Report to the FAA on the Airliner Cabin Environment

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National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE)

Airliner Cabin Environmental Research (ACER) Program

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1.0 EXECUTIVE SUMMARY

This report focuses on the results related to specific congressional mandates pertaining to the Airliner Cabin Environment Research Program of the National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE). . The report itself is intended to be a summary of work related to these mandates and is not intended to be a comprehensive report on all of the research conducted by the center since the center's research program extends beyond these initial mandates on the airliner cabin environment. In addition, several of the mandates required background research to be conducted before the mandate itself could be properly addressed. Not all mandates were fully funded at the time the center was created. Some studies are complete, some are still in early phases, and many are still in progress. A comprehensive list of publications and presentations for the center may be found in Section 9.1 of this report.

The Executive Summary consists of three sections. The first section presents the congressional mandates and key findings directly pertaining to these mandates. The second section presents related key results. The third section presents recommendations. The focus in these recommendations is on potential actions by the FAA. Recommendations are limited to those that are clearly based on the results of our research and not just professional opinions of the researchers.

1.1 CONGRESIONAL MANDATES AND KEY FINDINGS

MANDATE: Monitor ozone in the cabin on a representative number of flights and aircraft and determine compliance with existing Federal Aviation Regulations

KEY FINDINGS: On 8 of 46 domestic flights without converters, ozone levels exceeded, at some point during the flight, the "0.1 parts per million by volume" level specified in CFR 121.578. Ozone levels on one flight exceeded the "0.25 parts per million by volume at any time" level specified in CFR 121.578. However, the 0.1 ppm limit applies as a time weighted average and only for flight segments exceeding 4 hours. The highest time weighted average over the full flight for the 46 domestic flights without converters was within a few percent of the 0.1 ppm limit. In addition, the probabilistic flight planning approach specified by the CFR 121.578 only requires a statistical confidence of 84% that the limits for ozone levels will not be exceeded. Ozone converters reduce ozone levels substantially and there were no instances where the flight-average limit of 0.1 ppm was exceeded for the 22 flights on aircraft with ozone converters. Within the constraints that existed on the number of flights that could be monitored, it is concluded that ozone levels in aircraft cabins appear to be consistent with the requirements of CFR 121.578.

MANDATE: Collect pesticide exposure data to determine exposures of passengers and crew

KEY FINDINGS: Due to funding limitations, only preliminary research on this topic has been completed at this time and the actual exposure of occupants to pesticides has not been quantified.

A wipe sampling method has been developed and validated for measuring the amount of pesticides present on surfaces. Measurements were made on 15 US domestic flights and 46 international flights with the latter primarily those that go to countries which require pesticide treatment or spraying. Little if any measurable pesticide was found on the domestic flights and the levels on the international flights were in the tens to hundreds of ng/cm^2.

MANDATE: Analyze and study cabin air pressure and altitude

KEY FINDINGS: General compliance with the 8000 foot cabin altitude limit in 14CFR 25.841 was found. Human subject studies conducted with a simulated cabin altitude of 7000 feet found that a significant portion of the older passengers may be at risk of hypoxia and there was an increased risk of arrhythmias in those passengers with cardiac defibrillators.

MANDATE: Identify, analyze, and study incidents of air contamination associated with typical flight operations monitored with onboard sensors

KEY FINDINGS: Serious air contamination incidents occur on only a very small fraction of flights and are unpredictable, which requires sensors to be deployed on a large number of flights if actual incidents are to be monitored. A simple, small portable sampling device was developed for this purpose and tested on a small number flights but could not be deployed widely due to non-technical reasons. The On-Board project, which is ongoing, has conducted detailed measurements on 130 flights. The small portable sensor has been flown on nearly 200 flights. These latter measurements have shown general compliance with cabin altitude requirements in 14CFR 25.841 and the CO_2 requirements in CFR 25.831.

MANDATE: Analyze samples of residue from aircraft ventilation ducts and filters after air quality incidents to identify the contaminants to which passengers and crew were exposed

KEY FINDINGS: Over 150 filters from non-incident aircraft were analyzed to provide baseline information and approximately 25 filters from aircraft with incidents or suspected incidents were analyzed. Analysis of filter residue was found to be a useful indicator for identifying contaminant sources to guide potential corrective action for problem aircraft but, by itself, was not found to be a definitive determination of the nature of a specific air quality incident nor a means for quantifying exposures.

MANDATE: Demonstrate decontamination of aircraft by adapting proven technologies such as vapor hydrogen peroxide

KEY FINDINGS: Demonstrations were conducted in ground-based DC9 and B747 aircraft. Vaporous hydrogen peroxide was effective at deactivating spores at all 28 locations evaluated in the DC9 cabin and at approximately 85% of the 28 locations evaluated in the B747 cabin. Thermal decontamination systems were able to generate the temperature and humidity levels required for efficacious antiviral process throughout the cabins of these aircraft.

1.2 Related Results

OZONE: Background research was conducted using a B767 cabin mockup designed for air quality research. Experiments indicated that more than half of the net ozone removal within the cabin was attributable to ozone reactions with passengers and crew. Ozone removal is dominated by reactions on surfaces. Ozone reacts rapidly with skin oils present on the exposed skin, hair and clothing of the cabin occupants, producing a number of reaction products that become airborne. Inhalation of these ozone-derived products may be meaningful for the health of passengers and crew members, especially on aircraft with elevated ozone levels. In human subject evaluations, occupants judged the air quality worse and reported various symptoms in response to exposure to ozone and its oxidation products in the cabin simulations conducted.

The adequacy of the requirements in CFR 25.832 and CFR 121.578 is questionable given that they were established about three decades ago and ozone limits for other settings have been or are being lowered.

Measurements on commercial flights found that ozone levels can be moderate to high on domestic flights without ozone converters. Elevated ozone levels (up to ~ 0.06 ppm for the peak hourly average) were measured on transoceanic flights equipped with converters.

AIR CONTAMINATION: An occupational health survey, completed by over 4000 flight attendants from two large US airlines, provides baseline information on flight attendant health and demonstrates the feasibility of conducting large-scale epidemiologic studies to assess the impact of air contamination.

DECONTAMINATION: The issues relating to the failure to deactivate biological indicators in certain locations in the decontamination demonstrations with vaporous hydrogen peroxide (VHP) are engineering issues that can be resolved.

The effect of VHP on materials is an important limitation that must be considered in any VHP-based decontamination. Laboratory evaluations showed that the mechanical properties of many metals, polymers, avionics and textiles, similar to those routinely used in aircraft cabin interiors, exhibit minimal to slight degradation after exposure to multiple cycles of vaporized hydrogen peroxide. The properties of wool were moderately degraded while leather was severely degraded after exposure to multiple cycles of vaporized hydrogen peroxide. Liquid condensed during VHP treatments has high concentrations of hydrogen peroxide and can severely degrade acrylics (as used in cabin windows) and can cause severe hydrogen embrittlement of high strength steel.

1.3 Recommendations

Given the elevated ozone found on some aircraft equipped with ozone converters, a periodic performance check should be required in addition to or as an alternative for the hours-of-service standard to ensure effective performance of ozone converters throughout a plane's service life.

There are no documented safe levels of ozone exposure and limits on ozone exposure are compromises between practicality and adverse impacts. As more information about the adverse effects of ozone has become available, limits for ozone concentrations in other settings have been or are being lowered. Given the evidence of adverse impacts at concentrations below those reflected in CFR 25.832 and CFR 121.578, the feasibility of reducing these limits should be examined.

Guidance for the medical profession and the elderly flying public as to who should use supplemental oxygen or take other measures to mitigate health risks associated with flying in commercial aircraft needs to be updated and disseminated.

Guidelines should be developed for the use of filter residue analysis for trouble shooting aircraft with recurring air quality problems. In particular, a new recirculation filter should be installed on such aircraft so as to minimize the unrelated residue present when it is removed and analyzed following an incident or series of incidents.

If whole aircraft disinfection using technologies based upon thermal/humidity sterilization is to be employed, then process control regulations or guidelines need to be written that specify the temperatures, relative humidity levels, and soak times.

If aircraft decontamination using technology based upon vaporous hydrogen peroxide is to be employed, then the process control regulations or guidelines need to be written that specify the temperatures, relative humidity levels, vaporized hydrogen peroxide concentration and times required to ensure that condensation is prevented within the aircraft.

2.0. INTRODUCTION

2.1 Background

As originally granted in the U.S. Federal Aviation Act of 1958 (Public Law 85-726), regulatory authority over the operation of civil aircraft in the United States resides in the Federal Aviation Administration (FAA). The Occupational Safety and Health (OSH) Act of 1970 (Public Law 91-596) was subsequently passed to ensure safe and healthful workplaces across the country and federal agencies were allowed the authority to exercise jurisdiction over their own workers. In 1975, the FAA asserted its jurisdiction over the safety and health of cockpit and cabin crews within operating civil aircraft (40 FR 29114, DOT). Since then, the FAA has been authorized to also protect the safety and health of passengers (49 USC 40101D and 40 USC 44701A).

The Federal Aviation Regulations (FARs) implement the FAA's various safety and health requirements. Relevant aspects for the design and operation of commercial aircraft are contained in "Title 14 - Aeronautics and Space" of the Code of Federal Regulations (14 CFR). Part 25 of 14 CFR provides the airworthiness standards (i.e., design specifications) for transport category airplanes. Part 121 of 14 CFR contains the operating requirements for air carriers and commercial operators. Part 125 of 14 CFR covers (i) the certification and operations of aircraft having a seating capacity of 20 or more passengers OR a maximum payload capacity of 6000 or more pounds and (ii) the rules governing persons on board such aircraft. These regulations provide the FAA's air quality standards with respect to aircraft cabin ventilation and pressure, maximum amounts of ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2) and other harmful or hazardous gases or vapors.

Increasing load factors on airliners and an increasing age of the flying public (with an expected decrease of the cardiopulmonary health of older passengers and crew) led to studies by the National Research Council[1,2] and later by the Government Accountability Office.[3] These studies recommended specific research into safety and health issues in airliner cabins. The U.S. Congress, in response to these public concerns, appropriated funds in 2004, 2005 and 2006 and provided legislative directives to the FAA to perform the needed research in this area. Specifically, the U.S. Congress directed the FAA to perform the following research activities (Public Law 108–176 (12/03)**,** Section 815):

- conduct surveillance to monitor ozone in the cabin on a representative number of flights and aircraft to determine compliance with existing Federal Aviation Regulations for ozone;
- collect pesticide exposure data to determine exposures of passengers and crew;
- analyze samples of residue from aircraft ventilation ducts and filters after air quality incidents to identify the contaminants to which passengers and crew were exposed;
- analyze and study cabin air pressure and altitude; and
- establish an air quality incident reporting system.

Simultaneously, the U.S. Senate (Senate Report 108-146, page 28, F&E Activity 1) also directed the FAA to:

- identify, analyze, and study incidents of air contamination associated with typical flight operations monitored with onboard sensors and
- demonstrate decontamination of aircraft by adapting proven technologies such as vapor hydrogen peroxide.

2.2 Establishment of the Center

After a nationally competitive process, the Air Transportation Center of Excellence for Airliner Cabin Environment Research (ACER) was initiated by the FAA in 2004. In 2007, the charter of the Center of Excellence was broadened to include other aspects of intermodal transportation and the Center was renamed the National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE). However, the primary research focus of the Center continues to be airliner cabin environment research.

Through the date of this report, the RITE/ACER Center of Excellence consists of seven core universities: Auburn University, Boise State University, Harvard University, Kansas State University, Purdue University, University of California - Berkeley, and the University of Medicine and Dentistry of New Jersey. In addition, a number of large and small organizations (companies, research organizations, other state and federal agencies, etc.) serving aerospace markets, public health needs and/or associated technology markets are or have been active with the RITE/ACER research team.

Overall, RITE/ACER's mission is to undertake the critical research and technology development necessary to (1) inform governmental rulemaking activities and (2) minimize compliance costs to the aviation industry. This focus compels RITE/ACER researchers to perform rigorous, scientifically valid environmental safety and health research in aircraft cabins and cabin simulators to quantitatively assess safety and health risks, and test and develop advanced technologies to detect and prevent environmental safety and health incidents within aircraft cabins.

2.3 Organization of this Report

This report presents an overview of research results, findings and recommendations as well as the current status of the airliner cabin environment research activities being pursued by the RITE/ACER team. Since the National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE) was founded initially to address specific concerns of the U.S. Congress, this report is structured around the original congressional mandates. Section 3 addresses the mandate to monitor ozone in the cabin on a representative number of flights and aircraft to determine compliance with existing Federal Aviation Regulations for ozone. Section 4 focuses upon the mandate to collect pesticide exposure data to determine exposures of passengers and crew. The research activities concerning the mandate to analyze and study cabin air pressure and altitude are found in Section 5. Section 6 covers the mandate to identify, analyze, and study incidents of air contamination associated with typical flight operations monitored with onboard sensors. The related mandates to (i) establish an air quality incident reporting system and to (ii) analyze samples of residue from aircraft ventilation ducts and filters after air quality incidents to identify the contaminants to which passengers and crew were exposed are discussed in Section 7. Section 8 details the research and development activities to demonstrate decontamination of aircraft by adapting proven technologies such as vaporized hydrogen peroxide. Finally, the Appendices to this report contain both the refereed archival publications of the Center relevant to the topics of this report (Section 9.1) as well as the relevant federal aviation regulations (Section 9.2).

3.0 OZONE IN THE PASSENGER CABIN

Congressional Mandate: *Monitor ozone in the cabin on a representative number of flights and aircraft and determine compliance with existing Federal Aviation Regulations*

In addition to the above stated *Congressional Mandate*, the FAA reauthorization bill requires the Administrator to carry out the studies and analysis called for in the National Research Council's report "The Airliner Cabin Environment and Health of Passengers and Crew" (National Research Council, 2002). In the NRC report, *Recommendation 1* called for the FAA to demonstrate the adequacy of FARs for cabin air quality. *Recommendation 9* called for investigations of how ozone concentration in the cabin is affected by various factors (e.g., ambient concentrations, reactions with surfaces, the presence and effectiveness of catalytic converters), and the relationship between ozone levels and health effects. The research team has attempted to be responsive to this broader framing while also addressing the narrower specific charge.

3.1 Introduction

Passengers and crew in aircraft cabins may be exposed to elevated ozone that originates naturally in the stratosphere. The level of ozone in aircraft cabins depends on ambient concentrations, the presence (or absence) of control devices and their effectiveness, the rate of outdoor air supply, and the rate of ozone loss through within-cabin transformation processes, such as reactions with interior surfaces, including those associated with occupants. Ozone levels outside the aircraft vary with season and depend on flight altitude, tropopause height, and on meteorological processes that affect vertical mixing between the lower stratosphere and the upper troposphere. Exposure to ozone in cabin air has potential health significance for the flight crew and for the general flying population, which includes individuals who may be particularly sensitive to respiratory health effects, such as asthmatics, infants, and adults with cardiopulmonary conditions. Exposure to ground-level ozone and its reaction byproducts are strongly associated with adverse respiratory and cardiovascular effects (Levy et al., 2001; Bell et al., 2006; Weschler, 2006; Jarrett et al., 2009). Acute effects from short-term exposure range from breathing discomfort, respiratory irritation, and headache for healthy adults (Strøm-Tejsen et al., 2008) to asthma exacerbation and premature mortality for vulnerable populations (Gent et al., 2003; Bell et al., 2004). Chronic exposure effects may include enhanced oxidative stress (Chen et al., 2007), reduced lung function in young adults (Tager et al., 2005), and adult-onset asthma in males (McDonnell et al., 1999). Physical activity, as is undertaken by flight attendants, results in increased intake. There is no established "safe" level of ozone exposure (Bell et al., 2006).

Real-time measurements made during flights in the 1960s and 1970s revealed that in-cabin ozone was commonly above 100 parts per billion by volume (ppb), especially on flight routes through high latitudes (Brabets et al., 1967; Bischof, 1973; Nastrom et al., 1980). In 1980, in response to these data and to associated health concerns for flight attendants (Reed et al., 1980), the Federal Aviation Administration (FAA) established regulations (FAR 25.832 and FAR 121.578) that are designed to limit levels of ozone in airplane cabins (National Research Council, 2002). To comply with the regulations, many planes are equipped with "catalytic converters" that promote the decomposition of ozone in the ventilation supply air. Alternatively, airlines may comply by means of flight-route planning to reduce the probability of encountering elevated ozone. Not all planes are equipped with converters, and the probabilistic planning approach permits, by design, up to 16% of the flights to encounter elevated ambient ozone concentrations. The ozone level in aircraft cabins is neither routinely monitored, nor has it been the subject of much additional research since the ozone standards were established. Spengler et al. (2004) presented a survey of flight-integrated ozone levels on 106 segments along with 3-h average ozone levels measured during the middle of the flight for Pacific segments. The presence or absence of an ozone converter was determined by proxy and was not verified. To our knowledge, prior to the efforts by ACER/RITE researchers, real-time in-cabin ozone data have been reported for just four flights since 1980 (Spicer et al., 2004). To address this data gap, the research team made real-time, continuous measurements of ozone levels in the passenger cabins of 76 commercial flight segments between February 2006 and August 2007.

When ozone is present in an aircraft cabin, ozone-derived reaction products are also present, both in the gas phase and on surfaces. The fact that ozone-initiated chemistry could meaningfully increase the level of certain volatile and semivolatile organic compounds in aircraft cabin air was first demonstrated in a Boeing-funded study (Wisthaler et al., 2005) conducted in a simulated section of a B-767 (3 rows, 21 seats) at the Technical University of Denmark. Given the results of this preliminary study, as well as our understanding of ozone chemistry and effects observed in various indoor environments, the ACER/RITE research team also undertook studies of the reaction of ozone with cabin materials, with a pesticide commonly used to disinsect aircraft, and with cabin occupants themselves.

Results from the various tasks that have constituted the ACER/RITE Ozone Project are summarized in the following paragraphs.

3.2 Results and Discussion

Ozone levels. Ozone levels in airplane cabins, and the factors that influence them, were studied on northern hemisphere commercial passenger flights on domestic US routes as well as transatlantic and transpacific international routes (Bhangar et al., 2008). Real-time data from 76 flights were collected during 2006 and 2007 with a battery-powered ozone monitor that works on the principle of ultraviolet spectrophotometry. Figure 3.1 shows representative ozone measurements from four consecutive domestic transcontinental U.S. segments monitored within a 6-day interval in April, 2006. Sample average ozone level, peak-hour ozone level, and flight-integrated ozone exposures were highly variable across the 68 domestic flight segments sampled, with ranges of <1.5 to 146 ppb for the flight average, 3-275 ppb for the peak hour, and <1.5 to 488 ppb hour for the flight-integrated exposures, respectively. On planes equipped with ozone catalysts (N = 22 flight segments), the mean peak-hour ozone level (4.7 ppb) was about a factor of 10 lower than on planes not equipped with catalysts (N = 46 flight segments; 47 ppb). Weighted cumulative distributions of peak 1 hour ozone mixing ratios for aircraft with and without converters are displayed in Figure 3.2. Peak-hour ozone levels on eight transoceanic flight segments, all on planes equipped with ozone catalysts, were in the range <1.5 to 58 ppb (Figure 3.3). Seasonal variation on domestic routes without converters is reasonably modeled by a sinusoidal curve that predicts peak-hour levels to be approximately 70 ppb higher in February and March than in August and September. The temporal trend is broadly consistent with expectations, given the seasonal cycle in tropopause height. Episodically elevated (>100 ppb) ozone levels on domestic flights were associated with winter-spring storms that are linked to enhanced exchange between the lower stratosphere and the upper troposphere.

Ozone reactions with cabin materials. We measured ozone consumption and byproduct formation on materials commonly found in aircraft cabins at flight-relevant conditions (Coleman et al., 2008). Two series of small-chamber experiments were conducted, with most runs at low relative humidity (10%) and high air-exchange rate (20 air changes per hour). New and used cabin materials (seat fabric, carpet, and plastic) and laundered and worn clothing fabrics (cotton, polyester, and wool) were studied. We measured ozone deposition to many material samples, and we measured ozone uptake and primary and secondary emissions of volatile organic compounds (VOCs) from a subset of samples. Deposition velocities, reflecting the effective rate of ozone uptake on the fabrics, ranged from 0.06 to 0.54 cm s^{-1}. Emissions of VOCs were higher with ozone exposure than without ozone in every case. The most commonly detected secondary emissions were C_1 through C_{10} saturated aldehydes and also the squalene oxidation products 6-methyl-5-hepten-2-one and acetone. For the compounds measured, summed VOC emission rates in the presence of 55–128 ppb (residual level) ozone ranged from 1.0 to 8.9 millimoles per hour per square meter. Total byproduct yield ranged from 0.07 to 0.24 moles of volatile product emitted per mole of ozone consumed. Results were used to estimate the relative contribution of different materials to ozone deposition and byproduct emissions in a typical aircraft cabin. The dominant contributor to both was clothing fabrics, followed by seat fabric. Results indicate that ozone reactions with surfaces substantially reduce the ozone concentration in the cabin but also generate volatile byproducts of potential concern for the health and comfort of passengers and crew.

Ozone reaction with permethrin. Permethrin is commonly used in aircraft cabins for disinsection. Theoretical considerations suggest that the reaction of ozone with residual permethrin on cabin surfaces could potentially form phosgene. Published evidence on ozone levels and permethrin surface concentrations in aircraft cabins indicated that significant phosgene formation might occur in this setting. A chemical derivatization technique was developed to detect phosgene with a lower limit of detection of 2 ppb. Chamber experiments were conducted with permethrin-coated materials (glass, carpet, seat fabric, and plastic) exposed to ozone under cabin-relevant conditions: 150 ppb of ozone, 4.5 per hour air exchange rate, <1% relative humidity, and 1700 ng/cm^2 of permethrin (Coleman et al., 2010). Phosgene was not detected in these experiments. Reaction of ozone with permethrin appears to be hindered by the electron-withdrawing chlorine atoms adjacent to the double bond in permethrin. Experimental results indicate that the upper limit on the reaction probability of ozone with surface-bound permethrin is low, $\sim 10^{-7}$. Extrapolation by means of material-balance modeling indicates that the upper limit on the phosgene level in aircraft cabins resulting from this chemistry is ~ 1 $\mu g/m^3$ or ~ 0.3 ppb. It was thus determined that phosgene formation, if it occurs in aircraft cabins, is not likely to exceed relevant, health-based phosgene exposure guidelines.

Ozone removal in a simulated aircraft cabin. As reported in Tamás et al. (2006), a series of experiments was conducted at the Technical University of Denmark's (DTU) simulated aircraft cabin facility, a full-scale mock-up of three rows (21 seats) of a Boeing 767 (Figure 3.4). In the first set of experiments, ozone concentrations were measured concurrently inside the simulated aircraft cabin and in the airstream providing ventilation air to the cabin. Ozone decay rates were also measured after cessation of ozone injection into the supply airstream. By systematically varying the presence or absence of (a) people, (b) soiled T-shirts, (c) aircraft seats and (d) a used HEPA filter, we were able — in the course of 24 experiments — to isolate the contributions of these and other factors to the removal of ozone from the cabin air. As is apparent from Figure 3.5, humans are large sinks for ozone; at the same ozone generation rates, ozone levels were much lower when passengers were present than when the cabin was empty. In the case of this simulated aircraft, people (including their exposed skin, hair and clothing) were responsible for almost 60% of the ozone removal occurring within the cabin and recirculation system; respiration can only have been responsible for about 4% of this removal; the aircraft seats removed about 25% of the ozone; the loaded HEPA filter, 7%; and the other surfaces, 10% (see Figure 3.6). A T-shirt that had been slept in overnight removed roughly 70% as much ozone as a person, indicating that skin oils are indeed important in ozone removal within aircraft cabins. The presence of the used HEPA filter in the recirculated airstream reduced the perceived air quality as judged by human subjects. Over a 5-h period, the overall ozone removal rate by cabin surfaces decreased at a rate of about 3% per hour. With people present, the measured ratio of ozone's concentration in the cabin versus that outside the cabin was 0.15–0.21, smaller than levels reported in the literature. The results reinforce the conclusion that the optimal way to reduce people's exposure to both ozone and ozone oxidation products is to efficiently remove ozone from the air supply system of an aircraft.

Ozone reaction with cabin materials and occupants in a simulated aircraft cabin. In a second set of experiments at DTU, we used multiple analytical methods to characterize the gas-phase products formed when ozone was added to cabin air during simulated 4-hour flights that were conducted in the reconstructed section of a B-767 aircraft containing human occupants (Weschler et al., 2007). Two separate groups of 16 females were each exposed to four conditions: low air exchange (4.4 air changes per hour) and low (< 2 ppb) ozone; low air exchange and elevated (61-64 ppb) ozone; high air exchange (8.8 air changes per hour) and low (< 2 ppb) ozone; and high air exchange and elevated (73-77 ppb) ozone. The addition of ozone to the cabin air increased the levels of identified byproducts from ~70 to 130 ppb at the lower air-exchange rate and from ~30 to 70 ppb at the higher air-exchange rate (Figure 3.7). Most of the increase was attributable to acetone, nonanal, decanal, 4-oxopentanal (4-OPA), 6-methyl-5-hepten-2-one (6-MHO), formic acid, and acetic acid, with 0.25-0.30 moles of quantified volatile product generated per mole of ozone consumed. Figure 3.8 shows the yields of the major ozone-derived products at both the low and high air exchange rates. Several of these compounds reached levels above their reported odor thresholds. A recently published study conducted by researchers at NIOSH indicates that *in vitro* exposure of pulmonary epithelial cells to 4-OPA results in expression of various inflammatory markers (Anderson et al., 2010). In our research, most of the byproducts of ozone-initiated chemistry were derived from surface reactions with occupants and their clothing, consistent with the inference that occupants were responsible for the removal of more than 55% of the ozone in the cabin. The observations made in this study have implications for better understanding the health hazards of being exposed to ozone and its byproducts not only aircraft cabins but also for other indoor settings. Whenever human beings and ozone are simultaneously present, one anticipates production of and increased human exposure to acetone, nonanal, decanal, 6-MHO, geranyl acetone, and 4-OPA. Being exposed to a given level of ozone in a more densely occupied space will tend to pose higher health risks than in a less densely occupied space owing to the concomitant exposure to the byproducts of ozone-initiated reactive chemistry.

Impact of ozone and ozone oxidation products on occupants' self-reported symptoms. In a third set of experiments conducted in DTU's reconstructed section of a B-767 aircraft cabin, Strøm-Tejsen et al. (2008) evaluated human subjects' symptoms related to air quality and comfort during simulated 4-h flights identical to those described in the previous paragraph. Twenty-nine female subjects, age 19–27 years, were split into two groups. Each group was exposed to four conditions: two levels of ozone (less than 2 ppb and 60–80 ppb) were utilized at each of two outside air supply rates (4.4 and 8.8 h^{-1}; that is, 2.4 and 4.7 liters of air per second per person). The subjects completed questionnaires to provide subjective assessments of air quality and symptoms typical of complaints experienced during actual flight. Additionally, the subjects' visual acuity, nasal peak flow and skin dryness were measured. Based on self-recorded responses after 3.25 hours in the simulated aircraft cabin, the subjects judged the air quality (Figure 3.9) and eleven symptoms to be worse for the elevated ozone condition compared to the low ozone condition. Assessments for headache, eye achiness, nasal irritation and skin dryness are shown in Figure 3.10. Not shown, but also adversely impacted by ozone/ozone-derived products, are assessments for odor, lip dryness, other eye complaints, dizziness, mental tension, and claustrophobia. Taken together these results indicate that ozone and products of ozone-initiated chemistry are contributing to such complaints, and imply that such complaints are reduced when ozone is removed from the ventilation air supplied to an aircraft cabin.

3.3 Conclusions

The research undertaken by ACER/RITE on ozone in aircraft cabins has produced an interconnected set of results that significantly advance our understanding about the levels of ozone and its reaction byproducts to which passengers and crew are exposed during flight along with some important information about the consequences of such exposures. Measurements on commercial flights found that ozone levels can be moderate to high on domestic flights without ozone converters and moderate on transoceanic flights even though these planes are equipped with converters. When ozone is present within the cabin, various oxidation processes occur, mainly on surfaces, including those associated with the passengers themselves. Laboratory experiments indicate that ozone reacts with numerous cabin materials, yielding carbonyls, dicarbonyls, organic acids and other products. Experiments conducted in a reconstructed section of a B-767 aircraft cabin identified the same ozone derived byproducts as those measured in the laboratory experiments. Strikingly, in these simulated flights, more than half of the net ozone removal within the cabin was due to its reactions with passengers and crew. The reaction products, a series of carbonyls, dicarbonyls and hydroxycarbonyls, indicate that ozone is reacting rapidly with skin lipids on the clothing and other exposed surfaces of the cabin occupants. Self-assessed symptoms during simulated 4-hour flights with and without ozone indicate that ozone-oxidation products, in addition to ozone itself, may contribute to the complaints of mucous membrane irritation (e.g., irritated eyes and throat) commonly reported by the flying public. Additionally, certain ozone oxidation products (e.g., formaldehyde, acrolein, certain dicarbonyls) are known or suspected of adversely affecting human health at elevated levels. Whether repeated exposures to the levels that occur on aircraft without ozone converters contribute to long-term health effects remains an open question. On a positive note, laboratory studies indicate that if phosgene is formed via the reaction of ozone with residuals of permethrin (a commonly applied disinsectant), the resulting levels are very likely to be lower than appropriate health-based standards.

