in the coach smoking section (i.e., higher levels when smoking rates were higher) and distance from the coach smoking section (i.e., higher levels at shorter distances).

Levels of gas phase ETS contaminants that were monitored were also highest in smoking sections. Nicotine concentrations averaged near 13.5 ug/m3 in the coach smoking section, near 0.25 ug/m3 in the boundary region within the no-smoking section, and near or below 0.05 ug/m3 in other no-smoking areas and on nonsmoking flights. CO concentrations averaged near 1.4 ppm in the coach smoking section, near 0.7 ppm in no-smoking areas of smoking flights, and 0.6 ppm on nonsmoking flights.

Levels of these ETS tracers in the boundary region were not strongly correlated with observed smoking rates or distance from the coach smoking section.

Two separate techniques for estimating smoking rates on each monitored flight provided consistent results. Estimates based on technician observations of the number of lighted cigarettes during a one-minute interval every 15 minutes agreed well with estimates based on cigarette butts collected by technicians at the end of most smoking flights. An average of 20 cigarettes per hour, or 68 cigarettes per flight, was smoked by passengers in the coach smoking section on smoking flights that were monitored; an average of 13.7 percent of passengers were assigned to the coach smoking section.

Carbon dioxide (CO2) levels on flights monitored during this study were frequently above the level recommended by ASHRAE (1,000 ppm) to satisfy comfort (odor) criteria. CO2 concentrations on the monitored flights averaged above 1,500 ppm and exceeded 3,000 ppm on several occasions. Measured concentrations were 1,000 ppm or greater on 87 percent of the monitored flights, and the C02 levels were most strongly related to the number of passengers in the airliner cabin; on the average, 70 percent of the seats were occupied on the flights monitored in the study. Depending on assumed C02 exhalation rates, measured levels were as much as twice those predicted by a cabin air quality model. Even if the measured levels were to be lowered by half, however, C02 concentrations would still exceed 1,000 ppm on 24 percent of the study flights.

Relative humidity levels on monitored flights were quite low, averaging near 15 percent on smoking flights and near 20 percent on nonsmoking flights. Humidity levels were below 25 percent, outside the range indicated by ASHRAE for provision of adequate thermal comfort, on about 90 percent of all monitored flights. Temperatures in the cabins of monitored aircraft averaged near 24 oC (75 oF) for both smoking and nonsmoking flights and were within ASHRAE's comfort range.

Average levels of other pollutants (ozone, bacteria, and fungi) were relatively low on virtually all monitored flights. Measured levels of ozone did not exceed the FAA 3-hour standard of 0.1 ppm or the current EPA standard of 0.12 ppm on any of the monitored flights. The highest ozone level measured was 0.08 ppm, and the average measured level was between 0.01 and 0.02 ppm. Measured bacteria levels were somewhat higher in the smoking than no-smoking sections of monitored smoking flights, and the average level in the no-smoking section on these flights was nearly identical to that on nonsmoking flights. Measured fungi levels were somewhat higher on nonsmoking flights than smoking flights, but the bacteria and fungi levels in all cases were low, relative to those that have been measured in other environments.

The method used in the study to measure air exchange rates was generally adequate for aircraft with recirculation but was inadequate for other types of aircraft. The measurement method, involving release and sampling of perfluorocarbon tracers, was less effective on aircraft without recirculation because of the limited extent of lateral air movement on such aircraft. This limitation could have been overcome by increasing the number of tracer release and sampling locations, but such a strategy was deliberately avoided in this study in order to remain unobtrusive to passengers and flight attendants during monitoring.

The strategy of monitoring at multiple seat locations provided important insights regarding spatial variations in cabin air quality, particularly for ETS contaminants. This strategy provided some indications that the boundary region in the no-smoking section was affected by coach smoking, in addition to the distinct effects in the smoking section itself, and that spatial variations were relatively minor for CO2 and other pollutants (ozone, bacteria, and fungi) that were monitored.

The strategy of continuous monitoring where practical, combined with integrated sampling, also provided some important insights concerning cabin air quality. Continuous monitoring results provided the strongest indication of an effect of smoking in the no-smoking boundary region.

10.1.2 Risk Assessment

The risks faced by cabin crew members and passengers depend on such factors as frequency of flying, number of years flown, specific routes flown, and, in the case of ETS exposures, seat locations and prevailing smoking rates. The study conclusions pertaining to cancer risks are based on specific scenarios relating to number of hours per year in flight, number of years flown, and, in the case of ETS exposures, proportion of time spent in the smoking section, boundary region near smoking, and other no-smoking areas. Detailed descriptions of the scenarios and calculations underlying the risk estimates given herein are provided in Section 7.0 for ETS and in Section 8.0 for cosmic radiation. Estimates for cabin crew members relating to ETS exposure pertain only to flight attendants and do not include the cockpit crew.