3.4 Implications

The results derived from the *Ozone Project* have a number of implications:

- Health and safety evaluations should consider the products of ozone-initiated chemistry in addition to ozone itself. Inhalation of certain ozone-derived products may be meaningful for passengers and crewmembers, especially on aircraft without ozone destroying catalysts.
- Higher molecular weight products of ozone-initiated reactions with skin oils can accumulate on skin and may contribute to psoriasis and dermatitis (Thiele et al., 1997; Podda and Fuchs, 2004; Wisthaler and Weschler, 2010); however, separate research is needed to investigate this subject.
- It would be appropriate for FAA to re-evaluate the FARs for ozone to determine whether they are adequately protective of the health of passengers and crew. Concerns arise for the following reasons:
  - The current FARs do not reflect additional knowledge, accrued since 1980, regarding direct adverse health effects of ozone exposure.
  - The current FARs do not reflect ozone chemistry and resultant exposures of passengers and crew to the byproducts of ozone-intitiated chemistry.
  - The flying population may include more individuals who are vulnerable to the adverse effects of air pollutant exposure than was the case before 1980.
- Adopting as a standard practice the use of ozone converters on all commercial flights may be warranted. This practice appears to be common in northern Europe, based on conversations with carriers based in this region.
- A program of random periodic testing of in-service ozone converters could reduce exposures that result from degraded or poisoned catalysts.
- Methods to prevent “poisoning” and to extend the useful life of in-service converters is a desirable future research goal.
- Studies should be undertaken to investigate the benefits of using filters (e.g., activated carbon) to remove ozone and ozone-derived products from recirculating air in aircraft cabins.

3.5 References

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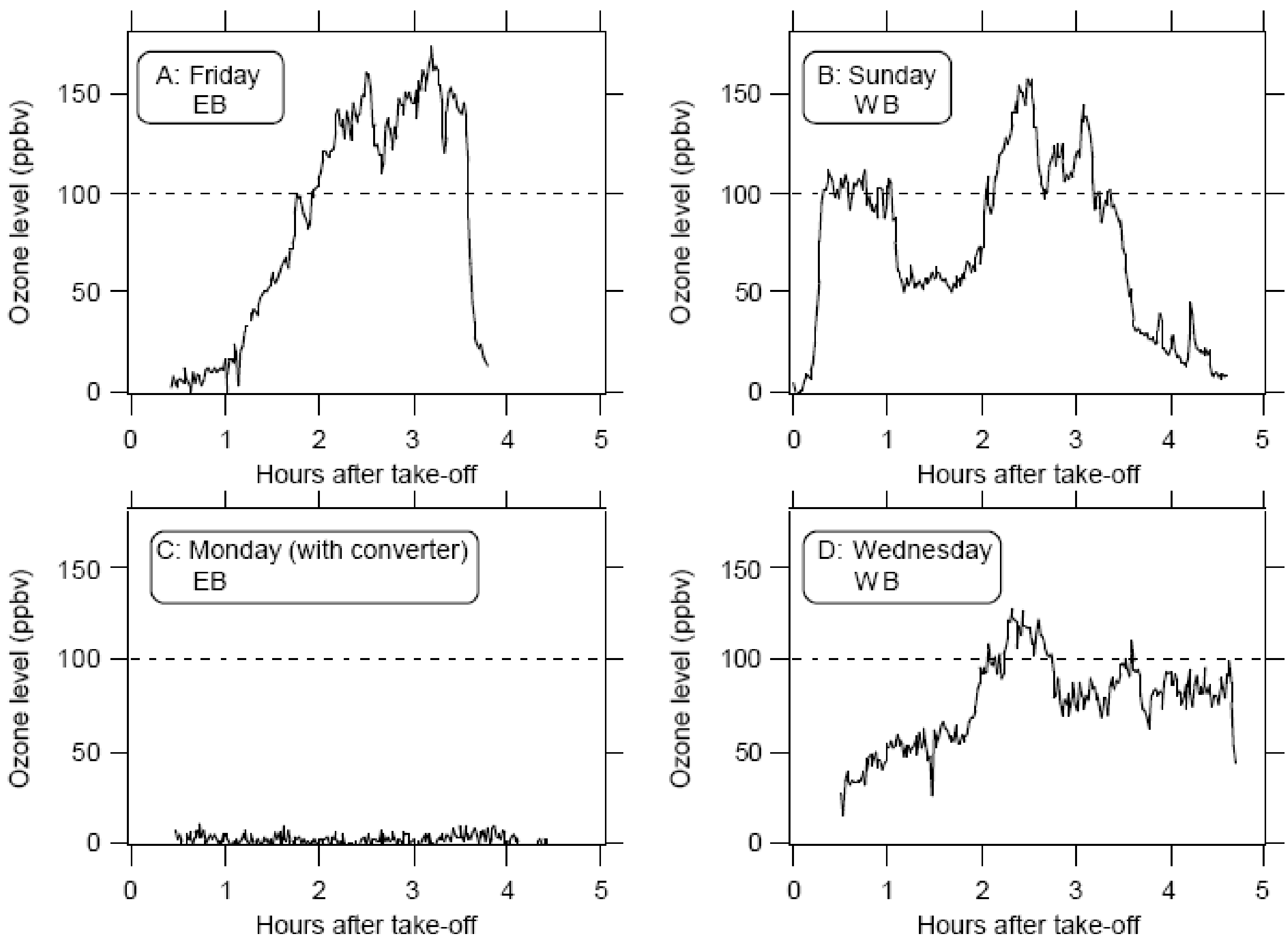

Figure 3.1 Real-time ozone data from four consecutive domestic transcontinental U.S. segments monitored within a 6-day interval in April, arranged chronologically in panels A-D. The direction (EB: eastbound or WB: westbound) is indicated for each segment. Panel C represents data from an aircraft equipped with an ozone converter; the three other flights were aircraft without converters.

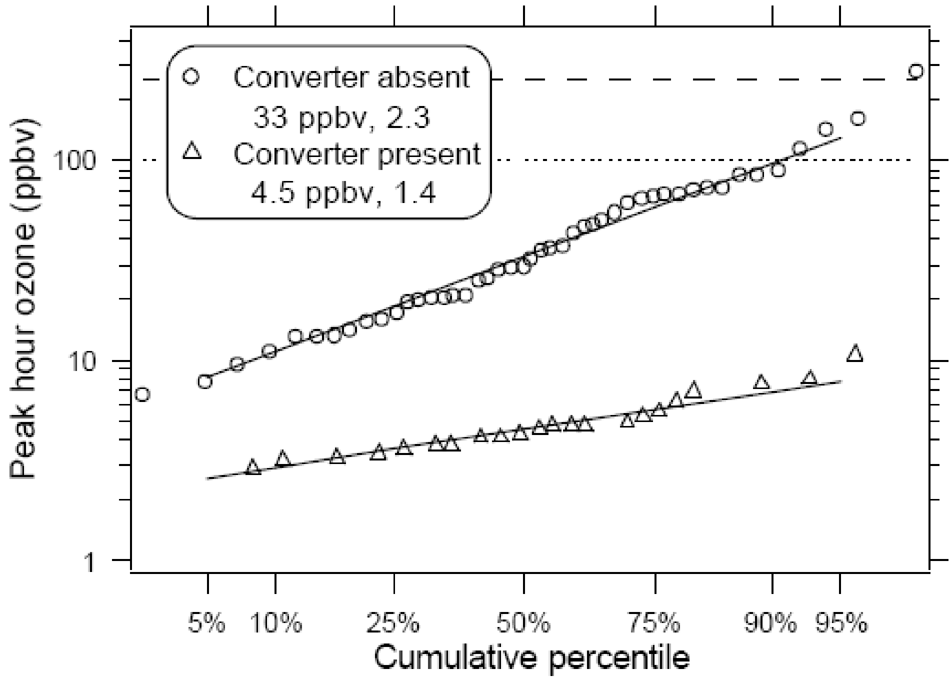

Figure 3.2 Weighted cumulative distributions of peak 1 h ozone mixing ratios sampled in passenger cabins on 68 domestic U.S. flight segments. Data are segregated by the presence or absence of an ozone converter. The weighted geometric mean and standard deviation, and the lognormal fits using these parameters, are presented for each distribution.

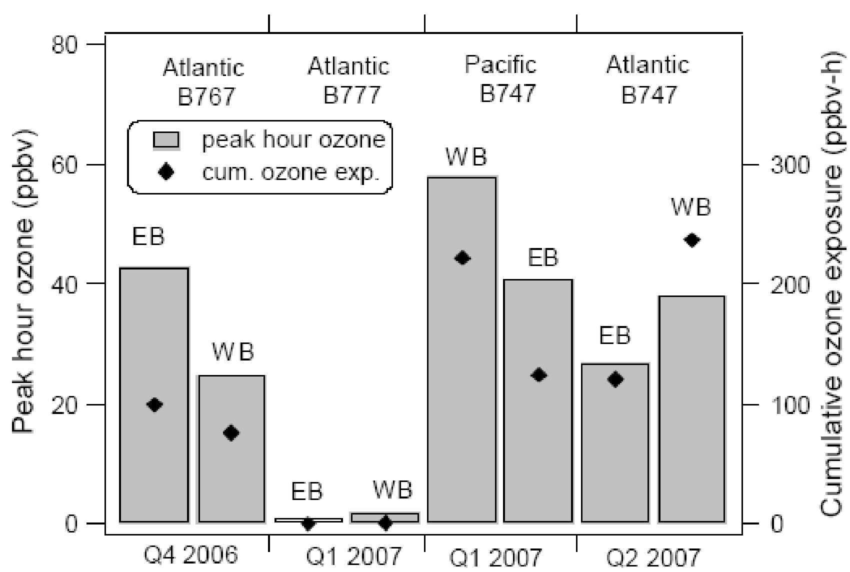

Figure 3.3 Ozone levels sampled on eight transoceanic flights. The shaded bars represent peak-hour ozone and the diamonds denote cumulative ozone exposure for each flight segment.

Figure 3.4 Section of simulated B-767 located at Technical University of Denmark. Three rows, 21 used seats; used carpet, wall sections and HEPA filter; volume of 28.5 m^3.

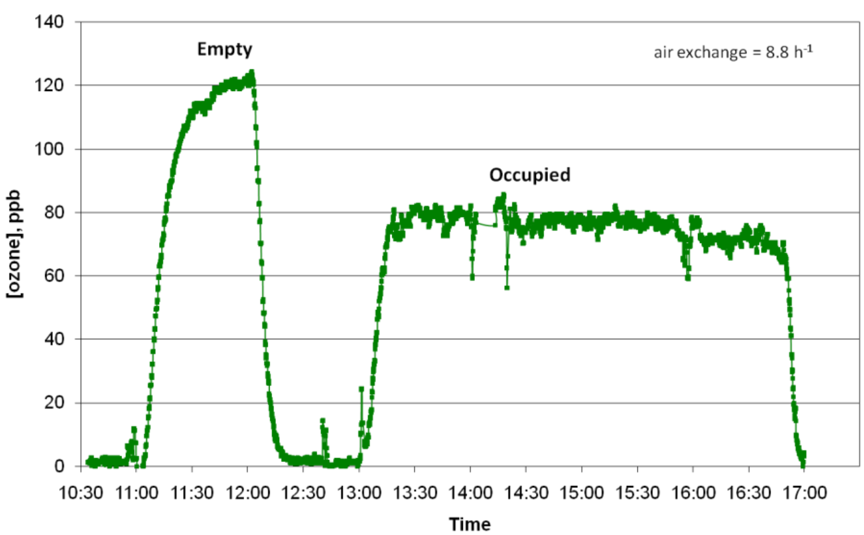

Figure 3.5 Ozone levels with the simulated B-767 when the cabin was empty and when 16 passengers were present; the ozone generation rate was the same for both conditions.

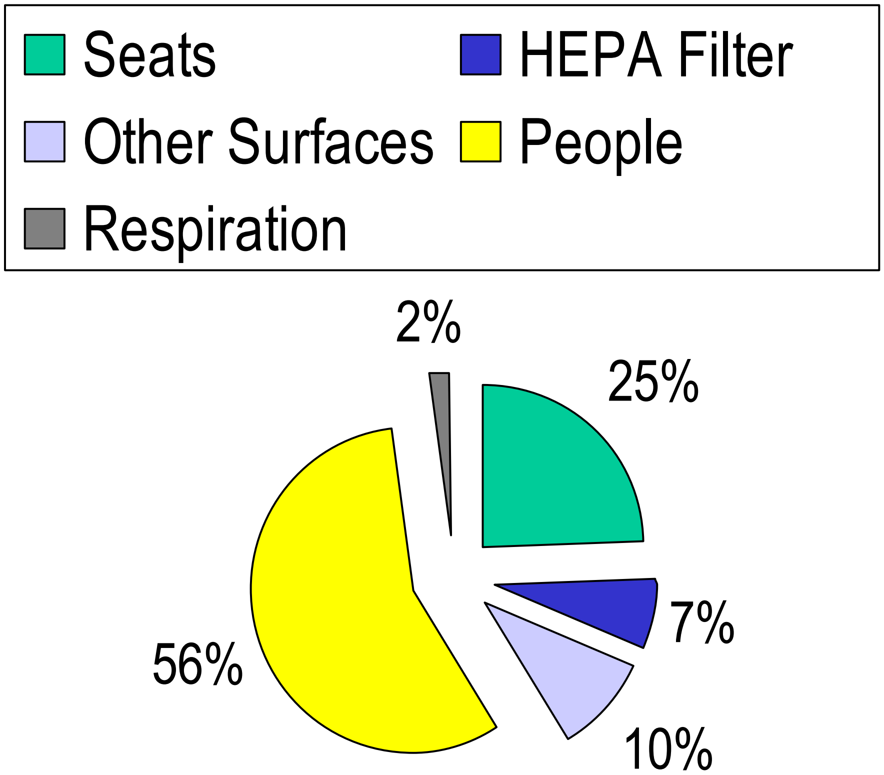

Figure 3.6 Fraction of ozone remove by the various sinks within the simulated section of the Boeing 767

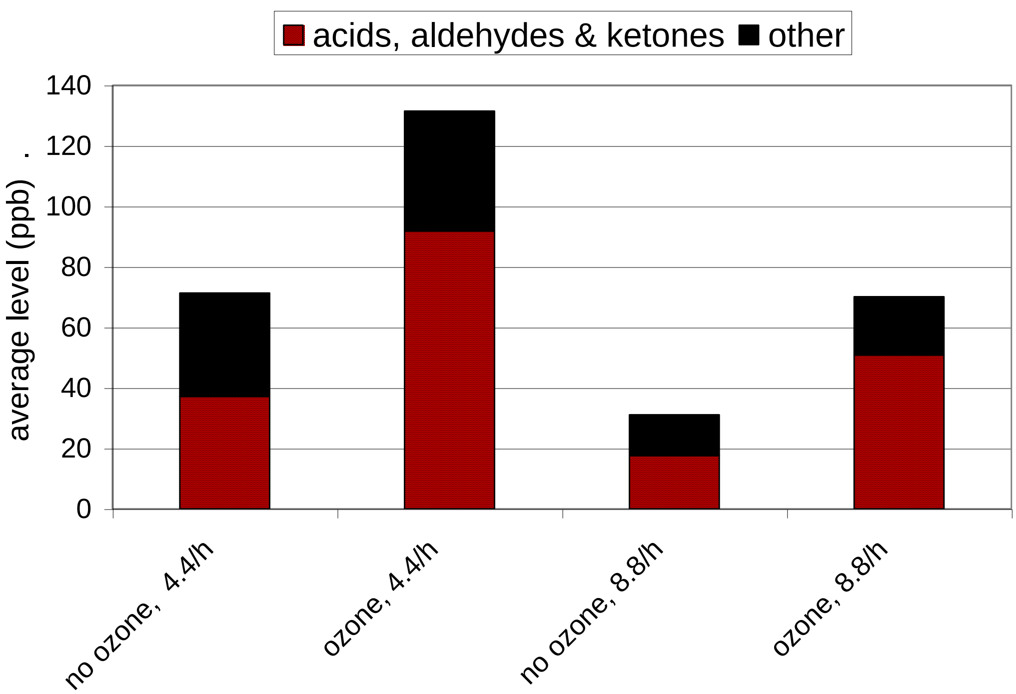

Figure 3.7 Sum of the organic compounds detected in the cabin air for the four different conditions indicated on the X-axis.

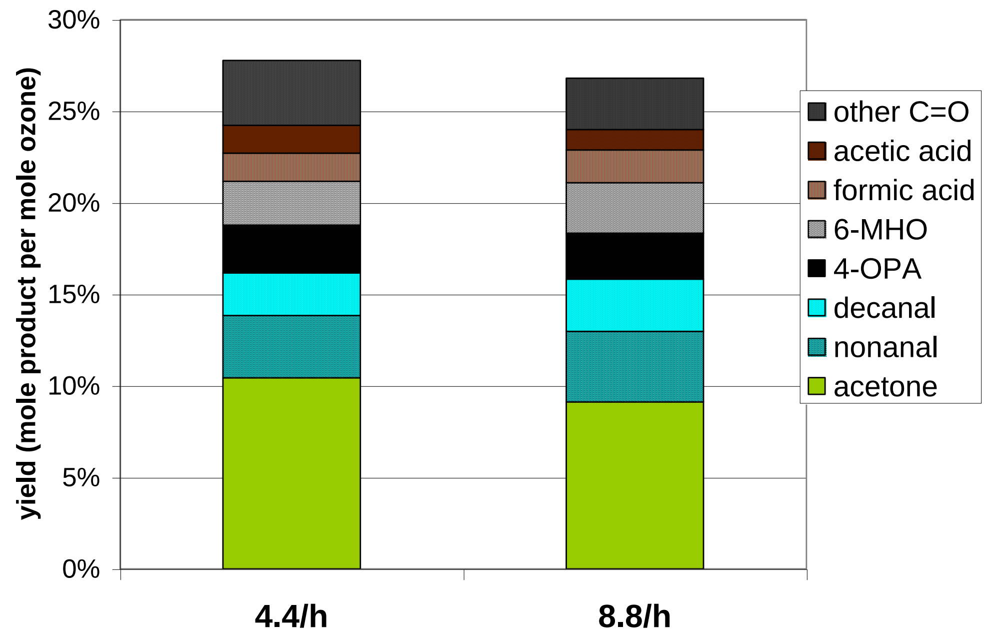

Figure 3.8 Yield of ozone-derived products at two different air exchange rates – 4.4 and 8.8 h^{-1}.

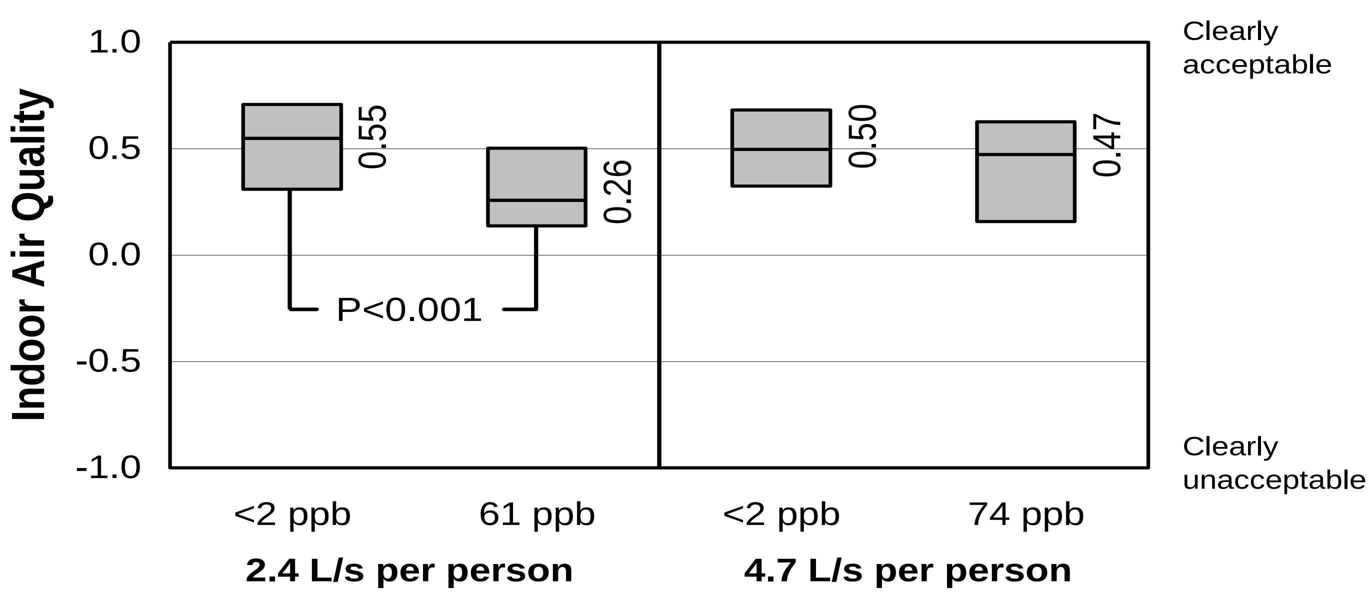

Figure 3.9 Assessments of indoor air quality for each of the four conditions (low air exchange, low O_3; low air exchange, 61 ppb O_3; high air exchange, low O_3; high air exchange; 74 ppb O_3) after passengers had been on the simulated flight for 3.25 hours. Each box represents the interquartile range, and the horizontal line dividing the box is the median, whose value appears to the right; all P-values are one-tail.

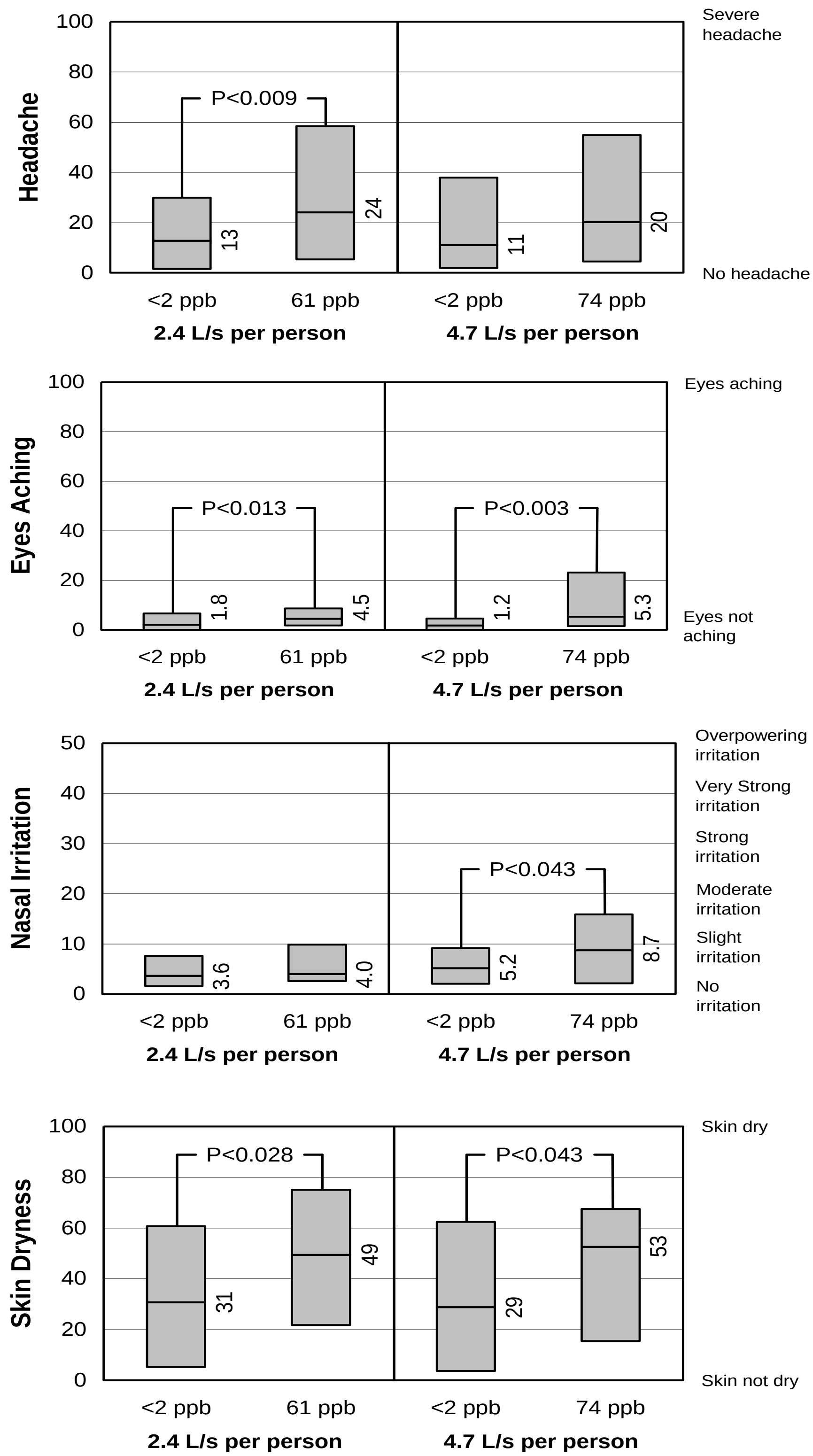

Figure 3.10 Assessments of headache, eye complaints, nasal complaints and perceived skin dryness for each of the four conditions. See Figure 3.9 for further details.

4.0 EXPOSURE AND RISKS OF PESTICIDES ON AIRCRAFT

Congressional Mandate: *Collect pesticide exposure data to determine exposures of passengers and crew*

4.1 Introduction

Disinsection of aircraft, while no longer routinely practiced in the US, is currently mandated by twenty five countries all or selected international flights landing in their borders (Table 4.1) to prevent inadvertent insects transport on commercial aircraft in order to protect populations and native animals and plant species. In addition, most countries reserve the right to require disinfection when there is a perceived threat of vector borne disease. The application of pesticide is done by either by active spraying of the aircraft while passengers are on board or by applying a residual level of pesticides onto the surfaces within the cabin and/or the cargo hold. Pyrethroids are the currently recommended pesticides to be used on aircraft with the World Health Organization recommending four active ingredients resmethrin, bioresmethrin, d-phenothrin and permethrin (cis/trans ration 25/75). New Zealand and Australia, two countries mandating disinection of aircraft, have published Guidelines for Treatment of Aircraft (New Zealand MAF 2007, AQIS 2009), which includes the use of d-phenothrin and permethrin and have approved commercially available formulations specific for use on aircraft. The United Kingdom recommends using deltamethrin.

Table 4.1 Countries Requiring Disinsection of In-bound Aircraft

Source: http://ostpxweb.dot.gov/policy/safetyenergyenv/disinsection.htm
Last Updated 4/21/2010

While Passengers on Board	Residual Treatment	Flights from Selected Areas
China	Australia	Czech Republic
Cuba	Barbados	France
Grenada	Cook Islands	Indonesia
India	Fiji	South Africa
Kiribati	Jamaica	Switzerland
Madagascar	New Zealand	United Kingdom
Seychelles	Panama	
Trinidad & Tobago		
Uruguay		

Residual application needs to be effective for at least 8 weeks with typical application rates to provide surface loading of 0.5 g/m^2 (50 µg/cm^2) on carpets and 0.2 g/m^2 (20 µg/cm^2) on other surfaces including seats, trays etc (Rayman 2006, New Zealand MAF 2007, AQIS 2009). The application is done using a spray containing 2% of the active insecticide. All surfaces, including storage areas, ceilings, walls, curtains, toilets, galleys, flight decks, behind curtains, etc. are to be sprayed. Similarly, when cargo compartments are sprayed all surfaces with particular attention to sidewall and floor cavities are to be treated. The total amount to be applied is aircraft dependent since the surface area varies with aircraft types. These applications are done by trained individuals usually while general maintenance is being performed.

Application with passengers aboard is often referred to as Top of Descent disinsection and can be combined with a pre-boarding treatment. The pre-boarding treatment is done before embarking by treating all surfaces with a pre-flight spray using a 2% permethrin spray no later than 1 hour before departure but after catering has been completed while the Top of Descent occurs while the passengers are on board immediately prior to commencing the final descent for landing with 2% d-phenothrin. An announcement is to be made to the passengers indicating that the spraying is being done and they should remain seated. The spraying is performed by trained flight crew who spray two cans each while walking down each aisle. The spraying is directed towards closed overhead lockers while the crew member walks at a rate of 1 row or step per second resulting in a rate of 10gms per 28.3 cubic meters. The application rates have been reviewed and approved as safe by the World Health Organization (Rayman, 2006; WHO 1998) though others have raised concerns about potential adverse health effects (van Netten 2002, Murawski 2005) and recent toxicological studies have identified adverse neurological and development effects at low levels of several pyrethroids (Das et al 2008, Breckenridge et al 2009, DeMicco et al 2010).

Air concentrations of pesticides have been reported during spraying while simulating the Top of Descent protocols when the aircraft was on the ground with the air conditioning unit on resulting in clearance half lives of 2.7 minutes and average air concentrations of 63 ± 39 $\mu g/m^3$ per gram of insecticide over a 40 minute sampling duration that included the time of spraying (Berger-Preiβ 2004, 2006). Surface loadings during these experiments were measured on various locations and the highest levels were ~0.1 $\mu g/cm^2$. The only in-flight air concentrations reported for commercial flights were in an ASHREA report and two of four domestic flights reported detectable levels of permethrin at 1 to 2 ng/m^3 (Spicer et al 2004).

The studies undertaken within ACER were a review of the literature related to exposure to pesticides on commercial aircraft to identify data gaps and design measurement and modeling approaches to fill those gaps and assess crew and passenger exposure and potential risk to pesticides.

4.2 Approach

To assess the potential pesticide exposure of flight crew and passengers within an the aircraft cabin of commercial airlines several steps were undertaken as part of ACER: a review of the current state of knowledge of the use of pesticides on-board aircraft; a wipe sampler was developed and deployed on in-use commercial aircraft to determine pesticide loading on surfaces within the airplane cabin; air concentrations and surface loadings within an aircraft is being mathematically modeling during disinsection and measurements to evaluate that model were made in the KSU aircraft model; and urinary pesticide metabolite levels are being measured for crew members who fly routes into countries requiring disinsection. A risk paradigm is being developed to provide the distribution of pesticide exposures and risks associated with disinsection for those flying on commercial aircraft.

a) Summary of Current Knowledge

The review of the current information about pesticide application practices was conducted by Drs. Randy Maddalena and Thomas McKone of LBNL (Maddalena and McKone 2008). The goal of this review was to provide a brief history of pesticide use on aircraft and to identify values for key inputs needed to evaluate pesticide exposures. It included a summary of the application methods, rates, frequency and the most likely pesticides used. Physiochemical properties of pesticides used on aircraft and environmental factors in the aircraft cabin were included for use in exposure models. Existing data exposure concentrations in the airliner cabin were also summarized.

b) Potential Dermal Exposure

To be able to determine the potential pesticide dermal exposures and provide an estimate of the reservoir of pesticide levels in an aircraft that could vaporize, a wipe sampler for the collection of pyrethroid pesticides was developed for use on both soft and hard surfaces in an aircraft (Mohan and Weisel 2010). The wipe sampler uses readily available round 9cm (3 ½ inch) diameter cellulose filter paper and a small amount of water as a wetting agent. These materials can be taken through security and brought aboard aircraft. The filter paper is placed on the surface to be sampled, wet with several drops of the water and the water remaining on the surface collected with additional filter paper. This procedure is repeated several times to collect the pesticides available on the surface that can be readily transferred to skin or food if on the tray table. The filter paper is transported back to the laboratory in a plastic zip-log bag where it is stored in a freezer until extracted in hexane facilitated by ultrasonication. The volume of the hexane is reduced and the pesticides analyzed by gas chromatography/mass spectrometry. The pesticide collection efficiency of the sampler is: 91± 6% from hard surfaces, 40± 4% from the seat material and 70± 5% from aircraft carpeting.

c) On-going studies

On-going studies include the collection of urine samples to assess the body burden of flight crew on aircraft that are disinsected, mathematic modeling of air concentrations and surface loading of pesticides during disinsection and a risk assessment of pesticides for flight attendants and passengers.

4.3 Results and Discussion

a) Summary of Current Knowledge

The literature review (Maddalena and McKone 2008) determined that insufficient information is publicly available from the airlines and other sources for estimating insecticide application rates in the U.S. domestic fleet and international fleets or for understanding how frequently equipment rotate into domestic routes following insecticide treatment. The World Health Organization (WHO) and several countries that require disinsection have recommend several methods for treating aircraft with insecticide, though there is evidence that deviations from these guidelines may exist. Even so, it still may be possible, based on general information about practices by various airlines, where an aircraft has flown, and/or applicator company, that the guidelines may be used in combination with how pesticides behave in other indoor environments to provide a plausible basis for estimating insecticide loading rates on aircraft, though experimental and measurement data are needed to evaluate those estimates. The review also found that while there are some measurements of exposure concentrations following simulated aerosol applications, measurements within in-use aircraft or during actual applications in domestic and international aircraft are lacking. No systematic modeling effort of exposure to pesticides within aircraft was identified.

b) Potential Dermal Exposure

The wipe sampler was used to measure pesticide loading on various aircraft cabin surfaces from 15 domestic and 46 international flights. The domestic flights were predominantly in the southeast during the spring and summer of 2008 when insect infestations are most likely which would require disinsection and included samples collected from seat cushions, the front and back of tray tables, the wall and other surfaces in the galley and in the lavatory. Permethrin was detected on only a single domestic flight, near its detection limit of 0.001 ng/cm^2 and at only one of the multiple locations sampled from that flight. These results are consistent with disinsection not being done on planes that fly only within the US and that no pesticide has been approved for use on aircraft within the US by the US EPA.

The samples collected from international flights were selected predominantly, though not exclusively, to include those landing in countries that require some form of disinsection or where residual treatment is performed. Flights included countries in the Caribbean, South and North America, Australia, New Zealand, Asia and Europe from the fall of 2008 to the spring of 2009. Pyrethroids were detected on 22 of 46 flights with the mean levels by country given in Figure 4.1.

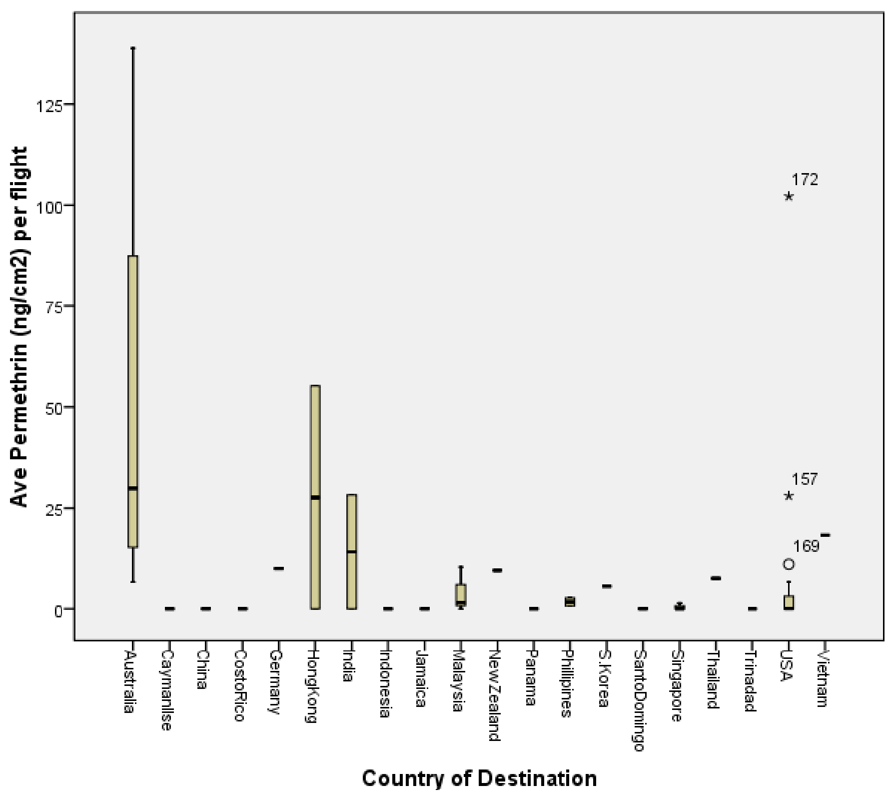

Figure 4.1 Box and Whisker Plot of Permethrin Surface Loadings Measured in Aircraft Cabins Organized by Country of Destination of the Flight.

The highest mean loadings were present in Australia, New Zealand and India which require disinsection of aircraft before landing in their country and in Hong Kong, Malaysia and Vietnam, countries that have been certified to do residual disinsection. Individual aircraft that landed in Germany, South Korea, Thailand and the US had measurable levels, with several samples being as in the upper quartile of measured loadings. The flights landing those countries were continuation of flights that originated in countries requiring disinsection.

Permethrin was present on all of the surface types sampled and on a deposition sample collected by placing a filter in a container on the top of the seat while and after the flight crew were conducting top of descent spraying (Figure 4.2).

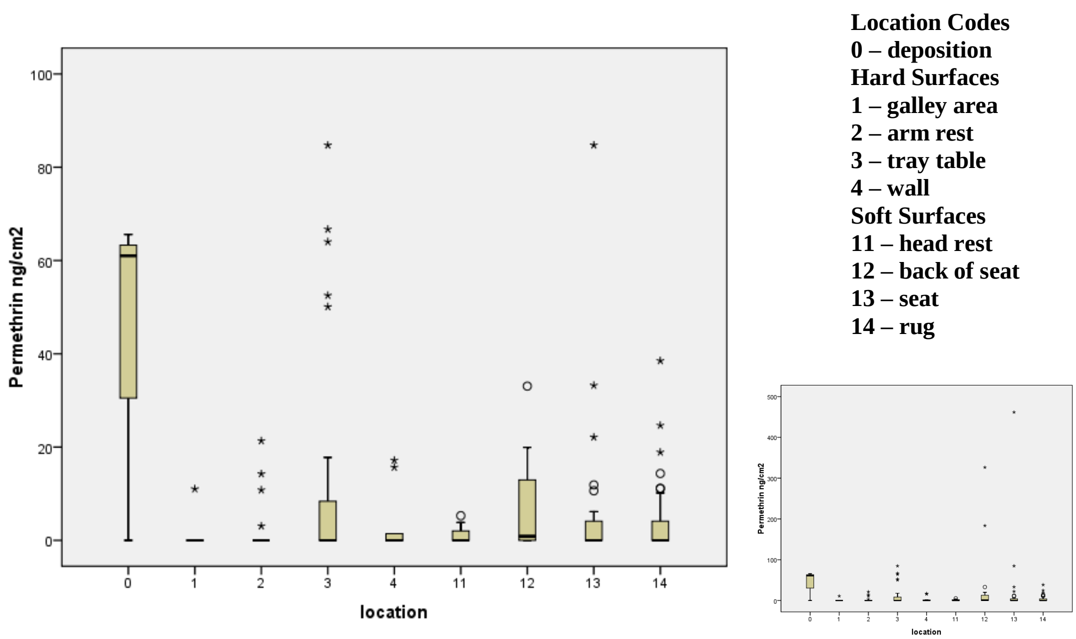

Figure 4.2 Box and Whisker Plot of Permethrin Surface Loadings Measured in Aircraft Cabins Organized by Location of Sample (Bottom figure shows that some individual samples had values between 200 and 500 ng/cm^2 , top figure scale is expanded)

The samples collected during spraying (deposition) confirm that permthrin is one of the pesticides being sprayed during the top of descent while passengers were on board the plane. The loadings measured were all lower that the application guidelines of residuals on seats of 20µg/cm^2, but pesticides were consistently present on the seats, head rest and arm presenting potential dermal exposure and were on both sides of the food tray tables which could result in dermal and ingestion exposures. In addition, permethrin and phenothrin were present in extracts from approximately 50 of the 100 HEPA filters removed from commercial aircraft, though the pesticides could have come spraying around airports rather than the cabin air.

c) On-going studies

We have adapted a CFD model developed by Yan Chen, Purdue University as part of ACER, to predict exposure in the air and on passengers and seats within the main cabin of a Boeing 767 and are evaluating that model with measurements made at the at Kansas State University a mockup of the aircraft. We are currently seeking to obtain urine samples from flight attendants on aircraft that have been sprayed and those that have not been sprayed, with a focus on evaluating differences among biomarker levels in the flight crew due to disinsection.

4.4 Conclusions

The information reported in the literature when ACER was formed is insufficient to determine the extent of pesticide exposure to the crew and passengers on commercial airlines. As part of the ACER supported research, a method to collect measure loading on in-use commercial flights was developed and used to document that little if any pesticides are present in the domestic fleet but is consistently present at the tens to hundreds of ng/cm^2 range in the cabin of aircraft that land in countries requiring disinsection, including aircraft that return to the US which can result in dermal, and since pesticides are on tray table, ingestion exposure. In addition, inhalation exposure to pesticides was documented during top of the descent exposure. The exposure levels are currently being measured and risk estimates will be completed within two years.

It is recommended that quantification of the exposure and risk to pesticides in airplanes that land in the US and fly to countries requiring or performing disinsection be done since multi-route pesticide exposures occurs to flight crew and passengers on those aircraft. While exposures to pesticides from foods and residential applications is substantial in the US population understanding the additional risk of pesticide exposures to flight attendants, frequent flyers, pregnant women and children resulting from encountering pesticide residues in airplanes is needed.

4.5 References

Publications from ACER:
R.L. Maddalena and T.E. McKone "Pesticide Exposures on Commercial Aircraft: A Literature Review and Screening Level Exposure Assessment**"** Report from the Environmental Energy Technologies Division of the Lawrence Berkeley National Laboratory (LBNL-1246E) October 2008

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5.0 CABIN PRESSURE

Congressional Mandate: *Analyze and study cabin air pressure and altitude*

FAA reauthorization bill requires the Administrator to carry out the studies and analysis called for in the National Research Council's report ―The Airliner Cabin Environment and Health of Passengers and Crew[1]. The report summarized the need for study of the effects of cabin pressure as follows: "The partial pressure of oxygen at the currently allowed maximum cabin altitude of 2440m (8,000ft) may not be adequate for cabin crew and passengers of varying age and health status, such as elderly individuals with cardiopulmonary impairments."[*]

5.1 Introduction

In the 50 years from 2000 to 2050, the world population of people age 60 and older will more than triple, increasing from 600 million to 2 billion.[†] Researchers expect the percentage of the over-65 population who utilize air travel and the frequency with which they do so will be greater than previous over-65 populations because the Boomer generation was the first for which air travel was a common part of life including both low-cost business and recreational travel. This familiarity with air travel is expected to cause more Boomers to fly more often than previous generations.[‡]

The increase in older passengers means also an increase in unhealthy persons flying. In the U.S. 11.5% of the population has some type of heart disease, with over 27% of those 65-74 and over 37% of those 75 or older having some type of heart disease.[§] Moreover, the National Heart Lung and Blood Institute (NHLBI) estimates that annually 175,000 first heart attacks occur silently, without prior symptoms or their recognition.[**] In several observation studies, cardiac events caused 10%-20% of all in-flight incidents [††]and accounted for 12 of 15 in-flight deaths on the five major US air carriers over a one-year period.[‡‡] The issue of cardiac health aboard aircraft

[*] National Research Council. The Airliner Cabin Environment and the Health of Passengers and Crew. National Academy Press, Washington, D.C. 2002.

[†] http://www.who.int/en/

[‡] http://www.siu.edu/~aviation/facultyhome/hwolfe/NewDelhi.pdf

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[**] American Heart Association and American Stroke Association. Heart Disease and Stroke Statistics, 2007 Update At-A-Glance. http://www.americanheart.org/downloadable/heart/1166712318459HS_StatsInsideText.pdf

[††] Possick SE, and Barry M. (2004). Evaluation and management of the cardiovascular patient embarking on air travel. *Annals of Internal Medicine* 141 (2), 148-154.

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has garnered enough attention to warrant the FAA to mandate the placement of at least 1 automatic external defibrillator on passenger aircraft.[§§]

Besides the higher prevalence of cardiac disease in aging Americans, these individuals have higher exposures to tobacco smoke from current or past cigarette smoking (either active or passive smoking), the number one risk factor for lung disease. The U.S. Surgeon General's 2004 report on the health effects of smoking indicates that there is sufficient evidence to infer causal relationships between smoking and sub-clinical atherosclerosis, coronary heart disease, stroke, abdominal aortic aneurysm and chronic obstructive pulmonary disease morbidity and mortality.[***] Chronic Obstructive Pulmonary Disease (COPD) affected 11.4 million American adults in 2004[†††] and an additional 12 million demonstrate evidence of impaired lung function, indicating a potential under diagnosis of COPD.[‡‡‡] Importantly, individuals with either lung or heart disease face special challenges in even mildly hypoxic environments such as that aboard aircraft.

Even in the absence of overt disease, older passengers may be vulnerable aboard aircraft. Medical scientists acknowledge that advanced age is accompanied by a general decline in organ function, such as, the function of the heart or lungs.[§§§] Although the body generally exhibits compensatory mechanisms to maintain equilibrium, response times and performance may be compromised under stressful conditions.[****] For example, vulnerability due to advanced age may be particularly true in an aircraft environment pressurized in accordance with research findings based on mostly healthy, fit, and younger subjects.

Many industries are studying how to best accommodate the aging population through innovations to make their activities both feasible and comfortable given some of the restrictions of older age. Boeing, for example, has worked with intergenerational designers to understand how to make the cabin design more attuned to the needs of the aging Boomer population and some of their changing capacities with respect to diminished vision, hearing, dexterity, flexibility, strength, and stamina.[††††]

In addition to the increasing numbers of potentially unhealthy passengers, the consideration of possible physiological effects from mild hypoxic environments on pilots and crew is important because the public relies on their optimal functioning to protect passenger safety in-flight. The

[§§] Federal Register: April 14, 2004. Volume 69, Number 72. http://a257.g.akamaitech.net/7/257/2422/14mar20010800/edocket.access.gpo.gov/2004/04-8512.htm

[***] U.S. Department of Health and Human Services. The Health Consequences of Smoking. A Report of the Surgeon General, 2004.

[†††] National Center for Health Statistics. Raw Data from the National Health Interview Survey, U.S., 2003. (Analysis by the American Lung Association, Using SPSS and SUDAAN software).

[‡‡‡] Mannino DM, Homa DM, Akinbami L, et al. Chronic Obstructive Pulmonary Disease Surveillance - U.S., 1997-2000. Morbidity and Mortality Weekly Report. Vol. 51 (SS06); 1-16.

[§§§] Priebe, H.J. The aged cardiovascular risk patient. British Journal of Anaesthesia. 85 (5):763078. (2000).

[****] Priebe, H.J. The aged cardiovascular risk patient. British Journal of Anaesthesia. 85 (5):763078. (2000).

[††††] Ehrenman G. (March 2005). Mechanical Engineering Design. http://www.memagazine.org/supparch/desmar05/grayskies/grayskies.html)

[15] Aerospace Medical Association.. Cabin Cruising Altitudes for Regular Transport Aircraft. Aviation, Space, and Environmental Medicine, Volume 79, Number 4, April , 2008 , pp. 433-439(7).

Aerospace Medical Association, Aviation Safety Committee, released a position paper [15] recommending further research about the effects of mild hypoxia for passengers and for these worker groups in particular. A number of research studies have shown performance decrements between 5,000 and 10,000 feet, notably at altitudes below the current requirement for supplemental oxygen. In addition, the aging workforce of crew and pilots may be vulnerable because of the reduced oxygen capacity related to aging and because of the increased metabolic demands for oxygen in crew as they push utility carts down the aisles of jumbo planes at 34,000 feet.

In sum, the current FAA regulations for limiting cabin pressures to 8,000 ft. equivalent altitudes allow for mildly hypoxic conditions. Theses environments are expected to have little effect on healthy passengers, pilots or crew, however, older individuals and persons with compromised cardiopulmonary status may be at risk. More than thirty years has passed since the thresholds for pressure were set. In the meantime, new composite materials in the fuselage that withstand greater pressure differential between the cabin and outside air provide a potential for reducing the maximum cabin altitude to less than 8000ft. Newer aircraft are able to fly higher and for longer periods, extending the exposure to hypoxia. Also, new portable devices that concentrate and deliver personal oxygen have been approved for medical conditions and for in-flight use. Yet experts argue that current guidelines that determine medical fitness for flying or need for in-flight oxygen lack sufficient scientific evidence for health protection[15]. The need for closing these gaps in information has never been more important given the rise in older and health compromised passengers (see Figure 5.1**).** The COE pressure studies attempted to answer this need by establishing the health effects of current cabin pressures in susceptible passengers.

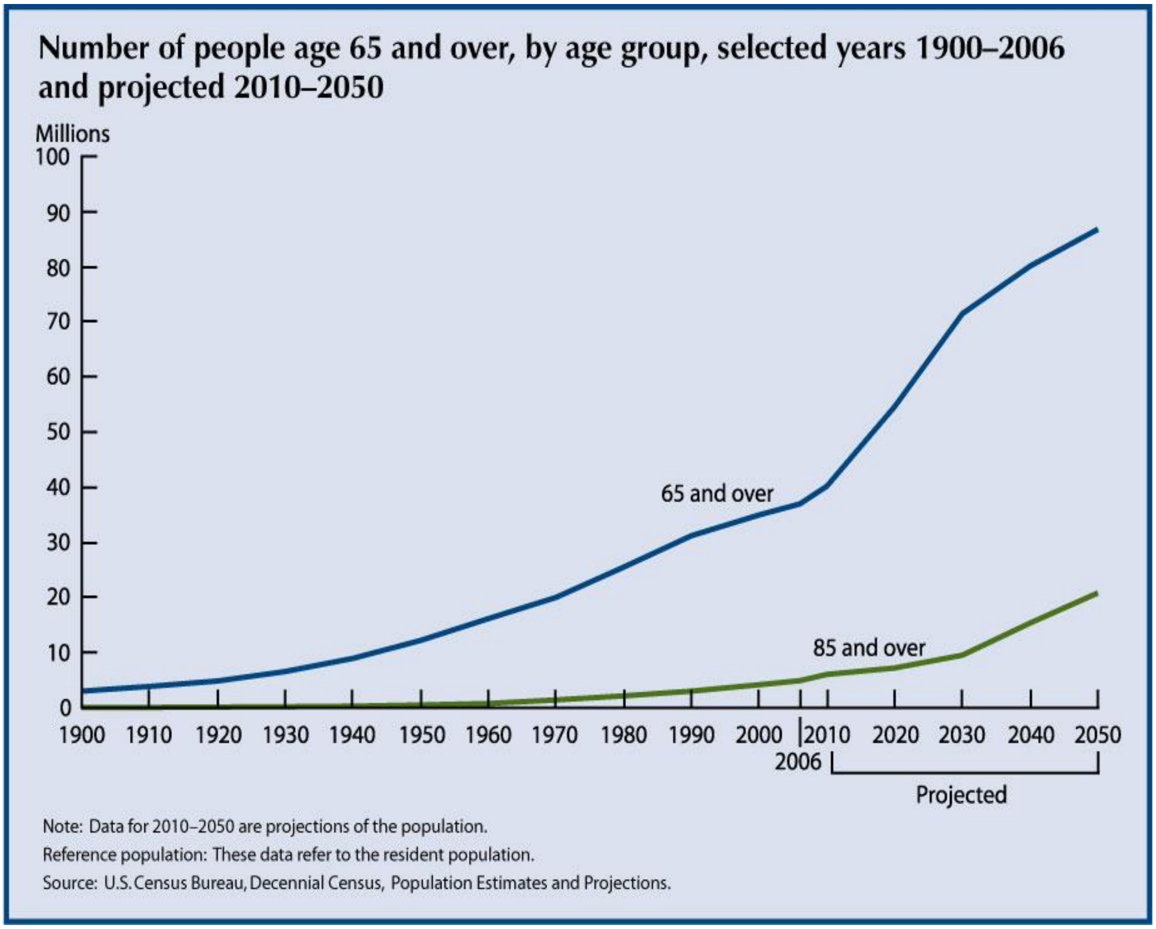


Figure 5.1 Number of people age 65 and over, by age group, selected years 1900-2006 and projected 2010-2050

Following the NRC recommendations, ACER/RITE researchers collected data about cabin pressures and examined pressure-related health effects. A number of complimentary studies were conducted to understand the relationship between cabin pressures and altitude and the health effects in susceptible passengers. Three projects aimed to collect the following information: 1) measurement of typical pressures and altitudes aboard commercial flights 2) measurement of the physiological responses in older passengers and susceptible passengers (passengers with chronic disease) in a monitored simulated flight [hypobaric chamber] and 3) measurement of physiological responses in passengers aboard actual commercial flights.

5.2 Approach

5.2.1 The design and deployment of miniaturized sensors to read pressure and altitude

To understand the effects of pressure on human health and comfort, it is necessary to know the range of cabin pressures that passengers typically experience aboard commercial flights. This information about pressure levels can be linked to personal monitoring of human responses in flight. To this end, Boise State and Kansas State investigators designed a portable sensor to capture cabin pressures. Pressure has been recorded on over 200 flights in the cabin throughout ascent, cruise and descent. These devices supported also a succession of health studies with passengers wearing personal monitors recording cardiac and respiratory function.

Data from these sensors explored the relationship between aircraft altitudes and cabin pressures. Scientists were able to chart usual pressures as seen in Figures 5.2 and 5.3. In total, minimum cabin pressure has been recorded on over 300 flights and no significant excursions above 8000ft cabin altitude (less than 75 kPa cabin pressure) have been found.

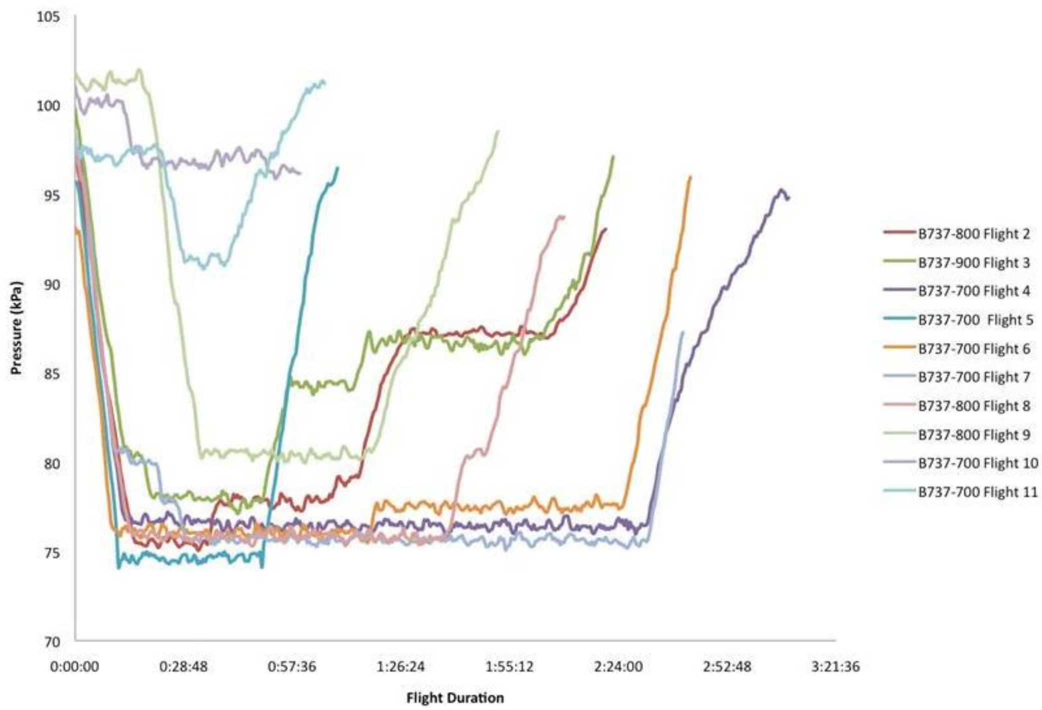


Figure 5.2 Sample cabin pressures from B737 aircraft

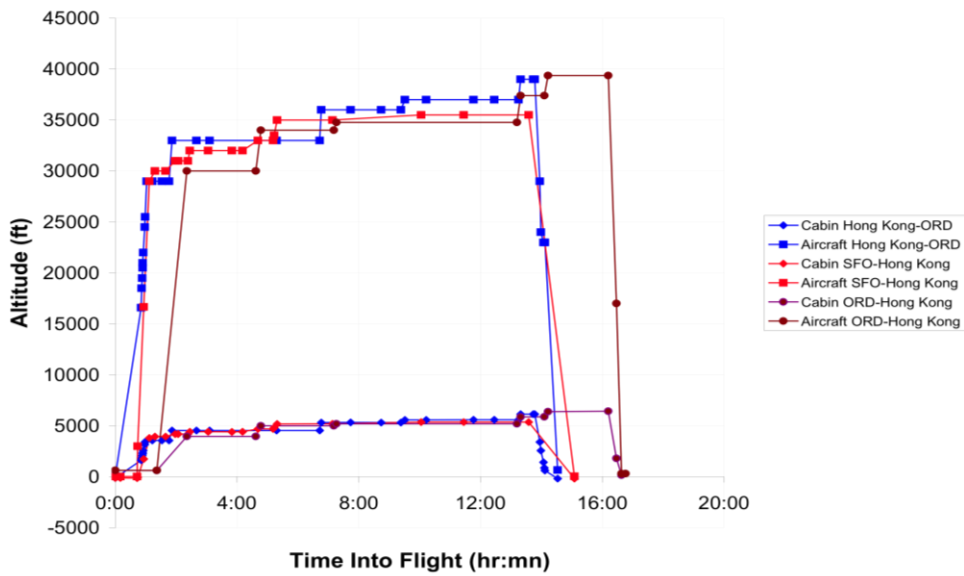


Figure 5.3 Data of aircraft altitude during a sample of international flights

5.2.2. The study of physiological responses of older passengers and susceptible passengers (passengers with chronic disease) in the course of simulated flight and actual commercial flight.

Study Design

To understand the effects of mild hypoxia in older healthy and compromised passengers, we monitored individuals before, during, and after, a 5-hour flight in a hypobaric chamber with pressurization equivalent to a commercial flight at 7,000 feet altitude (While commercial airplanes usually fly at altitudes around 34,000 feet, pressurization of the cabin results in a pressure equivalent to less than 8,000 feet.) In addition, we monitored these individuals for the same period of time on another day, including the time in the chamber, however, pressures were near sea level altitudes while individuals were in the chamber. Subjects were assigned to one of seven weeks to complete both chamber days (control day and exposure day) with 5 to 6 participants in each trial. Each group was blinded to the exposure condition (decreased pressure) and, the order of the exposure day varied among the groups.

For a subset of the participants (N=6), we repeated the physiological measurements over 3 days during 3 commercial flights between Oklahoma City and Baltimore, Baltimore and Las Vegas, and Las Vegas and Oklahoma City.

Study Sample

Participants in the study had a prior history of air travel and no contraindications for flying. In addition, participants were over 50 years of age, either male or female, and met criteria for one of three subgroups of particular study interest: “healthy” non-smokers, “healthy” smokers (i.e. smokers without diagnosed cardiac or respiratory disease), and stable cardiac patients without restricted activities of daily living. These subgroups were chosen to represent a “typical” older passenger, albeit, in the upper range of healthy for seniors. We targeted older passengers because few studies addressed the health consequences of mildly hypoxic aircraft environments for older passengers specifically, despite the known association between age and oxygen saturation in the blood. We included high functioning cardiac patients given the prevalence of the disease and the known risks for hypoxia with cardiovascular impairment. Finally, we selected smokers because of the potential for oxygen deprivation in the presence of carbon monoxide or mild respiratory disease secondary to smoking.

In the Fall of 2007, subjects were recruited via medical clinics, newspapers, senior centers and fitness centers in the greater Oklahoma City area because of access to the hypobaric chamber at the Federal Aviation Administration (FAA) Civil Aerospace Medical Institute (CAMI) in Oklahoma City. Volunteers were screened by a nurse practitioner on the telephone and scheduled for a physical exam if they met inclusion criteria. The clinical evaluation further excluded individuals with serious health conditions and documented the baseline health status for qualified individuals.

Selected subjects participated in 2 days of monitoring in a hypobaric chamber and one follow up day, in a given week during the period December 2007 through June 2008. Six of these subjects participated also in 3 commercial flights in the next calendar year. For the chamber experiment, researchers provided meals and paid participants three hundred dollars. For the commercial flight, participants received monies for meals, airline tickets and travel-related expenses. All study participants were consented in accordance with the protocols approved by the Human Subjects Committees at Harvard School of Public Health, CAMI, and the Oklahoma University Medical Center.

The final sample for the chamber study consisted of 14 healthy seniors, 13 cardiac patients (12 of the cardiac patients had a diagnosis of mild to moderate heart failure), and 14 smokers. All subjects completed both days of the chamber experiment except for one cardiac patient who did not return for the second day because of a work conflict. For the commercial flight, 4 of the cardiac subjects and 2 of the healthy non-smoking subjects were included.