ETS

Estimated lifetime lung cancer risks ascribable to ETS exposure for nonsmoking cabin crew members flying 960 hours per year on smoking flights for 20 years range from 12 to 15 premature cancer deaths per 100,000 nonsmoking cabin crew members for domestic flights and from 13 to 17 premature cancer deaths per 100,000 for international flights. The range of estimates was derived from two different cancer risk models (a phenomenological model and a multistage model) that assume different durations of exposure.) Applying these risk estimates to the entire U.S. cabin crew population results in an estimated 0.18 premature lung cancer deaths per year for domestic flights (that is, approximately 4 premature deaths can be expected every 20 years) and 0.16 premature deaths per year for international flights.

Estimated Lifetime lung cancer risks due to ETS exposure for nonsmoking passengers flying 480 hours per year on smoking flights for

30 years range from 0.3 to 0.8 premature cancer deaths per 100,000 nonsmoking passengers for domestic flights and from 0.2 to 0.6 premature cancer deaths per 100,000 for international flights. The range of estimates was derived from the two cancer risk models mentioned above, and the relatively broad range is due to differences in assumed durations of exposure and the sensitivity of the multistage model to assumptions concerning the age at which exposure begins.

Estimated lifetime lung cancer risks due to ETS exposure for nonsmoking passengers flying 48 hours per year on smoking flights for 40 years are approximately 0.1 premature cancer deaths per 100,000 for both domestic and international flights. Applying these risk estimates to the U.S. flying population results in an estimated 0.24 premature lung cancer deaths per year for domestic flights (that is, approximately 10 premature deaths can be expected every 40 years) and 0.12 premature deaths per year for international flights.

In terms of acute effects based on CO concentrations as a proxy for ETS levels, it is estimated that on one-third of smoking flights about 1 in 8 persons seated in the smoking section would experience irritation due to ETS exposure. Further, it is estimated that on about one-third of domestic smoking flights, ETS levels in the smoking section (based on nicotine concentrations as a proxy) would be sufficiently high to evoke a marked sensory response in the eye and nose of an airliner cabin occupant.

Differential effects of ETS and its constituents on such sensitive populations as asthmatics, children, and persons with ischaemic heart disease or other cardiovascular disease could not be estimated.

<u>Cosmic Radiation</u>

Estimated lifetime cancer risks due to cosmic radiation exposure for cabin crew members flying 960 hours per year range from 90 to 1,026 premature deaths per 100,000 individuals flying for 20 years on domestic flight: and from 220 to 512 premature deaths per 100,000 individuals flying for 10 years on international flights. The estimates, which pertain to cockpit crew members as well as cabin crew members, are lowest for relatively short north-south domestic flights and higher for coast-to-coast flights involving higher altitudes. The highest estimates are for relatively long, circumpolar international flights which also occur at high altitudes.

Estimated lifetime cancer risks due to cosmic radiation exposure for passengers flying 480 hours per year range from 45 to 513 premature deaths per 100, 000 individuals flying for 20 years on domestic flights and from 110 to 256 premature deaths per 100,000 individuals flying for 10 years on international flights. Like the above estimates for cabin crew, the range is governed largely by flight altitudes and latitudes. Another concern is the effect of cosmic radiation on a fetus, particularly during the first trimester.

Other Pollutants

The levels of bacteria and fungi measured in the airliner cabin air in this study were found to be below the levels generally thought to pose risk of illness. Because quantitative dose-response information on the health risks of biological aerosols was not available, the evaluation of the concentration data was performed by placing the prevalence of individual genera that were identified in rank order, and comparing the prevalence to biological aerosols in other indoor environments. The levels and genera measured in the cabin environment were similar to or lower than those commonly encountered in indoor environments characterized as "normal."

It was unnecessary to perform a risk assessment for ozone because measured levels on all monitored flights were well below the current FAA and EPA standards.

10.1.3 Mitigation

Among the methods evaluated for reducing risks due to ETS, a total ban on airliner cabin smoking would eliminate ETS exposure in airliner cabins and yield the greatest benefit to flight attendants *and nonsmoking passengers.* A total ban on smoking on domestic flights is estimated to result in an annual benefit of approximately 3 million to cabin crew and passengers, based on reduced mortality risks. In conducting this benefit/cost analysis, reduction in mortality and associated economic benefits were considered but benefits relating to reduced morbidity were not. Possible costs related to smokers' inconvenience and discomfort or to displacement of smokers to other modes of transportation were not considered due to limited data.