<u>Instrumentation -measures</u>

The CAMI hypobaric chamber contained 12 commercial airline seats arranged in 4 rows with 3 seats across. Participants were seated one on the aisle and one against the window, and the middle seat empty, in rows 2 through 4. Chamber gauges recorded humidity, temperature, noise, pressure, carbon dioxide, and pressure. A medical monitor and a research assistant were present in the chamber with the participants during the experiments.

Each participant wore a LifeShirt™ (Vivometrics, Inc. Ventura, CA, USA) to monitor cardiac and respiratory parameters. The LifeShirt is a fitted vest made of light weight lycra material and embedded with non-invasive sensors; a single-axis electrocardiograph and two respiratory sensors at the level of the rib cage and abdomen. The respiratory sensors are used for inductive plethsmography to derive respiratory measures such as minute ventilation (a proxy for oxygen consumption and directly related to metabolic activity) tidal volume, respiratory rate, fractional inspiratory ratio and peak inspiratory flow. The cardiopulmonary measures were recorded with an attached data logger that also recorded ambulatory blood pressure and pulse oximetry from peripheral devices. The recorder transmitted physiological waveforms to computers displays outside the chamber for monitoring of participants in real time throughout the experiment. Vivometrics software is used to process and analyze these data according to time, waveform or derived variables.

Subjects completed cognitive performance tests (ANAM test battery) on laptops while in the chamber. These tests included measures of reaction time, memory, and higher order mental processing. The tests were administered every two hours. In addition, subjects competed a series of surveys every hour to account for symptoms of altitude sickness (e.g. Acute Mountain Syndrome).

While in the hypobaric chamber, participants were encouraged to conduct themselves as they would aboard a commercial flight. They could eat, sleep, rest, read, watch movies, move about or talk freely. Meals and snacked were served by the research assistant. The back of the chamber also contained a bathroom.

When participants were exposed to hypoxia, research phlebotomists collected blood specimens at the height of maximal exposure after entering and leaving the chamber through an outside pressure-locked room.

In the morning of the experimental day, and in the morning of the following day, the researchers collected urine and blood samples, including overnight urine samples from the night before and the night after the hypoxic exposure. Each day of the protocol, researchers collected data about cognition, performance, health status, sleep quality, and fatigue.

5.3 Results and Discussion

Participants across the subgroups of "healthy", "cardiac", and "smokers", had similar sea level oxygen saturation and weight, however, the "healthy" group was slightly older on average and the "cardiac" group had decreased lung function as noted by the forced expiratory volume at one minute (FEV_1) and forced vital capacity (FVC) (see Table 5.1).

Despite good oxygen saturation at sea-level in all of the participants, half in each group markedly desaturated for the majority of the simulated flight. Marked desaturation (Table 5.2) was noted as peripheral oxygen saturation less than 90% (SpO2<90), the level at which patients typically receive oxygen in the emergency room.

Of note, age was associated with greater declines in oxygen, although this effect was diminished after 67 years of age (see Figure 5.4).

Table 5.1 Characteristics of Participants at Baseline

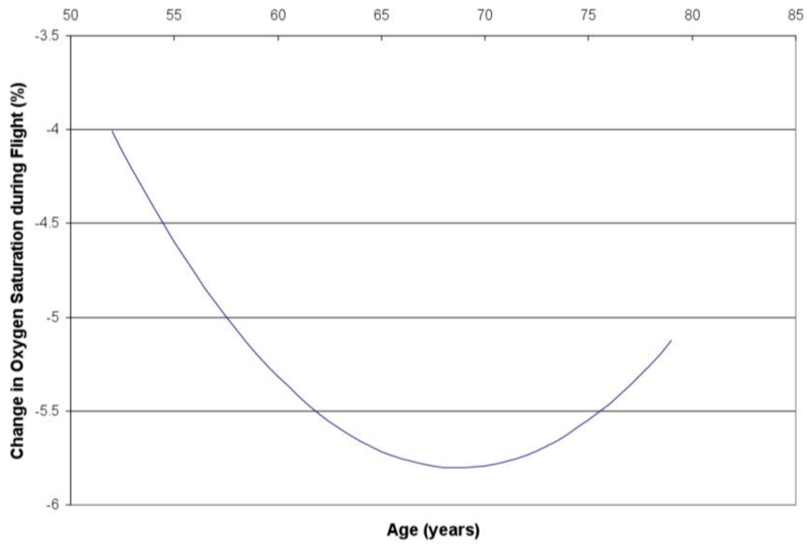
	Healthy (n=14) Females (n= 6)		Cardiac Disease (n=13) Females (n=3)		Smokers (n=14) Females (n=5)	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Age (yr)	67 (6)	60, 77	63 (8)	54, 73	61 (8)	52, 79
BMI (kg/m^3)	28 (5)	20, 41	30 (5)	21, 38	27 (5)	21, 40
SaO_2 (%)	97 (1)	94, 99	97 (2)	94, 99	98 (1)	96, 99
FEV1 (%)	93 (22)	56, 132	71 (14)	47, 91	81 (12)	60, 103
FVC (%)	89 (16)	59, 113	74 (12)	53, 94	88 (12)	64, 109
FEV1/FVC	0.80 (0.11)	0.49, 0.92	0.73 (0.08)	0.58, 0.87	0.71 (0.08)	0.55, 0.81

* FEV1 and FVC are based on percent of predicted capacity based on age, gender and ethnicity

Table 5.2 Number of Notable Desaturations during Cruise According to Subject Category

Effect of pressure (~7K altitude) in each group

Participant group	Total number participants	Participants with SpO2 < 90% for > 50% of flight
Older, healthy	14	7
Cardiac-compromised	13	7
Smokers	14	7



* Measure of change based on difference between control and flight days (middle column previous slide).
Estimates for healthy females of average BMI and FEV1 % predicted (across age range in study).

Figure 5.4. Association between age and change in SaO2 during flight.

In addition to age, other factors that were associated with declines in oxygen saturation at altitude ~ 7,000 feet were: female gender, smoking history, history of hypertension, being overweight or obese, decreased lung function, lower oxygen saturation at sea level, and sitting in window seat compared to an aisle seat. Each of these factors contributed to the level of desaturation in flight (See Table 5.3). Interestingly, only impaired lung function, such as chronic and severe asthma, emphysema, pulmonary fibrosis or chronic obstructive lung disease, typically triggers consideration of the need for in-flight oxygen by patients and medical providers. Yet, based on our results, other factors need to be considered also to more accurately predict of in-flight desaturation. Most importantly most medical guidelines suggest that a sea-level oxygen reading of less than 95% is an appropriate predictor of in-flight desaturation. Our results suggest this guideline would grossly understimate the number of passengers likely to desaturate given that half of our participants destaurated and most of them were clearly above that cut off for recommending in-flight oxygen.

Table 5.3: Predictors of SaO2 During Flight

	Estimate (95% CI)	p-value
Intercept	89.2 (87.9, 90.6)	<0.001
Age (10 y)	-1.40 (-2.24, -0.56)	0.001
Sex (male)	1.39 (0.33, 2.46)	0.010
Smoker	-1.47 (-2.58, -0.35)	0.010
Hypertension	-1.37 (-2.42, -0.33)	0.010
Asthma	-1.43 (-3.30, 0.44)	0.134
BMI (< 25 kg/m^2)	1.34 (0.17, 2.51)	0.025
FEV1/FVC (per 0.1)	0.99 (0.47, 1.51)	<0.001
Baseline SaO_2 (1 %)*	0.57 (0.15, 0.99)	0.007
Aisle	1.11 (0.06, 2.17)	0.039
CO_2 (0.1 ppm)	0.29 (0.14, 0.43)	<0.001

*Measured during pre-study screening by physician. Mean 97.2 (SD=1.5, range=94 to 99)

We also looked at other effects of flight conditions on physiological outcomes. Specifically, because oxygen desaturation causes compensatory reactions, such as increased heart rate, we looked at the risk of arrhythmias during flight. We found an increased rate of lower chamber beats (ventricular couplets and runs) (see Figures 5.5 and 5.6) during flight in passengers with susceptibility to arrhythmia (diagnosed heart disease with implanted cardiac defibrillators). In patients with implantable cardioverter-defibrillators, premature ventricular beats are the most common instigator of monomorphic ventricular tachycardia[16]. In addition, the presence of any prematureventricular beat in healthy men is associated with an increased risk of sudden cardiac death[17], suggesting that increased VE may put subjects at risk for malignant arrhythmia.

[16] Saeed M, Link MS, Mahapatra S, Mouded M, Tzeng D, Jung V, Contreras R, SwygmanC, Homoud M, Estes NA 3rd, Wang PJ. Analysis of intracardiac electrograms showing monomorphic ventricular tachycardia in patients with implantable cardioverter-defibrillators. Am J Cardiol. 2000 Mar 1;85(5):580-7. PubMed PMID:
11078271.

[17] Abdalla IS, Prineas RJ, Neaton JD, Jacobs DR Jr, Crow RS. Relation between ventricular premature complexes and sudden cardiac death in apparently healthy men. Am J Cardiol. 1987 Nov 1;60(13):1036-42. PubMed PMID: 3673904.

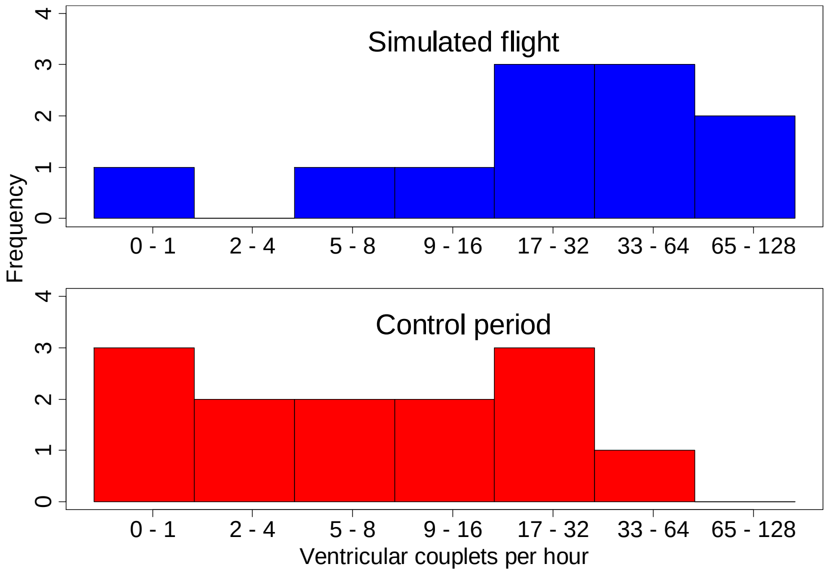


Figure 5.5 Frequency of ventricular couplets during flight compared to ground (control) conditions.

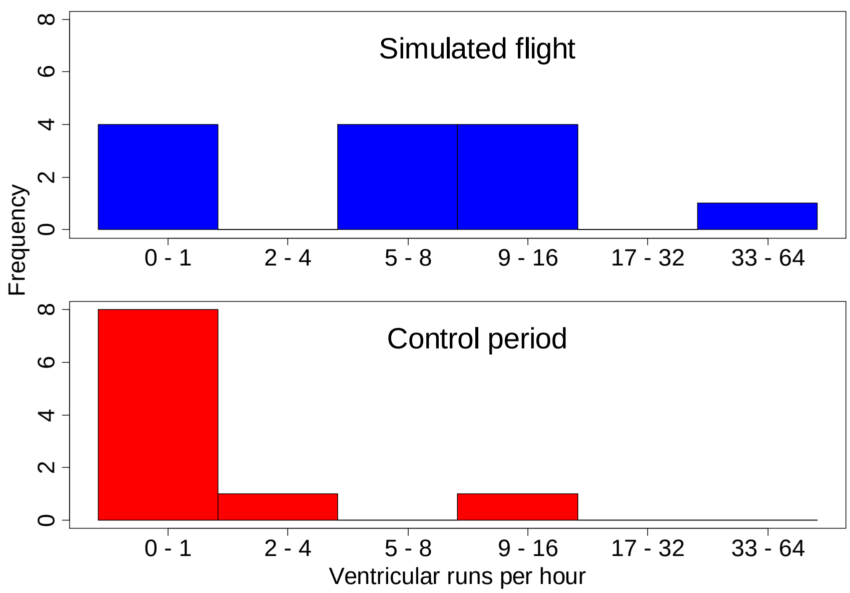


Figure 5.6 Frequency of ventricular runs [3 or more extra beats] during flight compared to ground (control) conditions.

The findings discussed above apply to the simulated flight (chamber study). The in-flight study, aboard commercial planes is still in progress, although temporarily halted because of heightened on-board security this past summer. With just six passengers completing actual flight, the results show no significant differences between the simulated flights and the actual flights in terms of altitudes and cabin pressures, suggesting that the in-flight studies will add valuable information about the flight experience and health effects.

5.4 Implications

These studies are the first single-blinded investigations of the physiological effects of pressure in susceptible passengers we know of. These studies suggest that a significant portion of older passengers may be at risk of hypoxia at 7,000 feet equivalent cabin pressures. Further, there was an increased risk of arrhythmias in passengers with implanted cardiac defibrillators.

None of the passengers in the study had received a recommendation from their doctors to use supplemental oxygen in flight and they never considered inquiring about it. Further, according to current medical guidelines, oxygen would not be suggested for these individuals. This research brings into question the protections against significant desaturation at 7,000 feet equivalent pressures for susceptible individuals. Also, the risk of cardiac arrhythmias in flight demands more study to evaluate the safety of current cabin pressures in susceptible passengers, considering that our study evaluated only 7,000 feet equivalent altitudes when the FARs allow up to 8,000 feet. Additionally, this study raises other questions about the possible prolonged effects of cabin pressures in susceptible passengers in the context of ultra-long flights (the current study included 3.5-4.5 hour flights only) or when these passengers fly to high altitude destinations.

Still to be considered in terms of the health effects of pressure are pilots and crew. Crew may be at greater risk of desaturation because of increased activity that consumes more oxygen in the first place. Therefore, future studies should target these groups in particular.

6.0 Incidents - Cabin Air Quality

Congressional Mandate: *Identify, analyze, and study incidents of air contamination associated with typical flight operations monitored with onboard sensors*

FAA reauthorization bill requires the Administrator to carry out studies of cabin air quality events including a series of studies to assess the feasibility of collecting in-flight exposure data and the possible relationship to health symptoms in cabin crew.

6.1 Introduction

In this study, we sought to advance information about specific cabin environmental contaminants that may affect the health and performance of flight attendants. We planned and tested a process for gathering the relevant data including the development and deployment of portable air monitoring devices. Another outcome of the project was the systematic collection of data about prevalent health conditions in this highly mobile workforce that had not been fully characterized.

The study, " Cabin Air Quality Incidents Project", was funded by the FAA to research the incidence and prevalence of health effects in flight crew due to exposure to bleed air contaminated with pyrolyzed engine oil or hydraulic fluid. "Bleed air" refers to outside air that is compressed in the aircraft engines or auxiliary power unit (APU), conditioned and cooled in the aircraft environmental control systems, mixed with about 50% recirculated air (typically, only applies to the cabin), and then routed to the cabin and flight deck. The design, operation, and maintenance of the bleed air system could lead to pyrolyzed engine oil or hydraulic fluid leaks into the cabin and flight deck air supply. Some causes of contamination include worn oil seals that would otherwise separate the dry and wet sides of the engine/APU compressors, overfilling the engine oil reservoir, burst hydraulic fluid lines, and positioning the APU inlet at the six o'clock position in the aircraft tail. No systematic fleet-wide or industry-wide audits have been conducted to document the incidence of bleed air events.

There are two other research components conducted in response to this Congressional Mandate relates to assessing the air contaminants associated with "typical" operations. ACER investigators joined with Battelle Memorial Laboratories to assess passenger and crew responses to multiple flight parameters including air quality. This joint effort funded by ASHRAE and FAA is still ongoing with over 100 flight segments completed and 24 currently being monitored. In this research component, the instruments are fitted into "suitcases" that can be carried on board. In the second research component, a highly portable sensing system is used. Sections 6.2 through 6.4 relate to the feasibility of conducting an evaluation of incidents of bleed air contamination with the primary focus on evaluation of the baseline health status of flight attendants. Section 6.5 thought 6.8 pertain to the research and preliminary findings of the joint ACER/Battelle ASHRAE study of on-board conditions. Section 6.9 shows the approach and findings of the portable sensing system.

To address concerns expressed in the Congressional Mandate and provide the basis for the eventual creation of appropriate standards, ASHRAE developed the RP-1262 program to relate air quality and other factors to the comfort and health of airline passengers and crew. Battelle conducted Part 1 of the RP-1262 program and the Battelle-ACER project team was awarded a contract to conduct Part 2. The project team has been working in close collaboration with other partners in the Federal Aviation Administration (FAA)-sponsored Center of Excellence (CoE) on Airliner Cabin Environment Research (ACER) and now Research in the Intermodal Transport Environment (RITE) to address complimentary project

6.2 Approach

The Study of Possible Health Effects in Cabin Crew Related to Incident Events.

Study Design

We obtained baseline health information in a sample of flight attendants via a health survey. The information could be used as a baseline for future comparisons with repeated administration, including after a fume event. Although the contemporaneous collection of exposure information with updated health surveys was not possible in this pilot study, we gathered important data about prevalent health conditions in a flight attendant workforce. This survey was the largest random sample of flight attendant health we know, and establishes benchmarks for health promotion activities and occupational health and safety prevention programs, including further investigations into the work-relatedness of health symptoms and workplace interventions to mitigate them.

Instrumentation - Measures

The flight attendant health survey fulfilled three main purposes: (1) to collect a baseline description about the health of the flight attendant population; (2) to collect health information that could be used for later comparisons in the event of particular exposures; and (3) to test the feasibility of recruiting flight attendants to participate in further monitoring and evaluation, including the possibility of on-board air sampling of fume events.

The survey questions were developed after we conducted several focus groups with flight attendants to discuss their work and their health. We recruited volunteers through union websites, posters displayed in crew rooms, and flyers distributed by the Association of Flight Attendants-CWA, AFL-CIO (AFA) labor union. We held a total of six focus groups in Chicago and Los Angeles in the fall of 2005. The focus group participants helped us to define specific content to be included in the survey. With the benefit of the focus group member insights, we identified specific subject matter for the survey, using standardized survey questions whenever possible or developing new questions tailored to the work of flight attendants.

Study Sample

To insure that our findings were not biased and represented the larger workforce, we administered the survey in two ways (see Figure 6.1). The first method was a mailed survey based on a subset of addresses selected by randomization from a union list that included two airlines, referred to as Airline A and Airline B. We selected from only those addresses connected to five airport hubs (the largest hubs for each airline). We randomly chose 50% of the flight attendant addresses from those hubs to receive a survey in the mail (n =5398)[‡‡‡‡].

The randomized pick of addresses was important to insure that all flight attendants had an equal chance of receiving a survey. With randomization, we were likely to have the same distribution of flight attendant characteristics in our sample, such as age and gender, as in the overall population. In addition, if we selected participants in a random way, the respondents would be less likely to reflect only flight attendants with health interests (because they were very healthy or very unhealthy) if a fair number of the invited participants responded. The response rate from the mailed survey was close to half of those we invited (48%) and exceeded our expectations. We had been forewarned by union representatives, focus group participants and airline management to expect a participation rate between 3 and 10 percent. We considered this response sufficient to guard against significant reporting bias (such that non-participants were remarkably different than participants).

We mailed a survey packet to every address selected from the master list of flight attendants in target hubs. The survey packet contained a nine-page double-sided questionnaire with a cover sheet explaining the study and a postage-paid return envelope. All flight attendants targeted through the mail received two copies of the survey packet over a several week period. The specific protocol included the mailing of a survey packet, a reminder postcard, and a second survey packet in the 6th or 7th week. The AFA union publicized the study through print materials such as newsletters, faxes and posters, in addition to messages on their website. Participation was encouraged by the chance to win lottery prizes with the return of a completed survey. The Human Subjects Committees at Harvard School of Public Health and the University of Oregon approved all protocols.

[‡‡‡‡] Importantly, there were some differences in procedures between the two airlines. Airline A had the opportunity to complete an online survey, but this mechanism was chosen least by flight attendants. Another difference was that we oversampled Airline A to capture more full-time workers that were less prevalent in this population (selecting 70% of the hub population for the mailed survey versus 50% at Airline B).
The second method of survey administration involved on-site distribution of the survey at the five target hubs. Generally this was done in public spaces close to the flight attendant crew rooms (i.e. where the flight attendant would go at the airport to prepare/check-in for their flights or check-out after flight). We spent approximately 250 hours on location distributing surveys along with a postage paid envelope for return mail if the flight attendant preferred to complete it at a later time. Otherwise, we collected the surveys in the airport. At the same time, as a visible draw for the survey campaign, we displayed gifts that would later be raffled among survey participants. Airline B also had an incentive donation of $1 to their union relief fund for every survey returned.

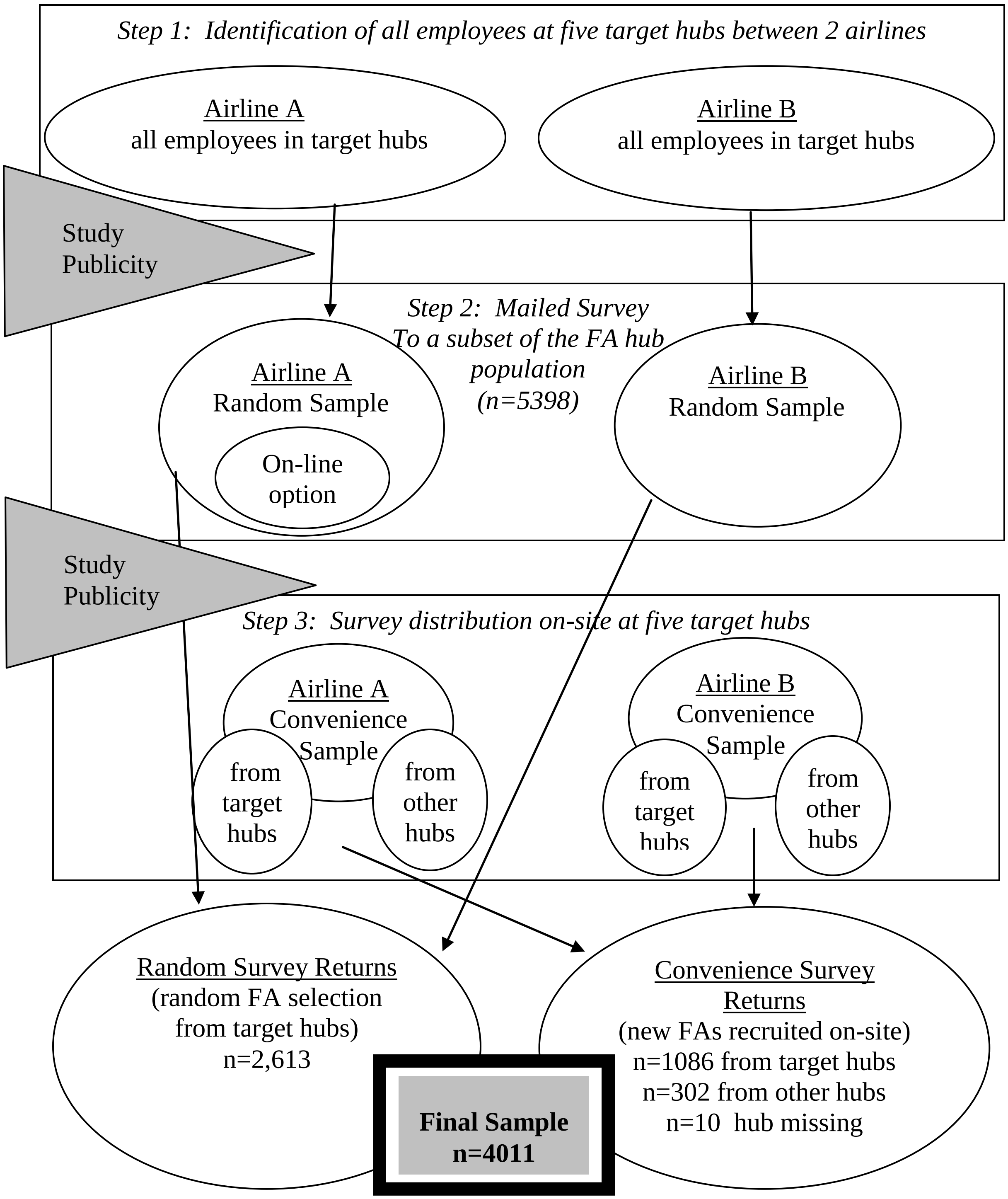


Figure 6.1 Flow chart for sample selection and distribution of the survey

We handed out the survey in person to supplement our mailed sample because we expected very low participation in this highly mobile workforce (we projected at 3-10% returns rate based on feedback from our focus groups and reports from the union and statements from the airlines). In addition, because we were unable to obtain airline management support to distribute and collect the survey on the job despite nearly two years of effort, we were concerned about how management's objections would affect employee participation.

The on-site campaign targeted flight attendants not selected by the random pick for the mailed survey. We also accepted surveys from flight attendants chosen at random to receive a survey by mail. Numerous flight attendants mentioned that they had received the survey in the mail but that it was easier for them to complete and return one to us on-site. All surveys were tracked with numerical codes and only one survey per flight attendant counted. All survey names selected by the random draw for the mailing were classified as such, even when the survey was collected on-site. For all takers of the on-site survey, our physical presence was intended as a convenience and as an invitation for participation. In addition, by being on-site, we attracted participation from 605 flight attendants from outside the target hubs who happened to be passing through the hubs while we were on the premises.

The final tally of surveys collected by mail or by our researchers stationed at the hubs was 4011. The flight attendants in this sample included: 1) flight attendants randomly selected for the mailed survey (n =2615), 2) flight attendants not randomly chosen for the mailed survey, but nonetheless employees from that hub that we reached while on the premises (n = 1086), and 3) flight attendants, not part of the target hub populations yet employees from other domiciles of the same airlines, "on-route or passing though" while we were on location. Flight attendants from domiciles outside the target hubs comprised 605 of the 1086 surveys collected on site. Not considering this last group of participants, we successfully recruited 37% of the entire population in the target hubs. The large majority of the surveys (almost two-thirds) were chosen at random, the preferred participation to avoid a self-selected non-representative participant sample.

6.3 Results and Discussion

Flight Attendant Sample - Personal and Job Characteristics

In the series of graphs and figures that follow, we show the personal and job characteristics of the survey respondents.

Gender

Overall, the sample was predominately female (80 %). Airline A had a slightly higher ratio of male to female flight attendants

Age

The mean age was 47 years with forty flight attendants between 64 to 76 years. Fifty-eight percent of the flight attendants were 45 years of age or older and the average age of the participants in Airline B was slightly higher. Overall, the average age of the respondents matched the mean age for the entire crew population in the target hubs (including non-participants) at Airline A and Airline B, 45 and 47 years respectively.

Education

The number of respondents in the sample with a 4-year college degree or higher level of education was 45 %. Relative to Airline A, Airline B had slightly more years of education.

Smoking

We asked about current and past smoking. The majority of respondents did not smoke.

Job Characteristics

We asked specific questions about the job such as length of service, average hours worked in the previous three days, past month or last year. Two-thirds of respondents worked as a flight attendant for their current employer for more than 10 years and 36% worked for the same employer 20 or more years. Forty-one percent had 20 more years of experience as a flight attendant counting previous employers (not shown below). Once again, the sample characteristics mirrored the experience profile of the entire crew workforce in the target airline hubs; for Airline A, the average tenure was13 years, and for Airline B, the average tenure was 18 years.

Flight Attendant Health - Prevalence of Conditions

Self-Reported Health

In the survey, we asked the flight attendants about their health in several ways to understand the most prevalent health conditions. We queried the participants about symptoms, diagnoses, care seeking, treatment and work-related injuries to chart the most common conditions in the workforce.

We attempted to characterize health conditions according to descriptions of temporality, frequency and severity. For example, we sorted conditions that were active by asking whether the flight attendant had experienced these conditions in the last week or in the last 12 months, or whether they had been diagnosed ever with a condition. For the most recent problems, we asked the flight attendant to delineate how often the problem occurred over the last several days. We assumed that more frequent problems were suggestive of greater severity (i.e. problems that the flight attendant experienced almost everyday in the past week). Further, we assumed that more severe problems would lead to seeking care (i.e. the flight attendant saw a health care provider), although we asked about care seeking over the last year to account for intermittent or chronic conditions. Also, as an alternative proxy for severity, we asked about all conditions that drew a medical diagnosis by a health care provider (e.g. “Did a health care provider ever tell you that you had...”).

The information about health is presented in a series of tables below that correspond also to four main questions in the survey; questions about health experience in the past week, questions about health experience in the past 12 months, questions about health experience defined by particular diagnoses, questions about work-related injury or illness.

Health Experienced over the Past Week
We asked the flight attendants about specific health symptoms over the previous week to index active or current problems. We gauged the severity of these problems by eliciting information about frequency or duration. For example, for any condition in the survey, the flight attendant could respond according to the number of days that he/she experienced the condition in the last week, such as "Never; 0 days", "Rarely; 1-2 days", "Sometimes; 3-4 days", "Often; 5-6 days" and "Everyday; 7days".

We categorized the problems according to the most prevalent conditions. In the table below (Table 6.1), we note the most frequent problems (i.e. "Often" or "Everyday"] in red. These conditions were cited by at least 20% of the flight attendants. The symptoms highlighted in blue designate slightly less common conditions in comparison reported by at least 10% of flight attendants. In all, these symptoms profile the current health experience of the flight attendants in the past week.

The more notable conditions in order of most prevalent among flight attendants include: sleep problems (35%), all types of musculoskeletal pain (between 23-28%), sinus congestion (28%), fatigue (26%), anxiety/stress (20%) and bloating (20%).

Considering all frequent conditions together, the most prevalent conditions fall into several main categories according to body system affected (listed in no particular order): 1) respiratory (sinus, ear, cough) 2) neurological/psychological (dizziness, loss of coordination/balance, muscle weakness, fatigue, irritability, anxiety, depression) 3) musculoskeletal (general aches and back/shoulder/elbow/wrist/hand/feet pain) 4) eye problems 5) other general problems (bloating).

Table 6.1 Percentage of Sample Reporting Condition in Past Week by Frequency

CONDITION	In the past week, how many days did you experience the symptom?					
	Never (0 days)	Rarely (1-2 days)	Some-times (3-4days)	Often (5-6 days)	Every-day (7days)	Number of Flight Attendants
Eye irritation, pain	43.3%	27%	18.8%	7.3%	3.5%	3,707
Blurred /altered vision	57.2%	21.6%	13.7%	5.1%	2.4%	3,623
Sinus congestion	26.5%	20.5%	24%	18.1%	10.9%	3,789
Ear pain/blockage	46.3%	25.6%	18%	7.5%	2.4%	3,705
Nosebleeds/irritation	72%	15.7%	7.3%	3.7%	1.3%	3,666
Sore throat/irritated/burn	55.2%	24.1%	13.7%	5%	2%	3,696
Cough	48%	25%	16.2%	6.2%	4.6%	3,743
Hoarseness/loss voice	66.2%	18.6%	10.1%	3.5%	1.6%	3,704

(Table 6.1 continued) CONDITION	In the past week, how many days did you experience the symptom?					
	Never (0 days)	Rarely (1-2 days)	Some-times (3-4days)	Often (5-6 days)	Every-day (7days)	Number of Flight Attendants
Shortness of breath	66.3%	19.0%	9.8%	3.5%	1.5%	3,721
Chest tightness	76.2%	14.2%	7.1%	1.8%	.6%	3,694
Chest pain	84.7%	10.4%	3.8%	,8%	.2%	3,671
Heart racing/pounding	67.7%	19.8%	9%	2.7%	.7%	3,706
Stomach pain	62.1%	21.5%	11.7%	3.4%	1.4%	3,715
Nausea	67.2%	21.7%	8.2%	2.3%	.5%	3,703
Vomiting	91.3%	7.2%	1.3%	.1%	.08%	3,684
Diarrhea	64.7%	21.7%	9.8%	3.0%	.8%	3,703
Bloating	30.4%	21.0%	23.4%	17.2%	8%	3,750
Fainting	95.5%	3.1%	1.1%	.3%	.05%	3,670
Dizziness	62.4%	25.3%	8.5%	3.1%	.7%	3,708
Coordination/balance loss	66.0%	22.6%	8.2%	2.5%	.8%	3,702
Shaking/tremors	87.9%	7.8%	2.8%	.8%	.6%	3,650
Numbness/tingling-face,extremities	68.8%	16.5%	8.2%	3.5%	3%	3,714
Severe headache	57.9%	23.9%	11.6%	5.5%	1%	3,729
Confusion, difficulty Thinking/finding words	56.3%	22.5%	13.2%	5.4%	2.5%	3,737
Difficulty concentrating	45.3%	30.5%	15%	6.8%	2.5%	3,746
Fatigue/unusual tiredness	20.4%	27.3%	25%	17.5%	9.9%	3,817
Anxiety or stress	30.4%	29%	20.7%	13%	7%	3,778
Depressed mood	46.2%	27.2%	15.1%	7.8%	3.8%	3,751
Apathy	58.4%	21.8%	12.1%	5.2%	2.5%	3,662
Irritability	31.0%	36.1%	20%	9%	3.8%	3,696
Sleep disturbances Inability to stay awake or Go to sleep	16.9%	23.1%	25%	20%	15%	3,827
Alterations in taste/smell	81%	11.2%	5%	1.8%	1.1%	3,706
Chemical sensitivity	77.8%	10.4%	6.0%	3%	2.7%	3,684
Calf pain	64.2%	17%	11%	4.6%	3.1%	3,687
Back pain	26.4%	23.2%	22.7%	15.6%	12.1%	3,787
Foot pain	28.4%	22.5%	20.6%	15.2%	13.3%	3,775
Shoulder/elbow/ wrist/hand pain	31%	19.7%	19.8%	15.3%	14.1%	3,792
Generalized muscle aches	30.1%	24.9%	21.7%	12.3%	11%	3,775
Muscle weakness	54.7%	20.8%	12%	6.3%	6%	3,721

Health Experienced over the Last Year

In order to capture health problems that may be chronic or disabling, we asked the flight attendant about several *health conditions that resulted in seeking care or treatment in the past twelve months*. Table 6.2 summarizes these problems. The conditions highlighted in red were reported most frequently. Notably, health conditions experienced *in the past year* are not always the same as the health conditions experienced *in the past week* (see Table 6.1). In other words, problems in the past week or in the past year were not asked in the same way.

Table 6.2 Percentage of Flight Attendants Seeking Treatment for Condition in Last 12 months

CONDITION		# Respondents	SOUGHT TREATMENT (as percentage of respondents)	
Body System	Symptom		NO	YES
Respiratory System	Reactive airways, sinusitis,allergies	3,850	45.3%	54.7%
	Shortness of breath/ reduced lung capacity	3,787	84.5%	15.5%
	Other respiratory symptoms	3,436	85.4%	14.6%
Neurological System	Severe headache	3,804	76.6%	23.4%
	Coodination/ Balance loss	3,795	90.9%	9.1%
	Tremors/shaking	3,785	96.3%	3.7%
	Seizures/ Loss of consciousness	3,782	99%	1%
	Memory loss/Lack of concentration	3,783	85.3%	14.2%
	Altered vision (unrelated to glassess/contacts)	3,776	88.9%	11.1%
	Numbness/ tingling Face/extremities	3,801	83%	17%
	Dizziness/ lightheaded	3,796	80.6%	19.4%
	Fatigues/ unusual tiredness	3,809	63.2%	36.8%
	Muscle weakness	3,778	83.75	16.3%
Other	Joint pain/aches	3,813	66.7%	33.3%
	Nausea	3,778	88.8%	11.2%
	Rashes/hives	3,805	84.5%	15.5%

By far the most common conditions associated with care seeking in the past year include reactive airways, sinusitis or allergies (55%). Given that 39% of the flight attendants reported a diagnosis of allergies (see Table 6.3), this diagnosis probably contributed substantially to this category.

The next most significant conditions requiring treatment were fatigue (37%) followed by diffuse joint aches and pains (33%). These problems were ranked high also in the report of health conditions experienced *in the last week* mentioned previously.

Taken altogether, the report of symptoms *in the past year* shows that most medical attention is sought for problems of the respiratory system, the neurological system, and the musculoskeletal system.

Medical Conditions Diagnosed and Currently Treated
We elicited further information about chronic conditions by asking the flight attendant whether a health care provider had ever diagnosed them with particular conditions. Specifically, we asked the flight attendant, "Did a health care provider ever tell you that you had any of the following conditions...", (see the Flight Attendant Health Survey in the Appendix, Question #15, pages 6-8)

We asked also about conditions that were currently receiving treatment. These conditions are worth noting separately because they denote more severe conditions. To elicit the status of treatment, the respondent answered, "yes" for current treatment next to the diagnosis. We noticed however, that some respondents checked "yes" for treatment even without checking "yes" for the diagnosis. (For example, the number of individuals responding about treatment in the far right column was sometimes larger than the number of respondents who said "yes" they had the condition— e.g., Parkinson's disease.) We believe these rare inconsistencies do not detract from the overall picture of flight attendant health because each results in an undercount of diagnoses rather than an overcount. Further, the raw numbers of flight attendants receiving treatment for certain conditions underscores the relative scope of the problem.

Importantly, this accounting of medical diagnoses will likely miss the most serious and debilitating illnesses because flight attendants with these problems would be unable to perform their work and would likely leave the job. This censoring of disease prevalence in a working population, commonly referred to as "the healthy worker effect", will usually underestimate the full burden of illness in the population.

Table 6.3 Percentage of Flight Attendants Diagnosed with Particular Medical Conditions and the Raw Number Currently Treated for that Condition

CONDITION	Diagnosed by Health Care Provider		Currently receiving treatment for this condition
Overweight/Obesity	12.2%	(n= 3,877)	(n=121)
High blood pressure	16.7%	(n = 3,882)	(n =402)
Heart disease	2.5%	(n = 3,858)	(n= 64)
Heart attack	.5%	(n = 3,859)	(n=12)
Stroke	.5%	(n = 3,864)	(n=8)
Aneurysm	.3%	(n= 3,864)	(n=4)
Chronic Obstructive Pulmonary Disease (COPD)	.9%	(n= 3,933)	(n=18)
Lung fibrosis	.2%	(n= 3,927)	(n= 6)

(Table 6.3 -Continued) CONDITION		Diagnosed by Health Care Provider		Currently receiving treatment for this condition
Pulmonary embolism, blood clots , Deep Vein Thrombosis (DVT)		2.2%	(n= 3,897)	(n=29)
Pneumonia		16.2%	(n = 3,860)	(n=57)
Chronic bronchitis		15.6%	(n= 3,910)	(n=125)
Asthma		13.2%	(n= 3,918)	(n=258)
Cancer	Skin	6.9%	(n = 3,918)	(n=104)
	Bone	.05%	(n=3900)	(n=1)
	Blood	.3%	(n=3,905)	(n=7)
	Lung	.1%	(n= 3,902)	(n=0)
	Brain	.05%	(n= 3,872)	(n=1)
	Reproductive	4.1%	(n=3,911)	(n=64)
	GI	1.69%	(n=3,897)	(n=36)
	Kidney	.4%	(n= 3,904)	(n=5)
	Liver	.1%	(n= 3,900)	(n=2)
Kidney disease		1.2%	(n= 3,925)	(n=22)
Liver disease		1.1%	(n=3,925)	(n=16)
Parkinson's disease		0%	(n=3,925)	(n=1)
Multiple sclerosis		.6%	(n=3,918)	(n=14)
Epilepsy/Seizure disorder		.5%	(n=3,920)	(n=11)
Migraine headache		19.4%	(n= 3,934)	(n=371)
Infertility		8.7%	(n= 3,849)	(n= 61)
Dysmennorhea		4.5%	(n= 3,828)	(n=34)
Adverse pregnancy outcomes		7.6%	(n=3,809)	(n=38)
Hormonal irregularities		20.2%	(n=3,831)	(n=367)
Hearing loss		17%	(n= 3,853)	(n=78)
Vertigo		12%	(n=3,845)	(n=72)
Meniere's syndrome		1.3%	(n=3,830)	(n=20)
Low back pain		52.6%	(n= 3,861)	(n=748)
Rheumatoid Arthritis		4.7%	(n= 3,839)	(n=70)
Osteoarthritis		8.7%	(n=3,839)	(n=154)
Fibromyalgia		3.9%	(n= 3,832)	(n=68)
Chronic Fatigue syndrome		6%	(n=3,837)	(n=71)
Thyroid disorders		11.7%	(n=3,846)	(n=333)
Sleep disturbances		33.7%	(n=3,852)	(n=606)
Depression/Anxiety		36.3%	(n=3,851)	(n=687)
Multiple chemical sensitivity disorder		2.2%	(n= 3,832)	(n=25)
Immune Disorders (i.e. HIV, Lupus, etc)		4.3%	(n=3,850)	(n=117)
Eczema		10.8%	(n= 3,845)	(n=174)
Psoriasis		4.6%	(n=3,832)	(n=98)

(Table 6.3 -Continued) CONDITION	Diagnosed by Health Care Provider		Currently receiving treatment for this condition
Allergies	39%	(n=3,831)	(n=696)
Chronic intestinal disease	7%	(n=3,825)	(n=156)
Other illness	15.8%	(n=3,348)	(n=310)

Once again, not all conditions in Table 6.3 overlap with the conditions reviewed in the previous tables (i.e., Table 6.1 and Table 6.2 that reflected problems in the *last week* or *last year*). As before, the most prevalent conditions are noted in red. This perspective does not take into account, however, the expected rates of the condition in the general population considering other risk factors such as age, gender, and smoking. For example, the prevalence of hearing loss in this sample of flight attendants may be considered high in comparison to a sample of workers who are not flight attendants but of similar age, gender and smoking status, although this was not part of this analysis.

The most prevalent conditions in Table 6.3 include low back pain (52.6% with close to one in five flight attendants currently receiving treatment), allergies (39% of flight attendants with approximately 1 in 5 attendants currently receiving treatment) depression/anxiety (36% with close to 1 in 5 flight attendants currently receiving treatment), and sleep disturbances (34% with approximately 1 in 6 flight attendants currently receiving treatment for sleep problems).

Other notable conditions are hormonal irregularities (20%), migraine headaches (19%), high blood pressure (17%), pneumonia (16%), chronic bronchitis (16%), asthma (13%), hearing loss (17%) and vertigo (12%).

Work Related Injuries and Illnesses in the Past Year
We asked the flight attendants about the number of work-related injuries or illnesses (e.g. 0, 1, 2, 3, 4 or more) they experienced over the past year. Close to half of flight attendants (47%) told us they experienced one or more work-related injuries/illnesses in the past year and 29% said they had more than one injury in the last year. (n = 3,667)

Of the 47% of flight attendants who experienced one or more injuries, we asked them to describe their injuries. If the flight attendant had more than one injury, he/she could choose a description for up to the first 3 injuries. In addition, more than one description could be selected if the injury/illness involved multiple health effects. The choices for the description of the injury included the following:

- Musculoskeletal: *strain or sprain, joint aches and pains or fracture, contusion, laceration*
- Respiratory: *trouble breathing, infection*
- Neurological: *dizziness, headaches, numbness and tingling, fatigue*
- Psychological: *anxiety, stress, depression*
- Cardiac: *chest pain or tightness, high blood pressure, clots*
- Other

We found that the large majority of problems were musculoskeletal in nature (35%) followed by respiratory (21%), neurological problems (17%) and psychological problems (14%).

Integrated View of Health Conditions in the Flight Attendant Respondents
Table 6.4 reflects a composite profile of the prevalence of certain health conditions that are common to all previous queries about health in the *past week*, in the *past year*, or *ever* (as diagnosed by a health care provider), although different questions may reference the similar conditions in unique ways. For example, some health conditions are referenced by subjective symptoms while other health conditions are referenced by a medical diagnosis (usually involving one or more symptoms). Information about acute conditions comes from Table 6.1. Information about chronic conditions comes from Table 6.2 under the column heading “sought treatment in the last year” and comes from Table 6.3 under the column “told by a provider that FA has the condition”. “NA” or “not applicable” in the chart below denotes that information about a condition was asked about in this way. Also, we note that some conditions are not exactly the same but have some overlapping characteristics. In this case, we added notation about how the condition was interpreted in the corresponding box.

Table 6.4 Composite View of Health Conditions Common to Tables 6.1 through 6.3

Health condition	Acute (often or everyday)	Chronic	
		sought treatment in last year	Told by provider FA has condition
Fatigue	27% (n =3817)	37% (n=3,809)	NA
Sleep	35% (n=3827)	NA	34% (n=3852)
Low back pain	28% (n =3787)	NA	53% (n=3861)
Headaches-severe	6.5% (n=3729)	23% (n=3804)	19.4% (n=3,934) migraine
Rash or hives	NA	15% (n=3804)	10.8% (n=3,845) eczema 4.6% (n=3,832) psoriasis
Shortness of breath	5% (n=3721)	15.5% (n=3787)	13.2 (n=3,918) asthma
Dizziness	4% (n =3708)	19.4% (n=3796)	12% (n=3,845) vertigo 1.3% (n=3,830) Meniere's
Loss of memory/ concentration	9% (n=3746) difficulty concentrating	15% (n=3783)	NA
Nausea	3% (n=3703)	11.2% (n=3778)	7% (n=3,825) Chronic intestinal/ Stomach disease
Depression	12% (n=3751)	NA	36% anxiety/depression
Anxiety/stress	20%(n =3778)	NA	
Numbness/tingling	6% (n=3714)	17% (n=3801)	NA
Muscle weakness	12.4% (n=3721)	16.3% (n=3778)	NA
Altered vision	7.5% (n=3623)	11% (n=3776)	NA
Coordination/balance loss	3% (n=3,702)	9.1% (n=3,795)	NA
General/diffuse muscle aches	12.3% (n=3,721)	33.3%(n=3,813)	NA
Tremors/shaking	1.4% (n=3,714)	3.7% (n=3,785)	NA

6.4 Implications

We know relatively little about the health consequences of flight attendant work compared to other occupations, even pilots. A comprehensive review of the literature revealed only a handful of studies (n=21) (Nagda and Koontz, 2003). In addition, prior studies had one or more of the following problems; small sample size, selection bias, low participation, no objective measures, or narrowly defined health outcomes. To our knowledge, this current study represents the largest systematic survey of general health in a flight attendant population and a significant opportunity to advance the understanding of health and wellbeing in these employees.

Increasing the understanding of flight attendant health is important because the context of the job has changed dramatically over the last several decades. Today's senior flight attendants are the first group to be exposed to this type of work for an extended period of time, such as throughout most of their adult working lives. Before the civil rights movement, the flight attendant's average tenure was only about two years because of rules against getting married or age limits (Lessor, 1984). The turnover rate before 1970 was 30%, compared to today in which the majority of flight attendants work for the same employer well past 10 years. For example, in our study sample, 36% worked with their current employer for more than 20 years.

Given this long-term employment relationship, the health and safety of the flight attendant would seem a smart investment for prevention efforts on the part of the employer. Yet, some of the problems we learned about from the survey, such as musculoskeletal and respiratory problems, frequently plagued a significant portion of the workforce. Other problems that were commonly known for years, such as sleeping problems, are still prevalent today. Further, reports of frequent work related injury, anxiety and depression, are associated with lost productivity and disability, and consequently, substantial costs. Finally, particular conditions raise concern for the safe performance of the job, such as impaired memory, concentration and balance, and hearing loss, dizziness, and fatigue.

Without the ability to measure cabin exposures in conjunction with measures of flight attendant health we are limited in drawing conclusions about the work-relatedness of the health conditions. In addition, the health problems were self-reported only and cannot be further substantiated. Yet, the broad description of health in this population offers a window into prevalent health conditions. In order to fully characterize any excess burden of disease in this population, and lacking a comparative group of "non-exposed" workers in terms of the cabin environment (control group), further study is needed to sort out the relationship between the reported health conditions and the working environment or sources of exposure in the cabin. Important areas to investigate in terms of their impact of the health and productivity of the workforce would include: 1) fatigue 2) noise 3) musculoskeletal disorders 4) respiratory conditions and 5) neurological conditions. Some of these conditions have already been flagged as priorities in the recent FAA Reauthorization Bill (2010), namely, fatigue and noise. Now that FAA is establishing a more prominent role in occupational health and safety, these data and research tools can be useful in measuring the effectiveness of prevention programs and the need for future rule-making.

6.5 Approach to On-Board Study

The principal aim of this research project is to relate perceptions of discomfort or health-related symptoms of flight attendants, flight deck crew, and passengers aboard commercial transport aircraft to possible causal factors, including cabin and bleed air quality and other factors such as reduced air pressure, jet lag, inactivity, humidity, flight attendant duty schedule and fatigue, circadian rhythm, stress, and noise. In particular, the following specific objectives are to be addressed in this project:

- Measure and characterize contaminants in cabin air in a variety of aircraft types.
- . Assess ventilation rates
- Investigate the relationship of the measured cabin air contaminants, ventilation rates, and other factors with reported discomfort and health-related symptoms among passengers and flight crew.

Data are being collected on a sample of flights recording cabin air quality and other parameters. In parallel, perceptions of cabin and flight deck crew, and passengers are being recorded using questionnaires. The design of the study considers a variety of objective parameters such as aircraft type, air quality, cabin altitude, passenger load, length of flight, and thermal environment. The subjective parameters to be considered include passenger and crew comfort during flight, health status at the beginning and during flights, and indicators of susceptibility. The following specific parameters are being investigated:

- Aircraft type
- Cabin altitude
- Passenger load
- Length of flight
- Chemical and physical cabin conditions
- Ground air supply
- Ventilation
- Ozone scrubber in operation
- Passenger and crew comfort and health surveys during flight
- Indicators of susceptibility
- Additions effects (if possible)
    - Source of ground air supply
    - Cleaning and cleaning materials
    - Fueling and service equipment
    - Age of aircraft
    - Age of service equipment

The greatest impact to the community of air travelers and airline professionals is in having the data from the project available to participating airlines and eventually to aircraft manufacturers through ASHRAE and national and international rulemaking and advisory organizations (e.g., International Air Transport Association, International Civil Aviation Organization, Air Transport Association, FAA, etc.). The Battelle project team, including Harvard University, seeks participation in the ASHRAE project from additional airlines to complete the study design.

6.6 Progress on On-Board Study

Although substantial progress has been made in collecting data for the target parameters (i.e., flight duration, load factor, aircraft type), the dataset is incomplete, particularly with respect to the number of aircraft sampled and their ventilation rates. Our ability to complete the project matrix has depended on the flight options available to us with the cooperating airlines. Sampling on aircraft across the range of specified ventilation rates is a critical design component of the study. The aircraft sampled to date sufficiently represent aircraft with relatively high ventilation rates, but low ventilation aircraft, such as the Boeing 757 (B757) and Airbus 310 (A310), have not been sampled. The two airlines who have voluntarily participated in the study did not have these aircraft in their fleet. Thus, participation with at least one additional airline will be required to sample flights on 6 aircraft types, including at least one aircraft on the low end of the ventilation rate. (Actual approximate ventilation rates have not yet been calculated for flights sampled to date.) In addition, more robust data sets with respect to other parameters, such as use of ozone scrubbers, long duration flights, flights crossing more than 5 time zones, and summertime flights. As such, we aim to distribute surveys and conduct measurements on additional airlines to complete the parameter matrix in a way that provides sufficient data to meet the project goals.

In June 2010 a research teaming agreement was signed between Harvard, Battelle and a third airlines. A series of domestic and international flights were started in early July and were completed in mid-August. These additional 24 flight segments, while not fully optimizing our initial design do provide additional model types and routes. Laboratory and analytical work will be preformed in the fall of 2010.

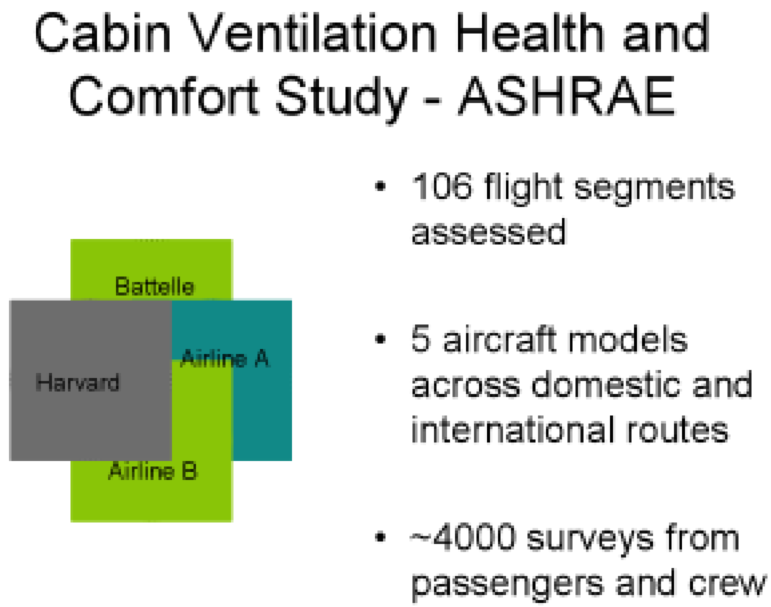


Figure 6.2 Summary of the Status of the On-Board Study as of May 2010

The participation of the 3rd airlines will yield a total of 130 flight segments, 6 aircraft models and over 6000 surveys from passengers and crew.

6.7 Air Contaminants Measured in the On-Board Study

The On-Board Study will provide a comprehensive set of measurements of cabin air environmental conditions. Monitored continuously during cruise were air temperature, humidity, noise, pressure, CO, CO2, Ozone, and ultra fine particles. In addition, integrated air samples were collected for the analysis of set of carbonyls, volatile organic and semi-volatile organic compounds. Table 6.5 provides a listing of the analyst tested for in the cabin air.

Table 6.5 List of Analytes Sampled in Cabin Air during On-Board Study

phthalates by EI GC/MS	other SVOCs by EI GC/MS	other SVOCs by EI GC/MS	VOC's TD GC/MS
diethyl phthalate	naphthalene	2,2-methoxyethoxyethanol	1,3-Butadiene
dibutyl phthalate	biphenyl	limonene	Methylene Chloride
butyl benzyl phthalate	acenaphthalene	phenethylalcohol	MTBE
di-2-ethylhexyl phthalate	acenaphthylene	benzyl acetate	2-Methylpentane
BDEs by NCI/GC/MS	fluorene	hexyl cinnamal	Chloroform
BDE 47	phenanthrene	HHCB	1,1,1-Trichloroethane
BDE 99	anthracene	AHTN	Benzene
BDE 100	fluoranthene	TRIS (2-Chloroethyl)phosphate	Carbon Tetrachloride
BDE 209	pyrene	TRIS (dichloropropyl)phosphate	2-Methylhexane
Ozone by products TD GC/MS	benz(a)anthracene	PCB 52	2,3-Dimethylpentane
6-methyl-5-heptene-2-one (6 - MHO)	chrysene	4,4-methylene-2-chloroaniline	3-Methylhexane
decanal	benzo(b)fluoranthene		Trichloroethene
nonanal	benzo(k)fluoranthene		2,2,4-Trimethylpentane
Carbonyls DNPH-Silica Cartridge HPLC	benzo(e)pyrene		1,3-Dichloropropene (cis+trans)
Formaldehyde	Benzo(a)pyrene		Methylcyclohexane
Acetaldehyde	indeno(1,2,3-cd)pyrene		Toluene
Actone	dibenz(ah)anthracene		Tetrachloroethene
Tri-cresyl Phosphates	benzo(ghi)perylene		Ethylbenzene
Chemical Desorption GC/MS	sumithrin		m/p-Xylene
T-o-CP	cis-permethrin		Styrene
T-m-CP	trans-permethrin		o-Xylene
T-p-CP	2-butoxy ethanol		1,4-Dichlorobenzene

The preliminary findings have confirmed the occasional presence of elevated ozone in cabin air. However, the OnBoard Study is providing new insight about the formation of reaction products and ultrafine particles. No incident of bleed air contamination was evident during the monitoring on the first 2 airlines. The TCP (Tricresylphosphate) compounds were detected on a few flights at very low levels near the analytical limit of detection. A few flights did have distinctly higher levels of a set of VOCs indicative of fuel combustion compounds. These few occurrences are being evaluated further to determine if passengers or crew perceived the cabin air quality different on these flights from others with more "typical" pattern of VOCs.

6.8 Implications for the On-Board Study

The need for advances in air cabin comfort and well-being is more important than ever. Despite the economic crisis, air travel remains a large and growing industry. "Frequent flyers" now form a substantial proportion of the travelling public and the volume of air traffic has risen steeply in recent years. The forecasted growth in the number of passengers over the next 10 years is expected to rise 4.1%, according to Airbus and Boeing.

The goal of comfortable flight is challenged by the increasing time passengers may spend in the cabin. With modern long-range aircraft, the need for "stop-overs" has been reduced leading to an increase in the duration of flights. The passenger capacity of these long-

distance aircraft is also increased leading to larger numbers of people travelling aboard a single aircraft over long distances.
The goal of providing comfort in the air is challenged also by the reality that an increasing percentage of the flying public will be older and sicker. The number of individuals over the age of 60 is expected to triple in the next decades and many will need special accommodations because of disabilities or disease. For example, at least 70% of those passengers over sixty will likely have some form of cardiovascular disease and passengers with more severe conditions may experience moderate hypoxia in an already mildly hypoxic cabin environment. In these instances, the pursuit of comfort may begin with an individual oxygen concentrator, for example, to avoid risk and medical diversions.

To meet the challenge of comfortable and healthy air travel in the 21st century, a strategic plan is needed. In order to achieve the “right” conditions for cabin health and comfort, the following objectives are proposed:

1. A comprehensive understanding of the current range of environmental conditions inside the aircraft.
2. A comprehensive understanding of the range of human responses during flight. This understanding must necessarily include an appreciation of the overall characteristics of passengers as well as the need-based characteristics that relate to disability and the expected class of service.
3. An analysis of the relationship between cabin environment and passenger and crew comfort, health and well-being.
4. Recommendations for changes in the cabin environment, as well as passenger services offerings.

As analysis of the On-Board Study data continues, we will address the following issues.

- Environmental Factors (i.e. temperature, pressure, humidity and ventilation) that impact on passenger comfort, along with recommendations for possible interventions that could improve passenger comfort and enhance the in-flight passenger experience
- The relationship between passenger health symptoms and their physiological response to the flight environment as determined by their experience of comfort and level of satisfaction.
- Analysis of factors that might be used to identify passengers with particular vulnerabilities making them more susceptible to symptoms and discomfort, along with recommended interventions (e.g. extra services for aged passengers, passengers with pre-existing conditions such as heart disease, diabetes)
- Characterization of the flight attendant experience and their physiological response to the flight environment, along with factors that impact on these issues. Data will be collected and presented in such a way as to potentially serve as a baseline indication for a larger, follow-up study on flight attendant fatigue

6.9 Portable Sensing System

Developing a clear picture of the range of conditions in aircraft cabins and how various factors affect those conditions within commercial aircraft across the full range of flights conducted is a daunting task. The variety of aircraft used is large. When all of the makes, models and various derivatives (737-200, 737-300, 737-400, etc) are considered, over 30 different types of aircraft are used on regularly scheduled medium to long distance flights by US carriers alone. This variety does not include the multiple engine options and cabin layouts that are used with many of these aircraft. There is not an accurate accounting of all of the possible combinations in use, but certainly it is significantly larger than the 30 base aircraft models. However, the variety of aircraft in use is small compared to the variety of other factors. There are literally thousands of different flights every day from departure points and destinations ranging from the tropics, to deserts, to the arctic. Even for any given departure point and destination, the route, altitude, duration, turbulence, etc. can vary from flight to flight depending on the weather, traffic, aircraft being flown, etc. All of these factors can potentially affect the conditions in the aircraft cabin and the total possible number of combinations is nearly infinite. There is no such thing as a typical aircraft, typical flight, or typical operating conditions. Conducting environmental measurements on a few dozen flights, or even a few hundred flights, is not likely to capture the full range of possibilities. While these numbers of measurements should be able to address important, specific questions adequately, they are not likely to give a complete picture of the variety of conditions encountered. This may lead to questions about the generality of the results for relatively small data sets.