Beyond the two-hour ban that reduces ETS exposures on domestic flights by approximately 45 percent, more restrictive bans could be implemented to reduce exposures by as much as 98 percent. Restricting smoking to flights of a 6-hour or greater duration would reduce ETS exposures by approximately 98 percent. and a restriction for flights of 4 hours or longer would reduce exposures by about 86 percent. A different type of strategy to curtail smoking, such as allowing smoking for a 10-minute period every two hours, could reduce average exposures to ETS by as much as 70 percent. Such a strategy, however, could substantially increase the risks of health effects from acute exposure during the brief periods when smoking would be allowed.

Two other mitigation measures -- increased ventilation and improved filter efficiency -- would reduce ETS exposures by lesser amounts, ranging from 5 to 33 percent. Annual costs of increased ventilation (6 to 50 million), which could reduce ETS exposures by as much as 33 percent, are substantially higher than the benefits (0.7 to 1.0 million) that could be calculated within the constraints of this study. Costs related to improved filter efficiency were not available, but improved efficiency would provide only a marginal reduction (5 percent) in ETS exposures.

Exposure management is the only viable option for reducing cabin crew member and passenger exposures to cosmic radiation. In the case of crew members, this strategy would involve careful scheduling of personnel to avoid persistent exposure to higher cosmic radiation levels generally associated with high-altitude flights and flight paths toward extreme northern or southern latitudes.

On aircraft with recirculation, C02 could be removed by sorption on solid adsorbent beds whose adsorbent capacity for C02 can be regenerated by heating. Increased ventilation could also bring C02 levels closer to the guidelines specified by ASHRAE. Cost or reliability data for a sorption system were not available for comparison with costs of additional ventilation.

In view of the low levels observed for ozone and biological aerosols, mitigation strategies were not assessed for these pollutants.

10.2 RECOMMENDATIONS

10.2.1 Actions for Improving Cabin Air Quality

Considerations should be given to a total ban on smoking on all flights departing from or arriving at U.S. airports as a means of eliminating the ETS risks currently faced by nonsmoking passengers and nonsmoking cabin crew members. The estimated benefits of such a strategy exceed the costs, based on currently available data. In considering this ban, consideration will need to be given to smokers inconvenience and discomfort, possible economic consequences of displacement of smokers to alternative transportation modes, and other potential consequences such as smoker withdrawal symptoms. Possible alternatives include limiting smoking to longer-duration flights or restricting the time periods when smoking is allowed on flights. In the latter case, further study would be needed of the potential health effects from acute exposure that could occur during the limited periods when smoking would be allowed.

Airlines should implement exposure management strategies to reduce risks faced by cabin crew members, particularly those related to cosmic radiation. Such strategies would include careful scheduling of personnel, especially those at highest risk, to avoid persistent higher exposures associated with flight paths at extreme northern/southern latitudes and higher altitudes.

Sorption should be considered as a means of reducing C02 levels in airliner cabins. The feasibility of implementing this approach needs to be further explored, along with potential costs, benefits, and practical considerations. Such an approach, or increased ventilation, could also reduce levels of other potentially hazardous chemicals, such as volatile organic compounds that were not measured during this study.

No actions need to be taken to reduce currently prevailing levels of ozone or biological aerosols. The types of preventive strategies that are currently in place for ozone, which may be partly responsible for the relatively low levels measured during this study, should be continued.

10.2.2 Information Needs

Due to constraints of unannounced and unobtrusive monitoring required to meet study objectives, this study could not take full advantage of the currently available state-of-the-art instrumentation for pollutant monitoring. Based on observations and conclusions from this study, the following areas of further study are recommended:

Additional measurements of C02 should be performed in commercial airliner cabins. Such measurements need to be conducted with continuous monitoring devices on different types of aircraft and at different levels of passenger occupancy.

A study of flight attendants' exposures with personal monitors should be conducted if a total ban on smoking is not enacted. Due to study limitations, flight attendants' exposures could not be estimated directly. A personal monitoring study of flight attendants would improve estimates of exposures by accounting for the different breathing height from that of passengers and time spent in areas such as galleys, which were not monitored during this study.

Further measurements of prevailing air exchange rates on aircraft should be performed. Due to the need to remain unobtrusive during this study, it was not possible to widely deploy sources and samplers to obtain more reliable measurements. Improved estimates will provide a stronger basis for cabin air quality modeling which is crucial to assessment of mitigation strategies related to ventilation.

Further information on special populations and short-term health effects would support improved risk assessments. The information required includes (1) the flying frequency of children and sensitive individuals such as asthmatics, (2) dose-response functions relating various types of short-term health effects (e.g., eye/nose/throat irritation) to levels of various ETS tracers, and (3) quantitative measures of ETS effects on the cardiovascular system of individuals with pre-existing cardiovascular disease.