In order to get a complete picture, one has to think in terms of measurements on thousands of flights, not hundreds. Deploying a complete set of high grade instrumentation on this many flights is not feasible from an economic perspective and, even if it were economically feasible, it would not be practical from a disruption perspective. The airlines, understandably, are not likely to accommodate an intrusive presence on thousands of flights. Consequently, a small instrument package that can collect useful environmental data and be readily carried on most any aircraft and flight is needed. The purpose of this task is to develop and test such an instrument package and to establish the feasibility of implementing a program to deploy the packages and establish a database from the collected data for use by RITE/ACER members.

Figure 6.3 shows a system that was approved for aircraft cabin operation in 2007. This system contains CO_2, pressure, humidity, temperature, and sound level sensors. It is powered using four AA batteries. This system is also designed to incorporate wireless capability, which may not be necessary for the proposed task and may be eliminated (pluggable module) due to its impact on EMI certification. This integrated sensor package has secure digital flash memory (SD flash memory, similar to those in cameras and digital music players) for long-term storage. This system meets all the desired design goals, with the exception of operating time. Testing shows that this unit has ~10 hours of operating time. This has been further extended by implementing a low-power mode using a subset of sensors. When the battery has been drained extensively, the system will shut down the relatively power hungry CO_2 sensor and continue to operate for several more hours.

Figure 6.3 EMI/EMC approved system

In order to keep costs for this task minimal, flights of convenience[16] were used. A simple measurement protocol (see Figure 6.4) was established such that most any educated individual can deploy the device in an aircraft and extract the data. Other than putting the device in place and turning it on (and off), the only information the operator will need to provide is the airline, flight number, departure and arrival airports, and date. With this information, the public flight track information can be used to determine the flight path and altitude, which through the time and date stamp can be directly combined temporally with the recorded date. Aircraft identification is also available from this source.

In addition to the note as shown in Figure 6.4, a whitepaper has been prepared to instruct individual operators what to do and what not to do. For example, if the flight crew objects to using the system, the researcher must politely refrain from using it. The system operator or carrier is instructed to place the system on the tray or hang the system on the seat pocket. It is advised that the unit be placed outside of any breathing zone, such that higher than normal cabin CO_2 is not being recorded.

[16] Whenever RITE/ACER researcher has business trip.

> The US Federal Aviation Administration (FAA) is funding research to monitor aircraft cabin air quality in which I am participating. As part of this research, I am carrying a small air monitor with me on today's flight. The monitor makes no noise, is unobtrusive, and is generally unnoticed by passengers and crew. A photograph of the monitor is on this note.
>
> I will be in seat _________ on today's flight.
>
> If needed, I have with me a letter of introduction from the FAA and documentation of the electromagnetic interference (EMI) testing for the monitor showing it meets requirements for all phases of flight. I would be happy to provide additional information about the monitor and the research if asked.

Figure 6.4 Note to crew.

For the duration of this project, we collected data on the following aircraft models: A319, A320, B737, B757, B767, CRJ, EMB, DC9, MD80, MD88, and MD90. The specific aircraft derivative (e.g. 737-200, 737-300, or 737-400) was not recorded. Data from nearly 200 individual flights have been recorded and a sample of these data is here.

The system is normally turned on near 10,000 ft (aircraft altitude) while ascending (when permission was given for electronic devices) and turned off on descent around 10,000 ft as required during landing. In some cases, the system was operating from gate to gate as the system without wireless communications meets EMI requirements for all phases of flight.

Cabin CO_2

Figure 6.5 show a sample recorded carbon dioxide concentrations. The concentrations of carbon dioxide for these flights typically fell between 900 and 1700 ppm, with only occasional measurements registering higher values. For these higher concentration readings, it is suspected that the CO_2 sensor was being breathed upon. Ignoring these higher values, the carbon dioxide concentrations never rose to the FAA regulation limit of 5000 ppm. The occasional spike to zero in the data is an anomaly of the CO2 sensor and does not reflect actual CO2 concentrations in the cabin.

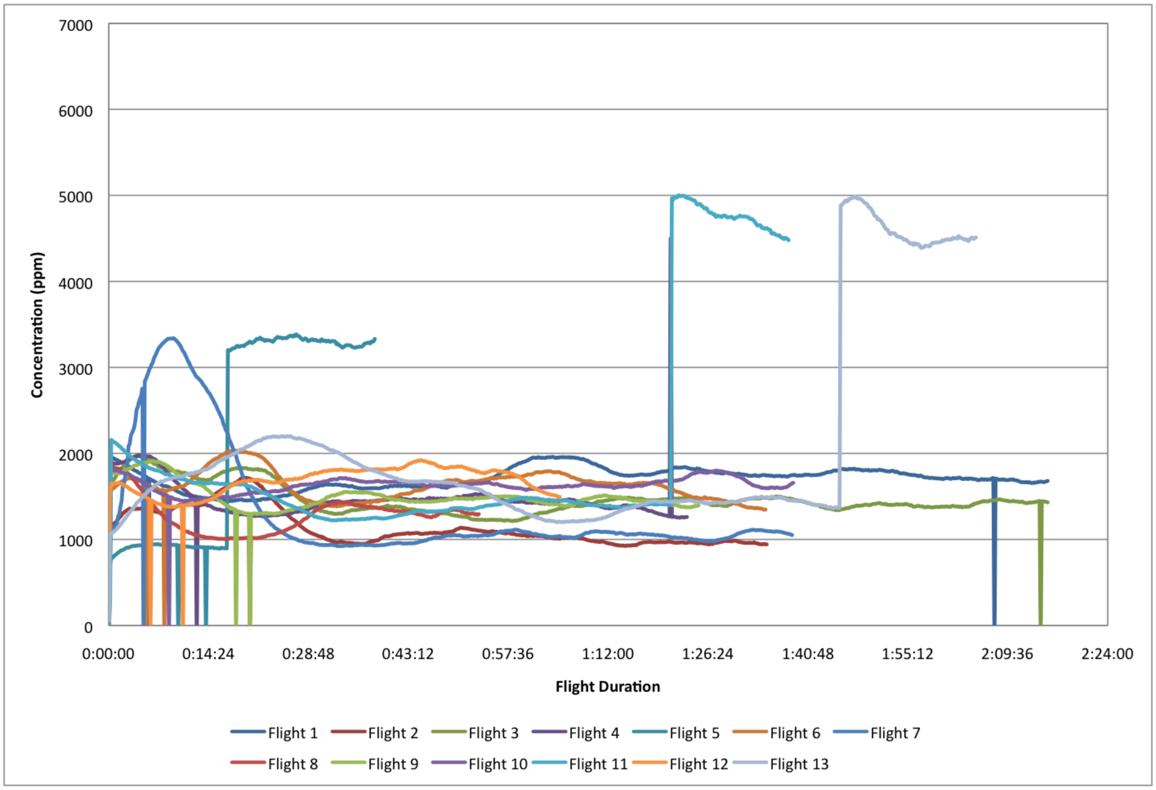


Figure 6.5 B757 Cabin CO_2 Concentration

Cabin Pressure

A sample of the cabin pressure data measured can be seen in Figure 6.6. None of the recorded flights had pressure readings below 74 kPa, which corresponds to 8000 ft cabin altitude as specified in CFR 25.841. Generally speaking, the cabin pressure drops on take-off, reaches a steady level at cruise altitude, then rises again as the aircraft descends for a landing.

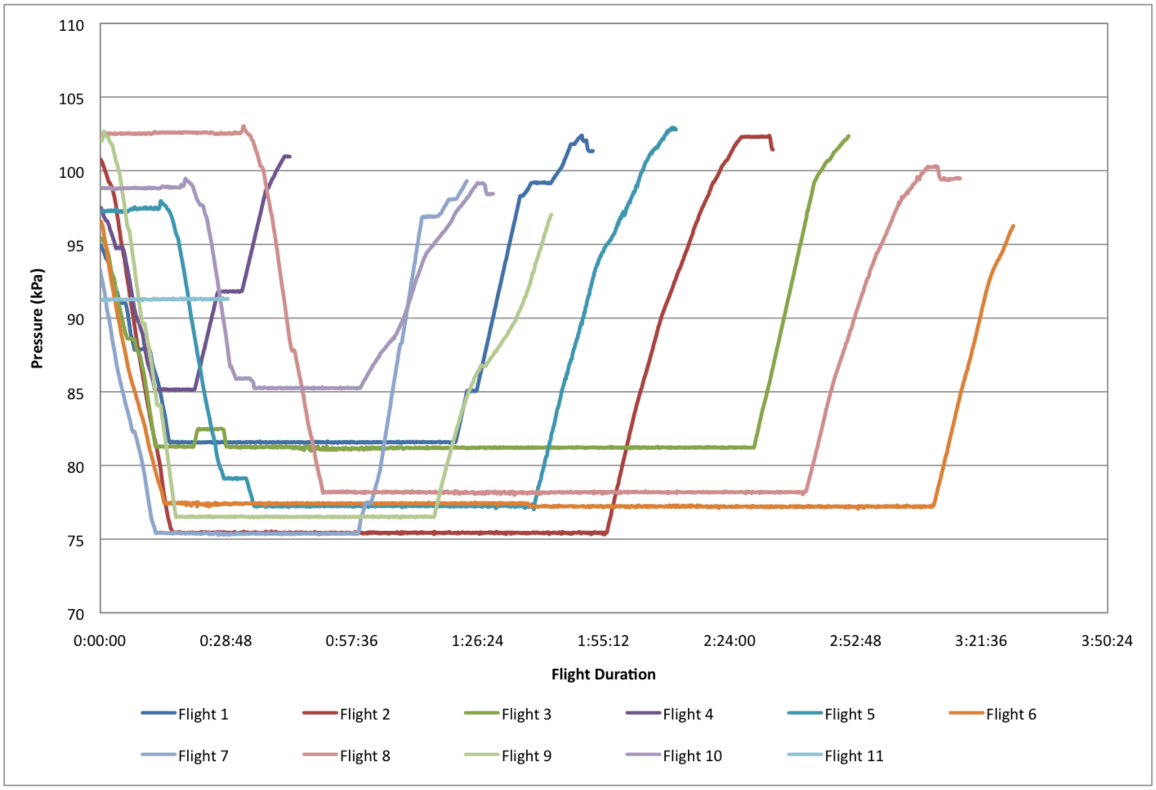


Figure 6.6 B737 Cabin Pressurization

Cabin Temperature

On most of the flights, the cabin temperature ranged from 22°C to 29°C (or 71.6°F to 84.2°F), see Figure 6.7 for sample data. Data would be needed from more flights to establish any correlations between temperature and other factors. There are occasional "blips" in some of the data. It is believed that these blips are an anomaly in the instrumentation and not actual temperature spikes.

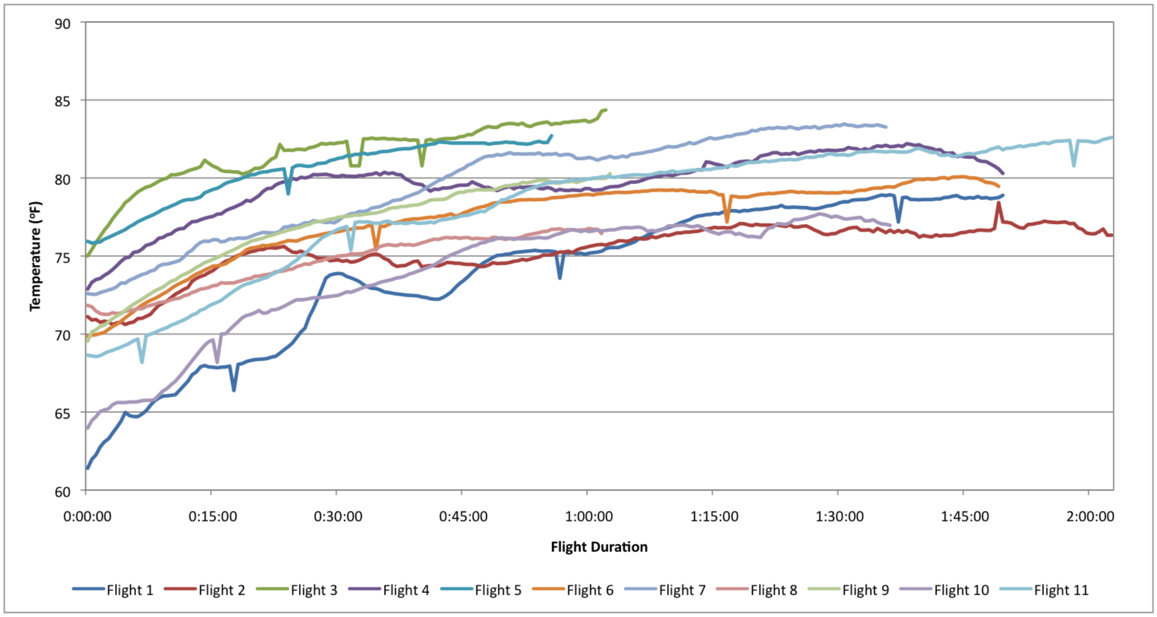


Figure 6.7 EMB Cabin Temperature

Cabin Humidity

For the most part, the humidity data (see Figure 6.8 for sample data) demonstrate a trend of starting at around 35-50% relative humidity at the beginning of the flight and dropping to around 10-25% as the flight progresses.

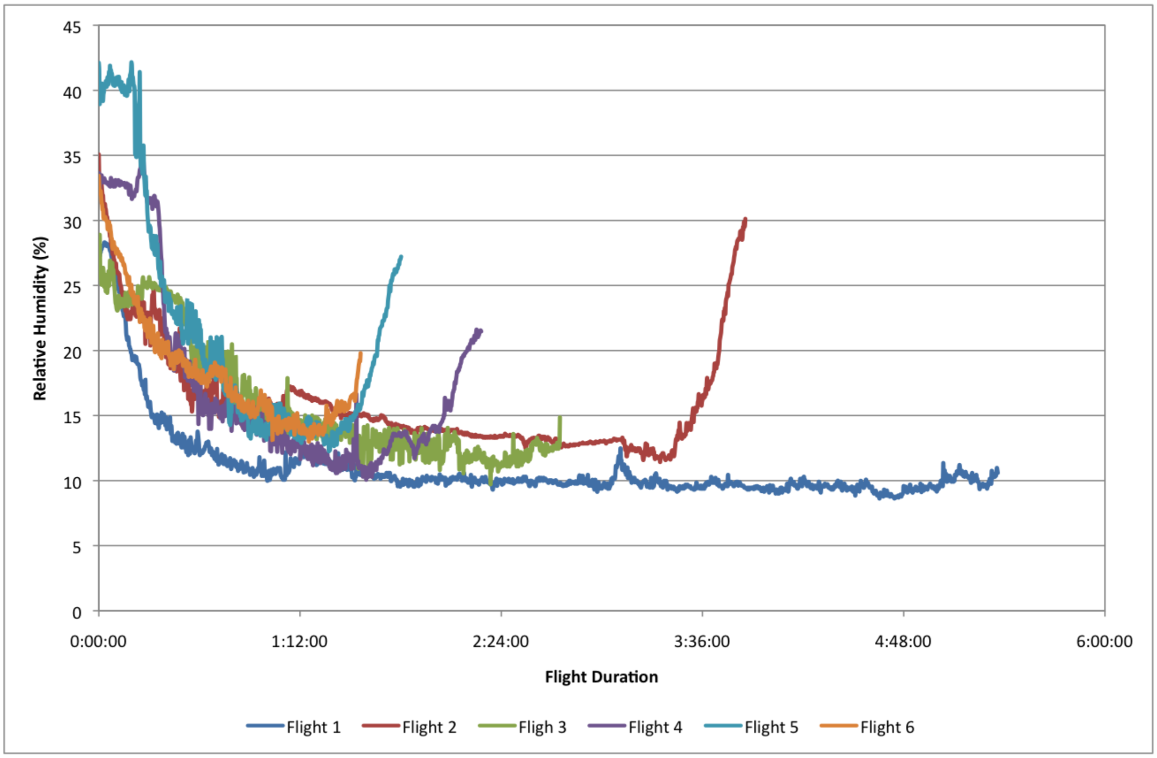


Figure 6.8 A319 and A320 Cabin Relative Humidity

Cabin Noise Level

A sample of cabin noise level is showed in Figure 6.9. The measured sound level of the cabin was typically around 86 dBA (± 2 dBA). This is above the level at which permanent hearing damage can occur (80 dBA and above) over long periods of time. However, this is below OSHA's limit of 90 dBA for an 8-hour duration. As the data show, newer generations of aircraft, are better at controlling noise in the cabin especially compared to the older MD-80 series. However, this difference may also be attributed to the difference between wing mounted and fuselage mounted engines. The row location for the data collection was not recorded. We may attempt to include this information in future work as the front of the aircraft is generally quieter than the rear. It should also be noted that we have not independently verified the accuracy of the sound level measurements.

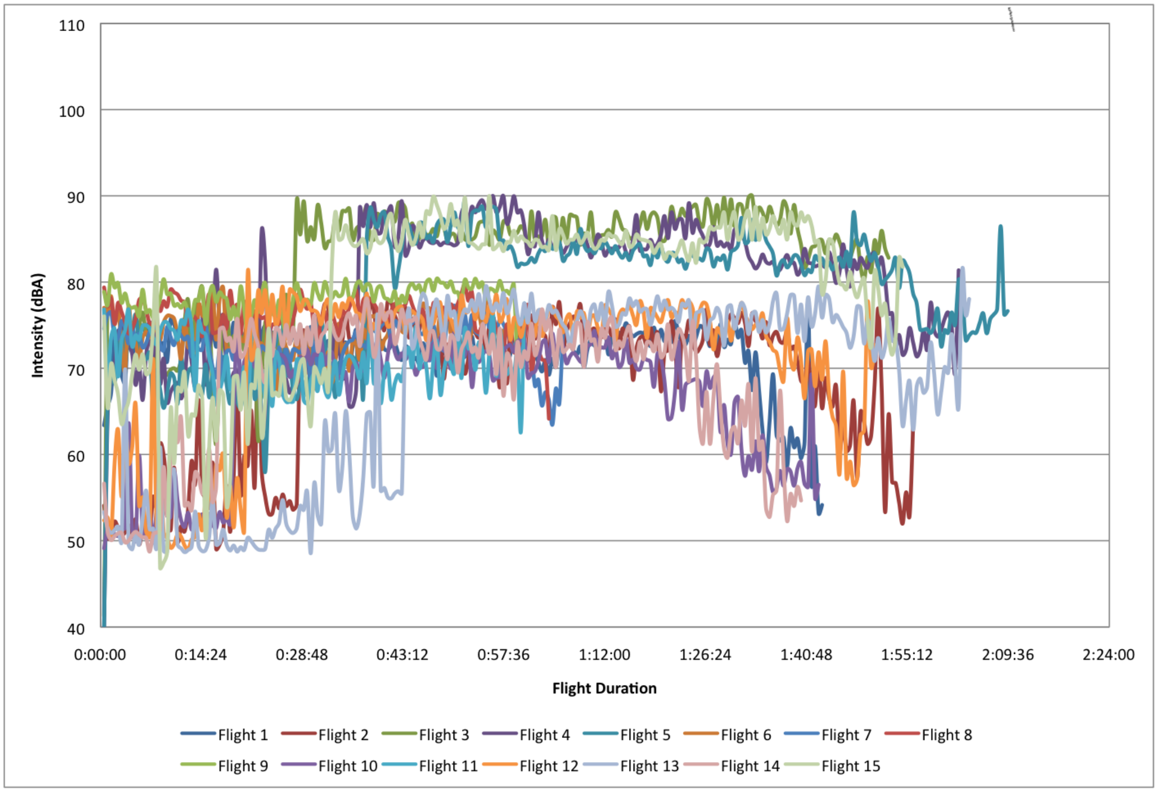


Figure 6.9 B757 Cabin Noise Level

7.0 RESIDUE IN FILTERS FROM AIR QUALITY INCIDENTS

Congressional Mandate: *Analyze samples of residue from aircraft ventilation ducts and filters after air quality incidents to identify the contaminants to which passengers and crew were exposed.*

7.1 Introduction

Essentially all modern airliners in the fleet today use compressor bleed air for cabin pressurization and ventilation when in flight. Figure 7.1 shows a schematic of a typical bleed air system. Figure 7.2 is a photo of a typical high-bypass turbofan aircraft engine with the cowling removed to expose the bleed air ducts. Typically, there are high-pressure and low-pressure bleed air ports to allow the source pressure to be matched to systems needs with different engine and compressor speeds. The bleed air is heated by the compression processes and leaves the engine at high temperature and pressure. Table 7.1 outlines representative temperatures and pressures for different phases of flights.

When bleed air supplied to the cabin has been sampled under normal operating conditions, no evidence of contamination from engine sources is found (Nagda 2001). However, under certain circumstances, the compressor seals can leak lubricating oil into the compressor and, ultimately, into the bleed air stream. In addition, modern aircraft contain a myriad of hydraulic control lines (Figure 7.3) including controls in and around the engines. Under certain conditions, leakage from hydraulic lines can be ingested by the engine compressor and ultimately end up in the bleed air. Both engine lubricating oil and hydraulic fluid are serious contaminants in the cabin supply air and are inconsistent with 14 CFR 25.831 which states, in part "….the ventilation system must be designed to provide a sufficient amount of uncontaminated air……"

Shortly after the bleed air is extracted from the engine, it passes through the pre-cooler. Thus, it only stays at high temperature for a very short time. Figure 7.2 shows the location of the pre-cooler. Although bleed air is cooled quickly, the temperatures and residence times are sufficiently high and long to create the potential for pyrolysis of contaminants in the bleed air adding further concern about the seriousness of the contamination in the air supplied to the cabin.

While incidents of bleed air contamination occur on a very small percentage of flights, given the number of aircraft flying, they still occur with some regularity with varying degrees of severity. They may be of relatively short duration and sporadic in nature, making it very difficult to analyze actual incidents as they occur. Unless large numbers of sampling devices are deployed on aircraft or large numbers of aircraft are equipped with sophisticated onboard instrumentation, the odds of having good measurements of the air during actual incidents are small. Once an aircraft lands after a contamination event, there may be little information available about the nature of the contamination that occurred and all systems may be functioning normally. However, it is important to know the nature of the exposure to which crew members and passengers were subjected and it is important to know the nature of the actual contaminants so the appropriate maintenance and other corrective actions can be performed to prevent future incidents in the aircraft.

If the contamination levels are high enough, one would expect residue to remain on various surfaces. Theoretically, an analysis of this residue could provide information about the nature of the contaminant and answer questions as to whether or not it came from engine lubricating oil, for example. Such information then could provide valuable guidance for follow up actions; hence, the motivation for the Congressional directive.

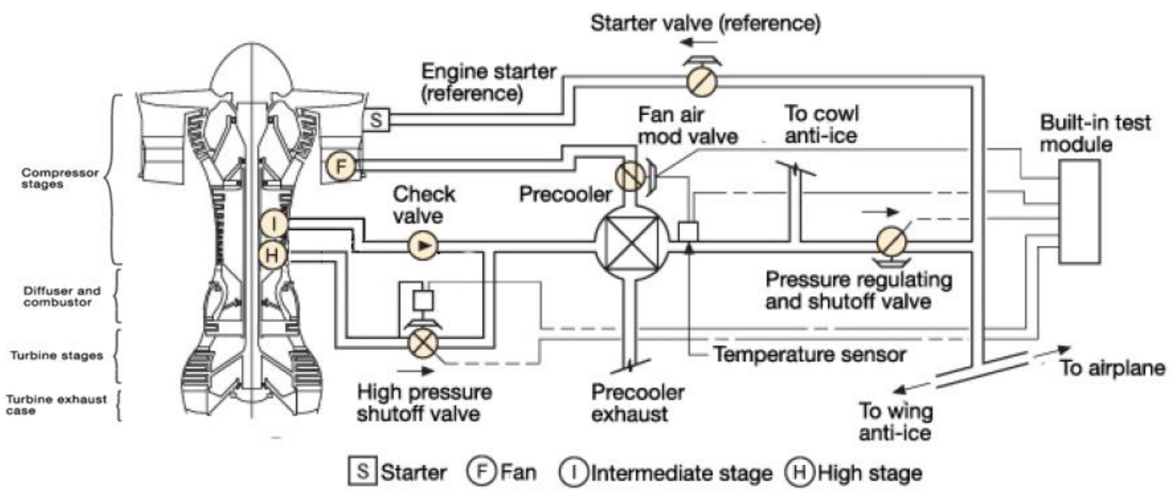


Figure 7.1 Typical Airliner Bleed Air Supply System (adapted from Hunt et al, 1995)

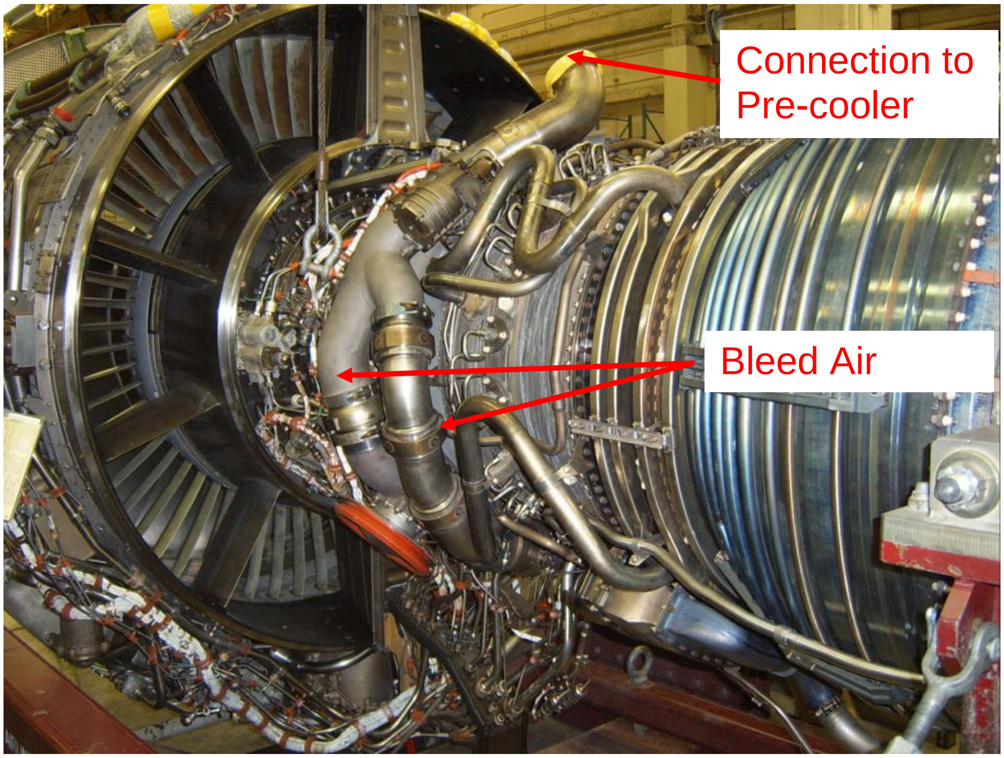


Figure 7.2 Turbofan engine showing bleed air lines and location of pre-cooler.

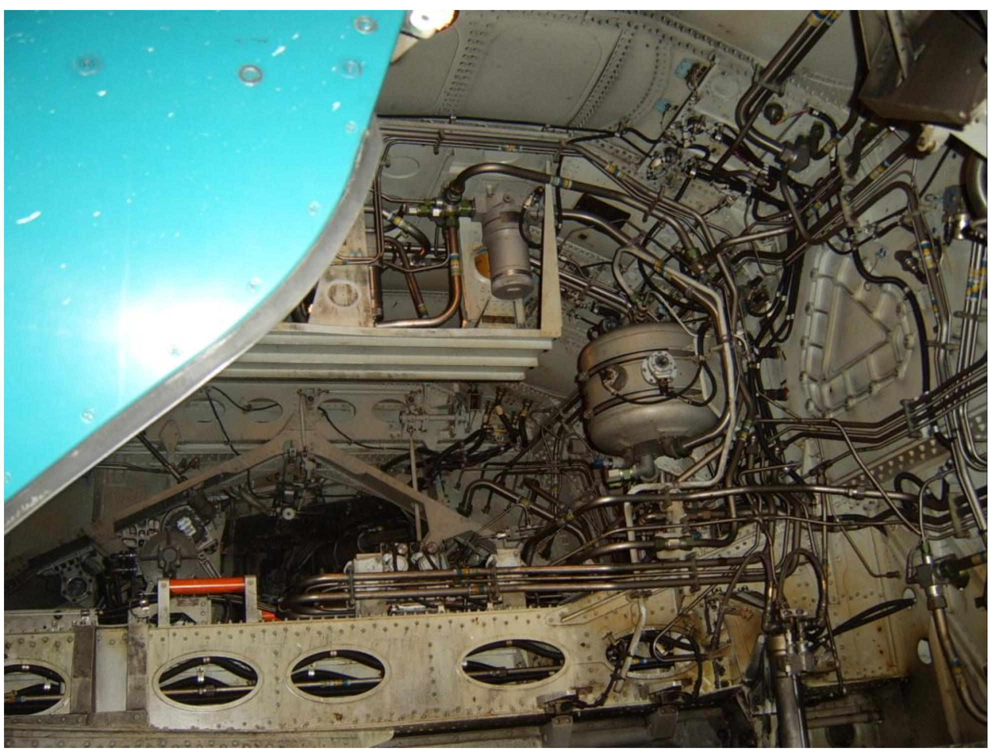


Figure 7.3. Hydraulic lines in an aircraft.

Table 7.1 Typical Bleed Air Temperatures and Pressure (Source: NRC 2002)

Mode of Operation	Temperature ^{o}C (^{o}F)	Absolute Pressure kPa (psi)	Extraction Stage
Top of climb	310 (590)	690 (100)	Low pressure
Cruise	250 (490)	340 (50)	Low pressure
Initial descent from cruise	185 (365)	200 (29)	High pressure
End of descent (ground level)	230 (445)	460 (67)	High pressure
High pressure to low pressure switch-over	280 (535)	480 (70)	High pressure
Ground operations	170 (340)	-	APU

7.2 Approach

In light of the Congressional mandate and the underlying challenge, a three-part experimental plan to address the challenge was developed. Attention was focused on the aircraft recirculation filters. The vast majority of the US airliners use recirculation filters for the cabin air. Figure 7.4 shows how they are incorporated into the system and Figure 7.5 shows an actual recirculation filter in an aircraft. In a typical aircraft, approximately 50% of the air exiting the cabin passes through these filters. Additionally, most aircraft use HEPA-grade recirculation filters which make them effective at trapping even the smallest aerosolized droplets and particles (e.g. smoke). Given the large amount of cabin air that passes through the recirculation filters and their effectiveness in trapping air contaminants, they provided a far more promising opportunity for gathering and examining contamination residue than other surfaces in the aircraft, air ducts in particular.

Attempting to examine residue from an air contamination incident from any surface poses a major challenge. Those surfaces may have been exposed to air for thousands of hours and the contamination incident may have been relatively short in duration. Residue that has accumulated for thousands of hours is present along with the residue from the relatively short incident. The filters are very effective at concentrating and collecting the air contaminants that are present during an incident but these contaminants are mixed in with other matter the filters may have been collecting for up to several thousand hours (Figure 7.6). Attempting to differentiate what came from the incident with what came from a host of other possible sources is a daunting task. It would be very easy to misinterpret the results of the analyses.

A three part experimental program was developed to address the challenges associated with collecting, measuring, and interpreting contaminants collected on recirculation filters:

- Part 1 developed a baseline database of contaminants found on aircraft recirculation air filters on non-incident aircraft.
- Part 2 Conducted laboratory measurements with controlled contamination of simulated bleed air.
- Part 3 evaluated filters removed from incident aircraft.

In Part 1, filters were collected from a cross-section of the aircraft fleet to establish a baseline database. Filters from aircraft known to have had or suspected of having a contamination incident were excluded from this database. The residue on these filters in the database was characterized using gas chromatograph-mass spectrometry (GC-MS) and instrument neutron activation analysis (INAA) methods. The intent was to be able to establish the characteristics of non-incident residue as a basis of comparison for incident residue. It also was used to develop and refine analysis procedures and techniques appropriate to this application.

In Part 2, oil and hydraulic fluid contamination events were simulated in the laboratory. A bleed air simulator and filter exposure facility was developed (Figure 7.7) to provide controlled exposure with controlled bleed air conditions. This part of the work established the detection limits of the analysis methods and the ability to identify known bleed air contaminants on filters.

In Part 3, filters were removed from incident aircraft and analyzed using the methods developed in Parts 1 and 2 to help identify possible causes of air contamination in aircraft with known or suspected air quality incidents.

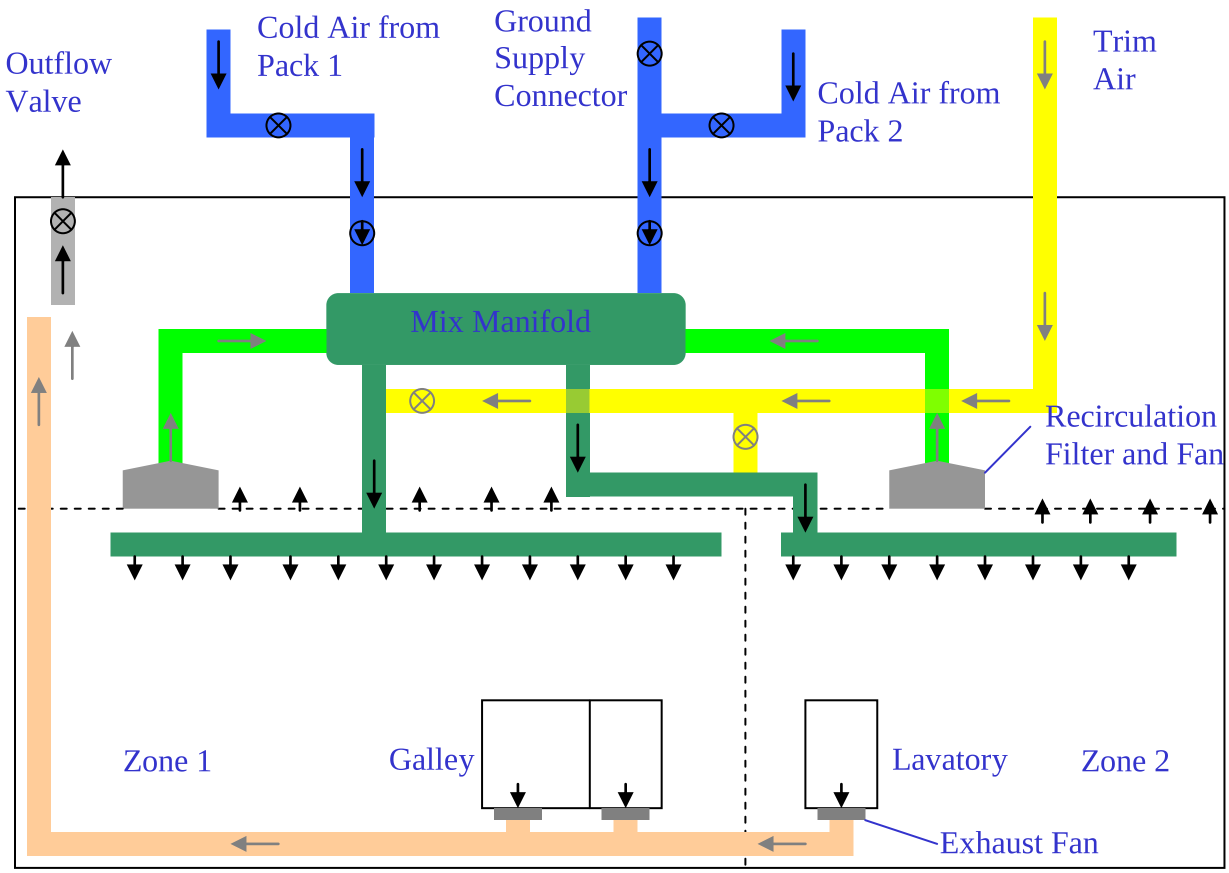


Figure 7.4 Diagram of aircraft air distribution system

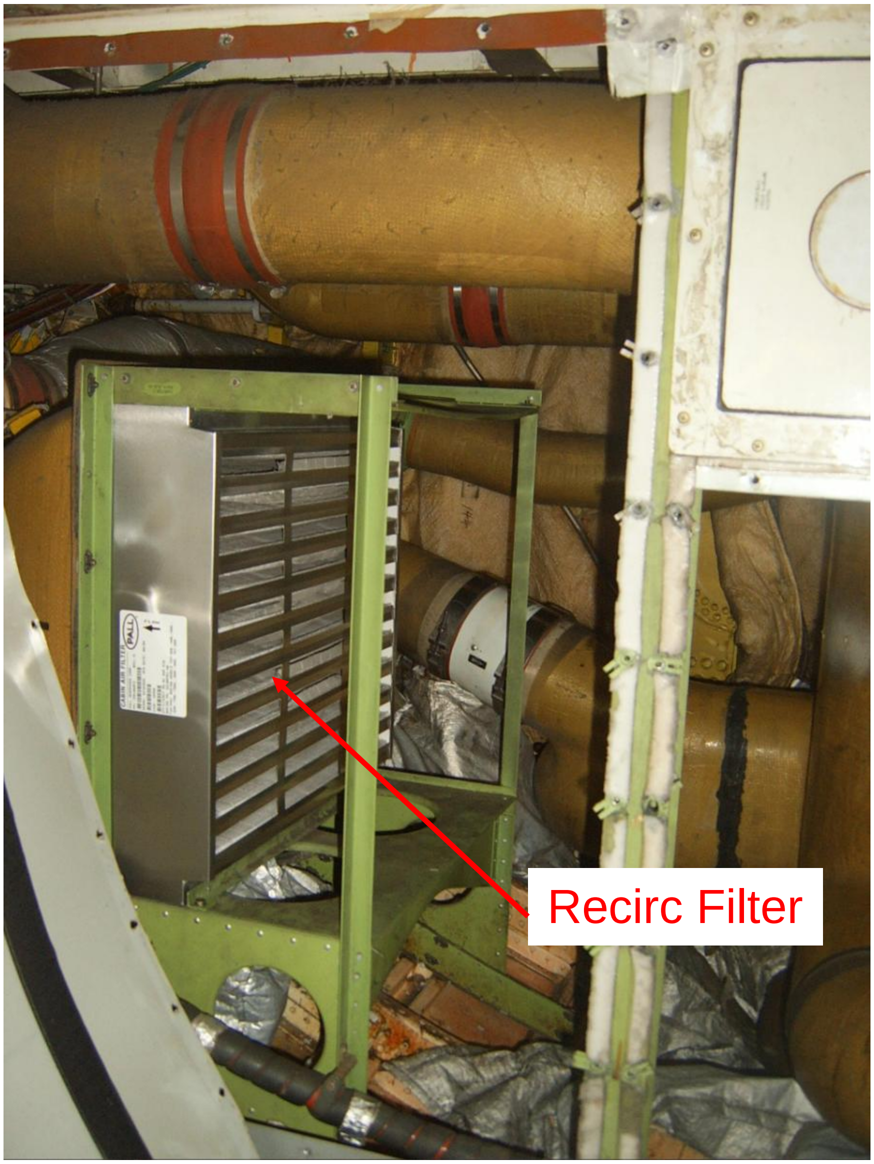


Figure 7.5 Recirculation filter installed in aircraft.

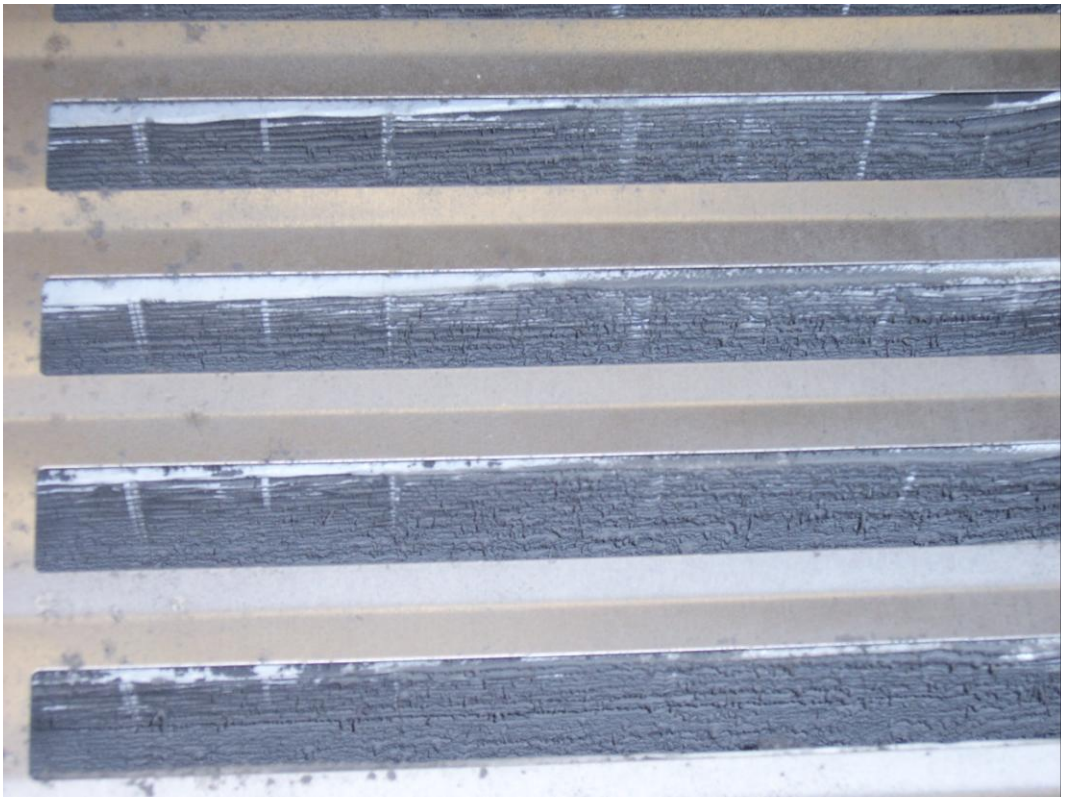


Figure 7.6 Example of filter removed from non-incident aircraft (Note: unusually heavily loaded).

Figure 7.7 Bleed air simulator and filter exposure facility.

7.3 Results and Discussion

In total, nearly 200 recirculation filters were obtained from a variety of sources. One or more specimens were cut from each of these filters (Figure 7.8). Most of the filters were removed during routine servicing and were from aircraft that were not known to have had significant air contamination incidents. However, we were able to obtain approximately 25 from incident or suspected incident aircraft. In addition, a number of filter specimens from controlled simulated incidents in the laboratory were analyzed. Data analysis and additional laboratory experiments are ongoing but preliminary results can be summarized.

By analyzing samples of oil, we were able to identify a set of compounds that can serve as a fingerprint of oil contamination. For any one compound, there are multiple sources that could explain its presence in the cabin and on the recirculation filters. However, the simultaneous presence of all of the markers is a good indication that the source is indeed the lubricating oil. Ultimately, we used the simultaneous presence of tricresyl phosphate (TCP), and its isomers in the correct ratios plus the presence of synthetic hydrocarbons as an indicator of engine lubricating oil contamination. The synthetic hydrocarbon is a major component of engine oil and, thus, would be expected to be present in abundance during a lubricating oil incident. Its absence is a fairly definitive indication there has not recently been major lubricating oil contamination. However, there are other possible sources so its presence is not a definitive indicator of engine oil contamination. While less common, TCP does have other sources as well. However, by looking at the isomers and their ratios, a strong link to engine lubricating oil is established. The combined presence of the TCP with isomers in the correct ratio plus the synthetic hydrocarbon is a pretty clear indicator that there has been engine oil contamination in the cabin air.

Of the filters sampled, those from the main database, which excluded aircraft without known or suspected air contamination events, had a much lower frequency of indicated engine oil contamination using the above criteria than for those filters from the known or suspected incident aircraft. Thus, there is good reason to believe measurements and criteria are valid and can be used as useful evidence that there has or has not been a serious engine oil contamination event.

It should be made clear that it is only evidence and cannot be used as single definitive means to determine the presence or absence of engine oil contamination. Also, a positive indication does not tell when the contamination occurred and does not differentiate a low-level long-term problem from a short-duration but intense event. For aircraft with repeating problems, it is advised that the filters be replaced after initial indications of problems. The presence of the markers on a nearly new filter is a more definitive indication of the source and also narrows the potential time period for the detected contamination, providing a more useful assessment.

The filters specimens exposed in the laboratory covered a wide range of contamination levels ranging from 100 nanograms to 100 micrograms of oil on a specimen in increments of a factor of 10. Specimens from unused filters were also included. These specimens were analyzed blindly in the laboratory and the detection limit is between 0.1 and 1.0 micrograms. This level of detection has not yet been related back to the magnitude of oil contamination or exposure to cabin occupants due to the non-specificity of the time of exposure as explained above.

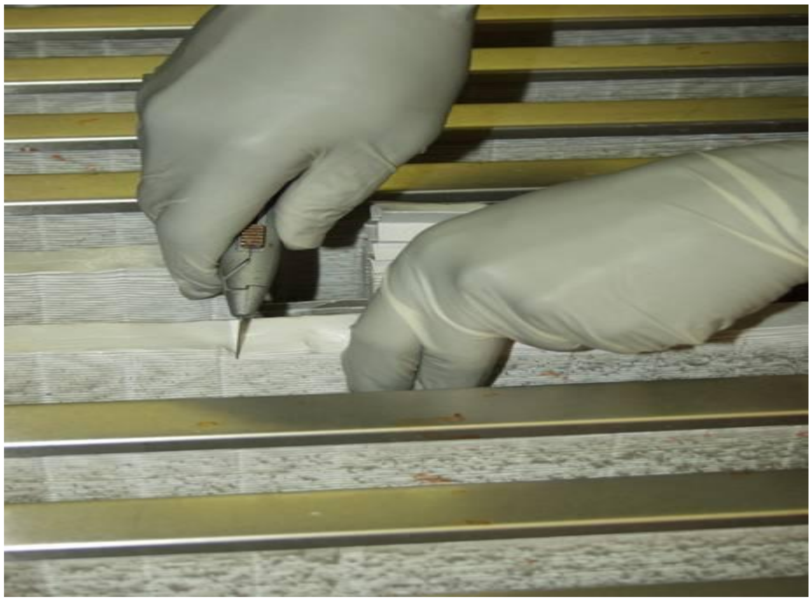


Figure 7.8 Specimen being cut from a recirculation filter

7.4 Conclusions

The methodologies developed can be applied to aircraft with a known or suspected air contamination incident to help identify the source of the contamination. While not 100% definitive, they can provide valid evidence of the presence or absence of substantial amounts of engine lubricating oil contamination. They are now being applied, to a limited extent, to aircraft with a history of air quality problems to help identify the source of the problems and guide appropriate actions to remedy the problems.

While these methods provide a means of after-the-fact assessment, they do not provide warnings of incipient contamination events nor do they provide information to the cockpit crew during an event to aid in quickly determining the correct response and minimizing the exposure of crew members and passengers. The next R&D step, which has been initiated, is to develop real time sensing systems to provide this information.

7.5 References

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NRC (National Research Council); 2002, The Airliner Cabin Environment and the Health of Passengers and Crew, Washington, DC, National Academy Press.

Nagda, N.L., H.E. Rector, Z. Li, and E.H. Hunt, 2001. "Determine Aircraft Supply Air Contaminants in Engine Bleed Air Supply System on Commercial Aircraft," ENERGEN Report AS20151, Prepared for the American Society of Heating, Refrigerating and Air-conditioning Engineers, ENERGEN Consulting Engineers, Germantown, MD.

8.0 AIRCRAFT DECONTAMINATION

Congressional Mandate: *Demonstrate aircraft decontamination by proven technologies such as vapor hydrogen peroxide*

8.1 Introduction

Field evaluations were conducted of (i) a stand-alone thermal decontamination system and (ii) the usage of the stand-alone technology as a means of delivery of vaporized hydrogen peroxide (VHP®#) in full-size aircraft. AeroClave& LLC's thermal decontamination system and STERIS Corporation's VHP® were used in the field evaluation studies discussed here. Among all the large-scale disinfection and/or decontamination technologies available, vaporized hydrogen peroxide (VHP®) is of particular interest due to rapid sterilization, easy usage, intrinsic environmental friendliness (*i.e.*, simple by-products composed of only water and oxygen) and compatibility with many materials and systems. VHP® has been used for years in decontamination studies, but prior attempts to apply VHP® to aircraft, i.e., C–141 demonstration, were not compatible with airline operations. In those previous attempts, bulk vaporizers were required to be mounted within the cabin. The studies reported here used vaporized hydrogen peroxide concentrations in the range of 150 - 600 ppm and cycle times of 80 - 120 min.[1,2] Maximum concentrations of hydrogen peroxide vapor were carefully controlled to avoid condensation in cool locations within the aircraft cabins.

A typical VHP® process cycle consists of an initial dehumidification step, then a conditioning phase followed by the actual sanitization/decontamination process. Finally an aeration phase is employed to remove any remaining residual hydrogen peroxide vapor. During the dehumidification phase, warm, dry air flows into the enclosure to lower the relative humidity to less than 10% which allows a higher concentration of hydrogen peroxide vapor to be injected into the enclosure while avoiding condensation. Hydrogen peroxide liquid concentrate (35% liquid H_2O_2 with a pH ~ 3) is then flash vaporized and injected into the enclosure during the initial conditioning phase as well as during the sanitization/decontamination phase. The purpose of the conditioning phase is to rapidly increase the hydrogen peroxide concentration to minimize overall cycle time. During the sanitization/decontamination phase, a steady concentration of hydrogen peroxide vapor (typically approximately 100- 450 ppm) is maintained to give the desired sanitization/decontamination cycle as often measured by the 6-log kill (*i.e.*, 10^6 reduction) of a commercial biological indicator (BI) spore population of *Geobacillus stearothermophilus*. Once the sanitization/decontamination phase is completed, the

VHP is a trademark of STERIS Corporation, Mentor, OH.

& AeroClave LLC is based in Orlando, FL.

enclosure is then aerated with fresh air while any residual hydrogen peroxide vapor breaks down into environmentally benign water and oxygen.

Many polymeric and textile materials are known to be susceptible to absorption of moisture. The small water molecules can diffuse into the matrix and force apart the macromolecules causing swelling. Increases in the distance between polymer chains reduce the strength of the secondary intermolecular bonds and increase the softness and ductility of the polymer. However, highly cross-linked epoxies used in aerospace-grade fiber composites as well as aviation avionics minimize moisture absorption and these materials exhibit good resistance to degradation in wet environments. While molecules of H_2O_2 vapor should be even less absorbed by epoxies than the smaller H_2O molecules, the intermolecular cross-links might be degraded by oxidation from the hydrogen peroxide. The extensive usage of polymers in aerospace structures and avionics dictates that the compatibility of these materials with hydrogen peroxide vapor be examined.[3-5]

In addition, a preliminary examination of the compatibility of common metal alloys used in airframes (2024 and 7075 aluminum alloys) and galleys and lavatories (304 austenitic stainless steel) has also been conducted.[6,7] The extensive presence of hydrogen atoms also mandates that any potential for hydrogen embrittlement of high strength steels be carefully evaluated.

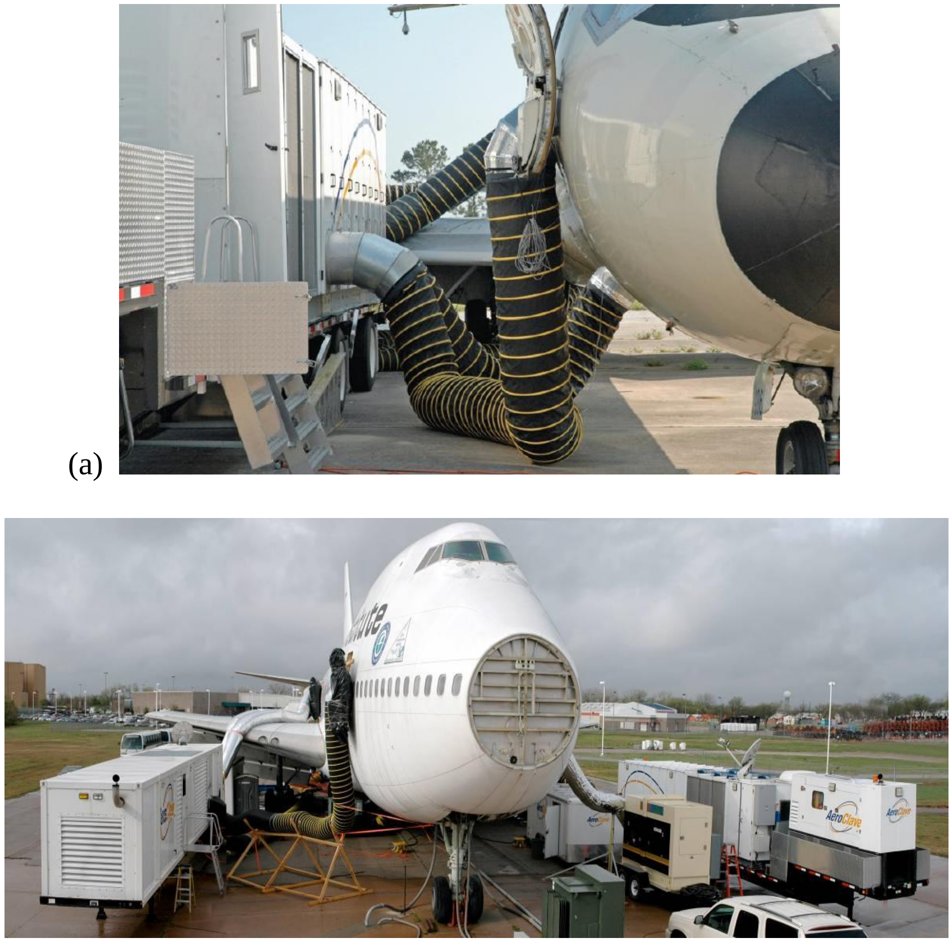
8.2 Approach

8.2.1 Field Demonstrations

The two full size aircraft used in the field demonstrations were a DC9 owned by Aeroclave LLC in Orlando, FL and a B747 at the Civil Aeromedical Institute (CAMI) in Oklahoma City, OK. It is important to note that the engines and auxiliary power units had been removed from both aircraft used in the evaluation; without these it was not possible to operate the aircraft's environmental control system and supplementary fans had to be used to distribute the decontamination chemicals. Furthermore, no effort was made to decontaminate the cargo bay of either aircraft.

The thermal decontamination system, as a stand-alone technology, was deployed in its standard configuration. The thermal decontamination system was designed to deliver heated or cooled air under feed-back control from a self contained unit housed in an adjacent semi-trailer. See Figure 8.1. The thermal decontamination system in its original configuration did not include a humidification capability. Thus Aeroclave LLC opted to add a steam-based humidification system to obtain the desired temperature and humidity conditions. The unit was connected to the cabin via flexible air delivery and return hoses. Custom aircraft door plugs connected to the inlet and outlet hoses were employed. In this configuration, the air inlets were at the emergency exit doors above the wing and the air outlets at the front and rear cabin doors. Air was also blown into the preconditioned air inlet with the intent of decontaminating the ductwork. In the stand-alone configuration, the thermal decontamination system is intended to deliver hot air of controlled humidity to achieve viral decontamination and then cool the aircraft back to a desired temperature and relative humidity so that people may re-enter the cabin.

The cabins of the DC–9 and the 747 were instrumented with 2 relative humidity sensors (one in the front and one in the rear of the cabin) and 36 thermocouples. All data were logged continuously.



(a)

(b)

Figure 8.1 Field demonstration testing of vaporized hydrogen peroxide decontamination in (a) Aeroclave LLC DC9 and (b) B747 at the Civil Aeromedical Institute.

In the case of the VHP® add-in, VHP® was injected into the air delivery system from an external bank of four hydrogen peroxide vaporizers located in a second trailer adjacent to the thermal decontamination system. The thermal decontamination system, when used in conjunction with the VHP® add-in, produces environmental preconditioning, prior to the injection of VHP®. This involves reducing the RH to below 40%, ideally 30% or lower, delivery of vapor to the cabin, and aeration to extract hydrogen peroxide vapor from the cabin. The cabin was instrumented with the same instrumentation (2 relative humidity sensors, one in the front and one in the rear, and 36 thermocouples) as for the stand-alone thermal decontamination system. In addition, six hydrogen peroxide vapor sensors for the working concentration of the VHP® were included in both the DC9 as well as the 747 aircraft.

Twenty-eight Apex 6 log G. Stearothermophilus biological indicators (BIs) were placed throughout the DC9 cabin for the formal evaluation; thirty BIs were used in the 747 evaluation. Some were located in partially occluded locations, to the extent reasonably practicable.

Peripheral sensors were placed around the aircraft, including near the outlet used to flush the VHP®, to demonstrate compliance with OSHA exposure limits. Handheld sensor(s) with manual data recording were used in lieu of suitably calibrated automated sensors that were not available on-site.

Multiple runs were performed with both aircraft, including one formal evaluation run on each aircraft. Runs were performed under the following conditions. The VHP® concentration was maintained at 150 ppm or higher at all locations sampled for at least two hours and was not allowed to exceed 500 ppm at any location to minimize the risk of condensation. VHP® concentrations were monitored on entering the cabin after each run using suitable hand held instrumentation. This did not exceed the 1 ppm personal exposure limit for those runs in which aeration was allowed to run to completion.

8.2.2 Materials Compatibility

All sample exposures to vaporized hydrogen peroxide were performed with a 1000ED Bio-decontamination Unit (STERIS Corporation, Mentor OH, USA) using VAPROX® as the sterilant in an enclosed chamber for 1, 10, or 25 VHP cycles. The exposure chamber was dehumidified to 10% relative humidity prior to VAPROX® injection to minimize any chance of unintended condensation of the hydrogen peroxide vapor. The chamber concentration was maintained at 450ppm H_2O_2 for 4.8 hours. Hydrogen peroxide concentrations were monitored with ATI Sensors (ATI Inc., Collegeville, PA, USA). These sensors are reported by the manufacturer as having an accuracy of $\pm$5% at concentrations above ~50ppm.

In order to investigate possible effects of hydrogen peroxide spillage or accidental condensation during a decontamination cycle, dip exposures of samples to 35% liquid phase hydrogen peroxide was carried out in opaque PVC bottles (Fisher Scientific, Fair Lawn NJ, USA) for 24 hours and 168 hours. After dip exposure, all dip specimens were rinsed in DI-water and then air-dried in an electrostatic film drying cabinet (Delta 1, CPM, Inc. Dallas TX) for 1 day.

Thin commercial-grade sheet samples of 2024-T351 aluminum (1.27 mm thick), 7075-T6 aluminum (1.22mm thick) and annealed 304 stainless steel (1.22 mm thick) were acquired from McMaster Carr Corporation (Atlanta, GA, USA). Thin sheets were chosen to maximize the surface area-to-volume ratio of the materials and enhance the potential measurable effects on the mechanical properties of the materials. A few samples of 2024 were solution heat treated and aged to the T6 condition.

Commercial-grade sheet samples of Hexcel Corporation epoxy impregnated carbon fiber fabric composites (6 fabric layers, 3.2 mm thick overall) were acquired from McMaster Carr Corporation (Atlanta, GA, USA). The carbon fibers in the fabric were oriented along the length direction as well as the transverse direction (i.e., 0/90 orientations) and exhibited a total fiber volume of 55% of the overall sheet volume. Additional samples of woven carbon/glass fiber fabrics impregnated with epoxy resin (2 fabric layers, 1.6 thick overall) from Acculam Corporation were acquired from McMaster Carr Corporation (Atlanta, GA, USA). These laminates were then sectioned into 75 X 12.5 mm test coupons for hydrogen peroxide exposure and mechanical testing.

Epoxy-impregnated glass fiber fabric composites known as FR4 laminate for printed circuit board manufacture (3 layer lamination, uncoated: 5.0 mm thick and coated 5.15 mm thick) were acquired from Park Electrochemical Corp. (Fullerton, CA). Some samples of the FR4 laminate were conformal coated with a 0.075 mm thick 1B31 protective acrylic coating at Humiseal Protective Coatings (Woodside, NY) before being sectioned into 152 X 12.7 mm test samples for 3 point bending mechanical tests.

Tension testing and flexural testing of the metals and epoxy-based composite samples was performed according to ASTM Standards E8M-00b and D790-0 (6) in an environmentally conditioned laboratory (21 ± 1 ºC, 65 ± 2 % relative humidity) using a screw driven Instron 4400R (Instron Inc., Canton MA, USA) universal materials testing machine. Hydrogen embrittlement testing was conducted per ASTM Standard F519-06. A minimum of 5 samples were tested for each condition. Samples were taken from the sheets in either the longitudinal or transverse orientation.

Sample weights were measured by an accuSeries[+] accu-124 balance (Fisher Scientific, Arvada CO, USA) before and after hydrogen peroxide exposures. The reported accuracy of this device is $\pm$100 μg. Samples of the composites were dried in a vacuum dessicator for 48 hrs and then a standard calcium sulfate filled dessicator for 48 hours prior to measuring the initial weights. The same sample drying procedures were followed after hydrogen peroxide exposures and prior to post-exposure weight measurements. Weight changes of the FR4 samples were measured immediately before and after the VHP® processes. Dipped FR4 specimens were air dried for at least 1 day prior to weight change measurement.

Detailed examination of metallographic samples (before and after exposure) was performed with an Olympus PME3 inverted metallurgical microscope. Keller’s reagent (2.5mL HNO_3, 1.5mL HCl, 1 mL HF and 95 mL H_2O) was used to etch the aluminum samples while an acidic mixture (2.5 mL HF, 10 mL HNO_3, 10 mL HCl and 27.5 mL H_2O) was used to etch the stainless steel samples. Electron microsopy was performed using a JEOL JSM 7000F field emission scanning electron microscope operating at 20kV with energy disdersive X-ray spectroscopy (EDS) employing an ultrathin window detector and Princeton Gamma-Tech analyzer.

[+] accuSeries is a registered trademark of Fisher Scientific, Fair Lawn, NJ, USA.

Chemical analyses of the composite samples were performed using Fourier Transform Infrared Spectroscopy (FTIR) using an IR Prestige – 21 (Shimadzu Scientific Instruments, Columbia, MD, USA) spectrometer over a scan range from 400 cm^{-1} to 4000 cm^{-1}. Raman spectroscopy was employed to complement the infrared spectroscopy. Raman spectra were acquired using an Invia Confocal Raman Microscope (Renishaw, Wotton-under-Edge, Gloucestershire, UK) using a 514.5 nm wavelength and 1 mW laser excitation source. Spectra were recorded using a 50X objective lens which generated a 1μm laser spot.

Analysis of variance of the test results was performed using the SAS statistical analysis software package (SAS Institute Inc., Cary, NC, USA) to evaluate the statistical significance of the observed changes due to hydrogen peroxide exposure.

8.2.3 Avionics Compatibility

In order to study different avionics compatibility characteristics, tests were performed on several different dummy circuit board layouts, as well as an active circuit board and also aviation wire. The three dummy board layouts were (i) wire, (ii) interdigitated and (iii) pad. An HP4263B inductance, capacitance, and resistance (LCR) meter was used to measure the impedance of the traces on each board. For the wire boards, the impedances of all 16 traces were measured at 100mV, 1kHz. For the interdigitated boards, the impedances were measured at 100mV (1kHz and 10kHz). For the pad boards, the impedances were measured at 100mV (1kHz). The resistance of the wires was measured and subtracted from the trace measurements to obtain the impedance of the traces themselves. Since conformal coatings are normally applied to avionics circuit boards, some of the samples were coated with 1B31 acrylic coating (HumiSeal Protective Coatings; Woodside, NY.) Multiple tests were performed for each board layout (uncoated, uncoated-VHP® exposed, conformal coated, and conformal coated-VHP® exposed).

To test the active boards, sine and square waves were generated by the active boards to verify the signal output capabilities. As the active circuit was digital in nature, the square wave output could be directly generated. The sine wave signal was generated through pulse-width-modulation and a filter circuit. The signals for the unexposed boards and the VHP® exposed boards were recorded and compared by using an oscilloscope. For input acquisition tests on the active boards, a function generator was configured to output a sine wave or square wave, which would be captured with the analog-to-digital converter present in the active circuit board.

To test for any potential degradation of the aviation wire insulation (MIL227597/34-20), a high-voltage power supply and current measuring electronics were set up to apply high-voltage stress to the insulation. This was done in to determine the effect of VHP® exposure on the time-to-breakdown of the wire insulation. In these tests, ~18.5 KV RMS and ~10 KV RMS at 60 Hz was applied to ~1 ft sections of aviation wire. One terminal was connected to one end of the wire with the insulation intact. The other terminal was connected to the wire's conductor. The high-voltage power supply system kept a record of when the insulation breakdown occurred (VHP®- exposed wires versus non-VHP®

exposed wires). Twenty samples were tested for both exposed and non-exposed wires. Breakdown was detected by the current spike associated with the resulting short circuit.

Chemical analyses on the printed circuit boards and aviation wire insulation were performed by Raman spectroscopy. This process used an Invia Confocal Raman Microscope with a 514.5 nm wavelength and 1 mW laser excitation source. The spectra were recorded using a 50x objective lens which generated a 1 μm laser spot. Additional examination of the surface composition of copper layer on the test boards was accomplished using X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy. The glass transition temperature of the wire insulation layer was measured by differential scanning calorimetry (DSC).

8.3 Results and Discussion

8.3.1 Field Demonstrations

As long as the DC9's cargo bay temperature was excluded from the stand-alone thermal/humidity decontamination evaluations, it was possible to achieve stable cabin surface temperatures in excess of 60 ºC at all 28 locations, with the surface temperature adjacent to the air inlet remaining significantly below 70 ºC. The addition of a humidifier enabled a RH of around 50 % to be maintained, which is important as an elevated RH is needed to achieve antiviral efficacy. Some thermal oscillation was seen in the measured surface temperatures inside the DC9 aircraft temperatures. These were considered to be due to the thermal decontamination unit's heating system being oversized and not properly "matched" for the volume of the DC-9.

It proved possible to heat the majority of the 747 cabin to approximately 60ºC and hold near to this temperature for an extended period with the use of two thermal decontamination units. Although the two thermal decontamination units appeared to be well matched to the thermal mass of the 747, in some cases it was not possible to hold at 60 ºC for 2 hours, as stipulated in the test protocol. Surface temperatures in other locations (e.g. adjacent to the inlet) were found to exceed 65 ºC, with a maximum temperature of 71 ºC being observed where the incoming air stream impinged on the cabin. In addition, it was not possible to bring the cabin RH above 20%, using the 100 kW steam generator.

The combined system (thermal+humidity+VHP) appeared to be capable of controlling the VHP concentration in both the DC9 and the 747 cabins, based on the output from the six hydrogen peroxide sensors. It was possible to maintain an average cabin hydrogen peroxide concentration of around 175 ppm under non-condensing conditions, which should be sufficient to produce a sporicidal action (concentrations above ~ 80 ppm are usually considered sporicidal). The hydrogen peroxide concentration measured adjacent to the inlet did not exceed 275 ppm, and hence there does not appear to be a risk of macroscopic condensation of the peroxide (localized condensation would require pockets of high humidity). However, some condensed peroxide was apparent in the return air cabinet of the thermal decontamination system air handler and at weather-induced breaches to the temporary wooden door plugs.

Twenty-eight biological indicators (BIs) were placed throughout the DC9 cabin, and all of these were deactivated, except in the case of experimental runs for which there were known control issues. At both the 48-hour interim evaluation and 7-day final evaluation, all exposed biological indicators were negative for growth, and all positive controls showed normal growth.

The BIs placed throughout the 747 cabin did not achieve complete kill in a few cases (~15%). These BIs were placed in locations where peroxide access proved difficult to achieve. The only cases of extensive kill failures in large portions of the cabin were due to weather-generated equipment failures that caused condensation of the peroxide. In both the DC-9 as well as the 747 aircraft, some additional issues were encountered with residual release of hydrogen peroxide that had been trapped in seat fabrics, cushions, etc. Optimization of the aeration cycle seemed to help significantly in addressing this problem, although this still remains an issue.

Computational simulations of the decontamination of a narrow-body aircraft as well as a wide-body aircraft were performed using Fluent. Schematics of the aircraft cabins investigated are shown in Figure 8.2. The single-aisle cabin had three rows of seats in first class and 25 rows of economy class. The twin-aisle airliner cabin had three rows of seats in first class in front and 30 rows of economy class. The self-enclosed spaces, i.e., closets, galleys and lavatories, were not modeled in the calculations. The overarching results of the simulations showed that predicted uniformities of vaporized hydrogen peroxide decontaminants were generally better (1) in the narrow-body and (2) with the aircraft environmental control system fans stopped. These computational predictions are consistent with the experimental findings.

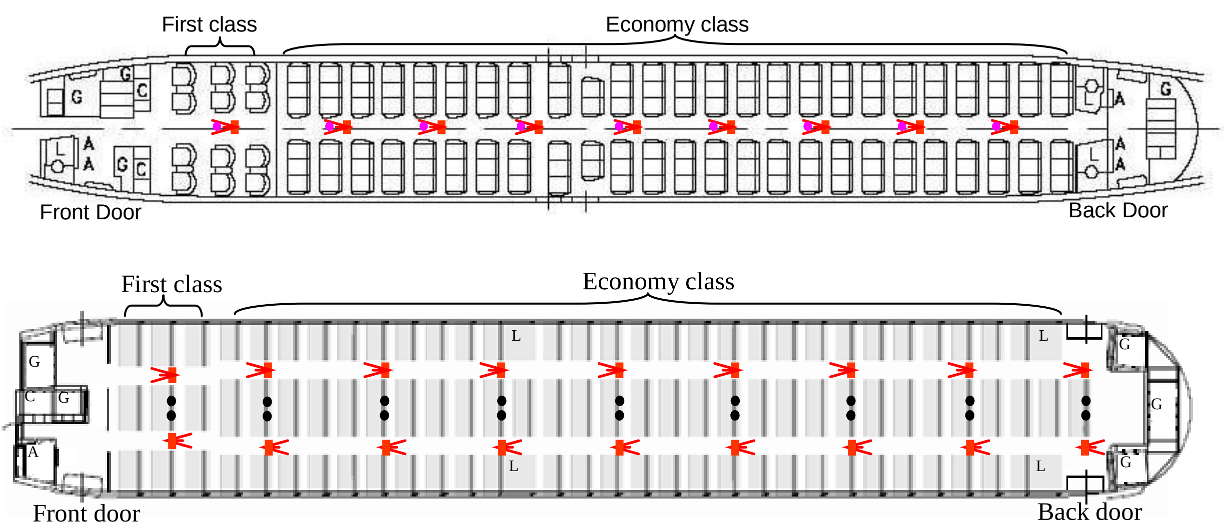


Figure 8.2 Single-aisle and a twin-aisle aircraft cabins used to computationally simulate decontaminant delivery methods. Red squares indicate mixing fans and arrows indicate airflow directions.

8.3.2 Materials Compatibility

Extensive materials compatibility evaluations of the effects of hydrogen peroxide exposure on the physical and mechanical properties of aerospace grade textiles, composites, metals, and avionics have been conducted.

The tensile strength and the elongation to failure of Nomex® were unchanged by exposure to 450 ppm vaporized hydrogen peroxide. The tensile strength of (i) nylon was minimally degraded (<10% loss), (ii) polyester were slightly degraded (~10% loss), and (iii) wool was moderately degraded (~20-30% loss) by exposure to 450 ppm vaporized hydrogen peroxide. The tensile strength and the elongation to failure of leather were severely degraded (~50% loss) by exposure to 450 ppm vaporized hydrogen peroxide.

Minimum changes were seen in the tensile properties of the following metals by exposures to either 450 ppm vapor phase or 35% liquid phase hydrogen peroxide: 2024-T351, 2024-T6 and 7075-T6 aluminum, and 304 stainless steel. However, although exposure of 4340 high strength steel to vaporized hydrogen peroxide levels as high as 1000 ppm did not cause hydrogen embrittlement, process conditions that led to condensation of the vapor on the 4340 high strength steel DID cause embrittlement. Work continues in this area.

Finally, carbon fiber/epoxy, glass fiber/carbon fiber epoxy and FR4 printed circuit board materials exhibited no significant changes in flexural strength or strain at peak load after 10 exposures to 450 ppm VHP®. However, some mechanical degradation in the composite samples was observed after 168 hour exposure to 35% liquid hydrogen peroxide. Delamination of the 1B31 acrylic confocal coating was observed on FR4 printed circuit board materials when exposed to liquid hydrogen peroxide. Finally, crazing of acrylics were also detected when the vapor process conditions enable condensation to form on the acrylic material.

8.3.3 Avionics Compatibility

The average resistance of the long, medium, and short length traces was about 11, 8, and 7 mOhms, respectively. The longer traces had slightly more resistance than the shorter ones, but there was only about a 1 mOhm difference between the non-exposed versus exposed boards. This difference is so small that it would not affect the DC characteristics of the traces. The impedance between the traces was also measured on the interdigitated board samples. No significant difference was found due to vaporized hydrogen peroxide exposures.

The pad board resistance had a maximum difference of approximately 2 mOhms between the uncoated and uncoated-exposed boards. Since the standard deviation was about 1 mOhm, this change was also insignificant. These tests were carried out on boards without solder mask. Solder mask (as is found on a typical PCB) would have provided another layer of protection against corrosion. A very thin layer of copper oxidation was detected on the tested boards. However, some oxidation due to air exposure would have occurred on these unprotected boards even without the presence of VHP®.

From all the sine and square waveforms test, the pre-and post-generated/measured waveforms were found to match with only minor deviations that may be attributed to expected noise. The input and output signals of unexposed boards and VHP® exposed boards were compared. No statistical difference was found, and the ability of the active boards to output or acquire signals was not found to be diminished in any way by the exposure to VHP®. However, some oxidation was visible on unprotected tin contacts.

In first set of high voltage wire test, ~18.5 KV_{RMS} was used. Wires not exposed to VHP® failed within 16 minutes on average. The wires that were exposed to VHP® failed on average within only 4 minutes, potentially indicating that VHP® decreased the dielectric strength of the wire insulation at this test voltage. However, in the interest of increasing the speed at which the breakdown would occur, the voltage stress applied was outside the operational voltages experienced by aviation wire. The stress voltage was ~18,500 V_{RMS} for these tests, whereas the normal aircraft operating voltage is only 28 Volts at 400 Hz. In a second set of high voltage wire tests, ~10,000 V_{RMS} was used. In this second test, the average (17 samples) fail time was 2 hours, 31 minutes and 36 seconds for the unexposed wires while the VHP®-exposed wires exhibited an average (17 samples) fail time of 3 hours, 36 minutes and 26 seconds. The VHP®-exposed wire samples thus lasted longer than the non-exposed wires. Thus the effects of VHP® exposure on wire insulation appear to be insignificant.

No statistical differences in chemical compositions or weight change were found among the circuit boards and aviation wires due to exposure to VHP®. XPS results on the circuit board copper layer revealed small surface changes due to oxidation on the sample exposed to 25 VHP® cycles.

8.4 Conclusions

8.4.1 Field Demonstrations

The thermal decontamination system appears to be capable of reproducing in full size aircraft the temperatures/humidities needed for an efficacious antiviral process. Further work is needed to improve the temperature control to eliminate overheating of some cabin surfaces. Reaching a relative humidity > 20 % was found to be a problem in the larger volume 747 cabin, but this appears to be addressable with the additional steam generation capacity.

The thermal decontamination + VHP add-in combination was found to be sporicidal at all locations within the narrow body DC9 and at most locations within the wide-body 747 cabin. The impact of issues relating to the failure to deactivate biological indicators in certain locations with limited peroxide penetration is an engineering issue that must be addressed. Issues related to the presence of residual peroxide in the cabin after aeration also must be corrected. Finally, additional engineering development is needed to prevent condensation of peroxide within the cabin of aircraft.

8.4.2 Materials Compatibility

Vaporized hydrogen peroxide conditions that lead to condensation can cause hydrogen embrittlement of high strength steel. Condensation must be avoided to prevent this very serious degradation of high strength steel. The tensile properties (0.2% offset yield strength, ultimate tensile strength and % elongation to failure) of samples of 2024-T351, 2024-T6, 7075-T6 and 304 stainless steel were unaffected by the various exposures to both vapor phase and 35% liquid phase hydrogen peroxide.

The carbon fiber/epoxy, the glass fiber/carbon fiber epoxy and the FR4 printed circuit board materials exhibited no significant changes in flexural strength after 10 VHP exposures.

Exposures of textile samples (wool, nylon, polyester and Nomex® to vaporized or liquid phase hydrogen peroxide caused increases in weight presumably due to absorption of water vapor from the treatment as well as decomposition of H_2O_2 to oxygen and water vapor. Exposure to 10 cycles of vaporized hydrogen peroxide caused the following changes in the textile materials:

- The tensile strength of wool was moderately degraded (~20-30% loss).
- The tensile strength of polyester was slightly degraded (~10% loss).
- The tensile strength of nylon was minimally degraded (<10% loss).
- The tensile strength of Nomex® were unchanged.
- The tensile strength of leather were severely degraded (~50% loss).
-

All preliminary flammability results for Nomex® - both as-received as well as after all exposures to hydrogen peroxide - were within the limits of FAR 25.853 for both vertical and horizontal flammability testing. The preliminary flammability testing of wool, nylon and polyester indicated complex effects on flame/burn times, burn lengths and horizontal burn rates presumably due to the presence of absorbed water vapor from the hydrogen peroxide exposures as well as the pre-test conditioning treatments. Additional research into these effects is necessary to fully understand and rigorously characterize this important behavior.

8.4.3 Avionics Compatibility

VHP® exposure had no significant effect on the electrical performance of the circuit boards or the electrical wire insulation materials. The discoloration of the copper boards would have occurred even in ambient environmental conditions.

9.0 Appendices

9.1 Archival Publications

9.1.1 2010 Publications

Coleman BK, Wells JR, Nazaroff WW, 2010. Investigating ozone-induced decomposition of surface-bound permethrin for conditions in aircraft cabins. *Indoor Air* 20, 61-71.

"Improvements on FFD modeling by using different numerical schemes," Zuo, W., Hu, J., and Chen, Q., Accepted by *Numerical Heat Transfer*.

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"On a hybrid RANS/LES approach for indoor airflow modeling," Wang, M. and Chen, Q., Accepted by *HVAC&R Research.*

"Comparison of different decontaminant delivery methods for sterilizing unoccupied commercial airliner cabins," Chen, X. and Chen, Q., *Building and Environment*, 45(9), 2010 2027-2034.

"Characterizing exhaled airflow from breathing and talking," Gupta, J.K., Lin, C.-H., and Chen, Q., *Indoor Air*, 20 (2010) 31-39.

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"Inactivating Influenza Viruses on Surfaces Using Hydrogen Peroxide or Triethylene Glycol at Low Vapor Concentrations," Rudnick SN, McDevitt JJ, First MW, Spengler JD, DOT/FAA/AM-09/7, April 2009.

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“Assessment of various turbulence models for transitional flows in enclosed environment,” Wang, M. and Chen, Q. *HVAC&R Research*, 15(6), 2009, 1099-1119.

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"A simplified approach to describe complex diffusers in displacement ventilation for CFD simulations," Zhang, T., Lee, K.S., and Chen, Q., *Indoor Air*, 19(3), 2009, 255-267.

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9.1.5 2006 Publications

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"A fluorescence-based biosensor for the detection of organophosphate pesticides and chemical warfare agents," Viveros, L.; Paliwal, S.; McCrae, D.; Wild, J.; Simonian, A.; *Sensors and Actuators, B: Chemical*, Vol 115, n 1 (2006) pp 150-157.

"TCP electrochemical detection," Vertelov, G.K.; Gale, W.F.; Simonian, A.L.; *ECS Transactions*, Vol. 3, n 10, (2006) pp 21-34,

"Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms," Zhang, Z.; Chen, Q., *Atmospheric Environment*, Vol 40, No 18 (2006) pp 3396-3408.

"Comparison of Large Eddy Simulation Predictions with Particle Image Velocimetry Data for the Airflow in a Generic Cabin Model" C.H. Lin, T.T. Wu, R.H. Horstman, P.A. Lebbin, M.H. Hosni, B.W. Jones, B.T. Beck, *HVAC & R Research*, Vol 12, No 3 (2006) pp. 935 – 951

9.1.7 2005 Publications

"Nanoparticle-based optical biosensors for the direct detection of organophosphate chemical warfare agents and pesticides," Simonian, A.L.; Good, T.A.; Wang, S.-S.; Wild, J.R.; *Analytica Chimica Acta*, Vol 534, n 1 (2005) pp 69-77.

"Prediction of Particle Transport in Enclosed Environment" Q. Chen and Z. Zhang, *China Particuology*, Vol 3, No 6 (2005) pp 364 – 372.

9.2 Applicable U.S. Federal Regulations

The federal aviation regulations applicable to the design and operation of commercial aircraft are contained in "Title 14 - Aeronautics and Space" of the Code of Federal Regulations (14 CFR). Part 25 of 14 CFR provides the airworthiness standards for transport category airplanes. Part 121 of 14 CFR contains the operating requirements for air carriers and commercial operators. Part 125 of 14 CFR covers (i) the certification and operations of aircraft having a seating capacity of 20 or more passengers OR a maximum payload capacity of 6000 or more pounds and (ii) the rules governing persons on board such aircraft. The current and full text of 14 CFR can be found on the U.S. Government Printing Office website.

9.2.1 Ventilation Regulations

14 CFR § 25.831 Ventilation.

(a) Under normal operating conditions and in the event of any probable failure conditions of any system which would adversely affect the ventilating air, the ventilation system must be designed to provide a sufficient amount of uncontaminated air to enable the crewmembers to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort. For normal operating conditions, the ventilation system must be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute.

(b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapors. In meeting this requirement, the following apply:

(1) Carbon monoxide concentrations in excess of 1 part in 20,000 parts of air are considered hazardous. For test purposes, any acceptable carbon monoxide detection method may be used.

(2) Carbon dioxide concentration during flight must be shown not to exceed 0.5 percent by volume (sea level equivalent) in compartments normally occupied by passengers or crewmembers.

(c) There must be provisions made to ensure that the conditions prescribed in paragraph (b) of this section are met after reasonably probable failures or malfunctioning of the ventilating, heating, pressurization, or other systems and equipment.

(d) If accumulation of hazardous quantities of smoke in the cockpit area is reasonably probable, smoke evacuation must be readily accomplished, starting with full pressurization and without depressurizing beyond safe limits.

(e) Except as provided in paragraph (f) of this section, means must be provided to enable the occupants of the following compartments and areas to control the temperature and quantity of ventilating air supplied to their compartment or area independently of the temperature and quantity of air supplied to other compartments and areas:

(1) The flight crew compartment.

(2) Crewmember compartments and areas other than the flight crew compartment unless the crewmember compartment or area is ventilated by air interchange with other compartments or areas under all operating conditions.

(f) Means to enable the flight crew to control the temperature and quantity of ventilating air supplied to the flight crew compartment independently of the temperature and quantity of ventilating air supplied to other compartments are not required if all of the following conditions are met:

(1) The total volume of the flight crew and passenger compartments is 800 cubic feet or less.

(2) The air inlets and passages for air to flow between flight crew and passenger compartments are arranged to provide compartment temperatures within 5 degrees F. of each other and adequate ventilation to occupants in both compartments.

(3) The temperature and ventilation controls are accessible to the flight crew.

(g) The exposure time at any given temperature must not exceed the values shown in the following graph after any improbable failure condition.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25–41, 42 FR 36970, July 18, 1977; Amdt. 25–87, 61 FR 28695, June 5, 1996; Amdt. 25–89, 61 FR 63956, Dec. 2, 1996]

14 CFR § 121.219 Ventilation.

Each passenger or crew compartment must be suitably ventilated. Carbon monoxide concentration may not be more than one part in 20,000 parts of air, and fuel fumes may not be present. In any case where partitions between compartments have louvres or other means allowing air to flow between compartments, there must be a means convenient to the crew for closing the flow of air through the partitions, when necessary.

14 CFR § 125.117 Ventilation.

Each passenger or crew compartment must be suitably ventilated. Carbon monoxide concentration may not be more than one part in 20,000 parts of air, and fuel fumes may not be present. In any case where partitions between compartments have louvres or other means allowing air to flow between compartments, there must be a means convenient to the crew for closing the flow of air through the partitions when necessary.

9.2.2 Ozone Regulations

14 CFR § 25.832 Cabin ozone concentration.

(a) The airplane cabin ozone concentration during flight must be shown not to exceed—

(1) 0.25 parts per million by volume, sea level equivalent, at any time above flight level 320; and

(2) 0.1 parts per million by volume, sea level equivalent, time-weighted average during any 3-hour interval above flight level 270.

(b) For the purpose of this section, "sea level equivalent" refers to conditions of 25 °C and 760 millimeters of mercury pressure.

(c) Compliance with this section must be shown by analysis or tests based on airplane operational procedures and performance limitations, that demonstrate that either—

(1) The airplane cannot be operated at an altitude which would result in cabin ozone concentrations exceeding the limits prescribed by paragraph (a) of this section; or

(2) The airplane ventilation system, including any ozone control equipment, will maintain cabin ozone concentrations at or below the limits prescribed by paragraph (a) of this section.

14 CFR § 121.578 Cabin ozone concentration.

(a) For the purpose of this section, the following definitions apply:

(1) Flight segment means scheduled nonstop flight time between two airports.

(2) Sea level equivalent refers to conditions of 25° C and 760 millimeters of mercury pressure.

(b) Except as provided in paragraphs (d) and (e) of this section, no certificate holder may operate an airplane above the following flight levels unless it is successfully demonstrated to the Administrator that the concentration of ozone inside the cabin will not exceed—

(1) For flight above flight level 320, 0.25 parts per million by volume, sea level equivalent, at any time above that flight level; and

(2) For flight above flight level 270, 0.1 parts per million by volume, sea level equivalent, time-weighted average for each flight segment that exceeds 4 hours and includes flight above that flight level. (For this purpose, the amount of ozone below flight level 180 is considered to be zero.)

(c) Compliance with this section must be shown by analysis or tests, based on either airplane operational procedures and performance limitations or the certificate holder's operations. The analysis or tests must show either of the following:

(1) Atmospheric ozone statistics indicate, with a statistical confidence of at least 84%, that at the altitudes and locations at which the airplane will be operated cabin ozone concentrations will not exceed the limits prescribed by paragraph (b) of this section.

(2) The airplane ventilation system including any ozone control equipment, will maintain cabin ozone concentrations at or below the limits prescribed by paragraph (b) of this section.

(d) A certificate holder may obtain an authorization to deviate from the requirements of paragraph (b) of this section, by an amendment to its operations specifications, if—

(1) It shows that due to circumstances beyond its control or to unreasonable economic burden it cannot comply for a specified period of time; and

(2) It has submitted a plan acceptable to the Administrator to effect compliance to the extent possible.

(e) A certificate holder need not comply with the requirements of paragraph (b) of this section for an aircraft—

(1) When the only persons carried are flight crewmembers and persons listed in §121.583;

(2) If the aircraft is scheduled for retirement before January 1, 1985; or

(3) If the aircraft is scheduled for re-engining under the provisions of subpart E of part 91, until it is re-engined.

9.2.3 Cabin Pressure Regulations

14 CFR § 25.841 Pressurized cabins.

(a) Pressurized cabins and compartments to be occupied must be equipped to provide a cabin pressure altitude of not more than 8,000 feet at the maximum operating altitude of the airplane under normal operating conditions.

(1) If certification for operation above 25,000 feet is requested, the airplane must be designed so that occupants will not be exposed to cabin pressure altitudes in excess of 15,000 feet after any probable failure condition in the pressurization system.

(2) The airplane must be designed so that occupants will not be exposed to a cabin pressure altitude that exceeds the following after decompression from any failure condition not shown to be extremely improbable:

(i) Twenty-five thousand (25,000) feet for more than 2 minutes; or

(ii) Forty thousand (40,000) feet for any duration.

(3) Fuselage structure, engine and system failures are to be considered in evaluating the cabin decompression.

(b) Pressurized cabins must have at least the following valves, controls, and indicators for controlling cabin pressure:

(1) Two pressure relief valves to automatically limit the positive pressure differential to a predetermined value at the maximum rate of flow delivered by the pressure source. The combined capacity of the relief valves must be large enough so that the failure of any one valve would not cause an appreciable rise in the pressure differential. The pressure differential is positive when the internal pressure is greater than the external.

(2) Two reverse pressure differential relief valves (or their equivalents) to automatically prevent a negative pressure differential that would damage the structure. One valve is enough, however, if it is of a design that reasonably precludes its malfunctioning.

(3) A means by which the pressure differential can be rapidly equalized.

(4) An automatic or manual regulator for controlling the intake or exhaust airflow, or both, for maintaining the required internal pressures and airflow rates.

(5) Instruments at the pilot or flight engineer station to show the pressure differential, the cabin pressure altitude, and the rate of change of the cabin pressure altitude.

(6) Warning indication at the pilot or flight engineer station to indicate when the safe or preset pressure differential and cabin pressure altitude limits are exceeded. Appropriate warning markings on the cabin pressure differential indicator meet the warning requirement for pressure differential limits and an aural or visual signal (in addition to cabin altitude indicating means) meets the warning requirement for cabin pressure altitude limits if it warns the flight crew when the cabin pressure altitude exceeds 10,000 feet.

(7) A warning placard at the pilot or flight engineer station if the structure is not designed for pressure differentials up to the maximum relief valve setting in combination with landing loads.

(8) The pressure sensors necessary to meet the requirements of paragraphs (b)(5) and (b)(6) of this section and §25.1447(c), must be located and the sensing system designed so that, in the event of loss of cabin pressure in any passenger or crew compartment (including upper and lower lobe galleys), the warning and automatic presentation devices, required by those provisions, will be actuated without any delay that would significantly increase the hazards resulting from decompression.