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CASE REPORT

Quantifying Risk to Flight Attendants from Secondhand Smoke Exposure in Airline Cabins Using Pharmacokinetic Modeling: A Case Report

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ABSTRACT

Background: Several studies of the health problems incurred by flight attendants flying during the smoking years concluded that they suffered elevated rates of chronic bronchitis, heart disease, skin cancer, breast cancer, melanoma, reproductive cancers, middle ear infections, hearing loss, asthma, pneumonia, chronic obstructive pulmonary disease, various pulmonary function abnormalities, plus depression and anxiety.

Aims: Systematic review of secondhand smoke risks to flight attendants, exemplified using a specific case involving a deceased flight attendant who suffered from a multiplicity of tobacco-smoke-related diseases, including asthma, breast cancer, carotid artery stenosis, cataracts, cervical cancer, chronic obstructive pulmonary disease, coronary artery disease, laryngeal cancer, pneumonia and chronic myeloid leukemia. The decedent died in 2014 at age 68, losing an estimated 18.5 years of life expectancy.

Methods: Pharmacokinetic modeling was used for the first time to estimate the risk from secondhand smoke for flight attendants on typical passenger aircraft flown by the decedent during an 18 year period ending in 1988.

Results: Based on in-flight cotinine dosimetry measured in an Air Canada study, typical flight attendants would have inhaled a dose-equivalent of fine particle air pollution exceeding the "Air Pollution Emergency" levels of the U.S. Environmental Protection Agency's Air Quality Index. The secondhand smoke cotinine dose for typical flight attendants in aircraft cabins is estimated to have been 6-fold that of the average US worker and 14-fold that of the average person. Thus, ventilation systems massively failed to control secondhand smoke air pollution in aircraft cabins, and led to extreme exposures. The decedent's estimated lifetime cancer risk from secondhand smoke was 18 times U.S. OSHA's Significant Risk of Material Impairment of Health level of 1 per 1000 per working lifetime.

Conclusions: In-flight exposure to toxic and carcinogenic tobacco smoke in smoky passenger cabins was the major risk factor leading to the decedent's multiple smoking-related diseases, and her premature death. This has implications for the extant and future health of the cohort of surviving flight attendants exposed to secondhand smoke on aircraft during the 20th Century Era.

INTRODUCTION

Flight attendants have worked on passenger aircraft since 1931. In 1985 there were 40 000 flight attendants employed by US airlines, and by 2000, the number had risen to nearly 116 000. For years, flight attendants reported health problems they attributed to their occupational exposures. Yet, as recently as the mid-1980s, little had been done to characterize either the quality of the air in airliner cabins or its possible health effects on cabin crew, and there were no federal standards governing secondhand smoke (SHS) exposure.[1] The objective of this paper is to calculate the occupational risk of an individual from secondhand smoke exposure in the airliner workplace. Evaluating risk in the environmental and occupational sciences often involves estimating exposures that have occurred in the past and need to be reconstructed using mathematical modeling. In the case of secondhand smoke, pharmacokinetic modeling is used to estimate personal dosimetric exposures of flight attendants based on the nicotine metabolite, cotinine in body fluids, as opposed to area measurements of secondhand smoke chemicals in aircraft cabins. An exposure-response model is then employed to estimate morbidity and mortality risks for a specific individual flight attendant compared to environmental and occupational health standards of acceptable risk. Applied to secondhand smoke, this novel technique is shown to be useful for occupational disease causation as well as for forensic purposes in litigation. Risk estimation for the entire affected class can similarly be used to relate past and present disease to secondhand smoke exposure. And as carcinogenesis has a long latency period, as future disease manifests itself in the class, risk assessment is used to relate its occurrence to their occupational exposures to secondhand smoke in aircraft cabins.

Several epidemiological studies of the health problems incurred by flight attendants flying during the smoking years concluded that they suffered elevated rates of chronic bronchitis, heart disease, skin cancer, breast cancer, melanoma, reproductive cancers, middle ear infections, hearing loss, asthma, pneumonia, chronic obstructive pulmonary disease, various pulmonary function abnormalities, plus depression and anxiety.[2-7] In a congressional hearing in 1989, flight attendants from several carriers testified before the U.S. House of Representatives that they had suffered health problems due to exposure to secondhand smoke on the job in aircraft cabins, including chronic lung inflammation, difficulty breathing, chronic bronchitis, lung disease, cancer, sinusitis, laryngitis, bronchial problems, blocked ears, burning eyes, and aphasia.[8]

The U.S. 1989 Congressional Hearing on Aircraft Smoking Ban.

The Subcommittee on Aviation of the Committee on Public Works and Transportation of the U.S. House of Representatives convened in June 1989, to consider a proposed renewal of a two-hour smoking ban on commercial passenger aircraft enacted in 1987.[9] The author participated in a U.S. federal interagency panel invited to provide official testimony, and was one of two representatives from the U.S. Environmental Protection Agency. The flight attendant panel's lead speaker, Ms. Connie Chalk, stated: "When I began my career as a flight attendant in 1968, I was in perfect health and never smoked cigarettes. After working as flight attendant for two decades, I am no longer in perfect health and I and my doctor blame my physical problems on the years of breathing cigarette smoke. Four years ago, I began to have health problems. I was coughing incessantly and having great difficulty breathing. … The official diagnosis was chronic inflammation of the lungs. The lung specialist warned me that if I did not stop working smoking flights, I only had five to seven years to live. Even the airline company doctor recommended that I not work on any smoking flights. … anybody in this room that has ever sat next to a smoker knows you reek, the odor is terrible when you get home. – you take your uniform off and wash it, the water is black, your hose are black, your blouse is black, … When you wash your hair, it runs a brown, black water. It is terrible … it has taken its toll on me, and it has taken its toll on many other flight attendants. … And … from our passenger counts, we have 25 rows of nonsmoking and four rows of smoking, so that that tells you … what our passengers want. They want a total smoking ban."[9]

Another flight attendant, Ms. Patricia Young, testified: "… I have been a flight attendant for 23 years. … Unlike other workers, flight attendants cannot step outside for a breath of fresh air or simply open a window when the air is full of cigarette smoke. … I suffer from chronic bronchitis and a partial loss of hearing from injuries to my ears while in flight because of cigarette smoke in my work environment. … I have also interviewed many flight attendants with smoke-related injuries … some with lung disease and cancer … the individuals will not talk on the record because they are afraid that their jobs and health benefits will be in jeopardy. … The ability to remedy the problem rests with you, the Members of Congress. Please be our voice. Let the American public know we, the flight attendants, are not a disposable workforce. Grant the over 100,000 flight attendants in this country the basic right to a healthy and safe work environment." …[9]

A third flight attendant, Ms. Cathy Gilbert-Silva, related: … "I have been a flight attendant for a major airline for 20 years … and have never been a smoker. … I can recall being on the sick list as far back as 1972 for blocked ears. As the years went by, I had to take more and more time off work because of a recurring sinus infection, bronchial problems, laryngitis, scratchy throat and blocked ears. In 1976, my supervisor told me either do something about my problems or find new work. … I was on weekly shots for about five years, I was still getting sick on extremely smoky flights … while I did feel better with the shots, I would get on the plane feeling perfectly well, … and by the time we landed my lungs were congested and tight, and my sinuses and eyes burned, my ears were blocked. … Following an exceptionally smoky flight, I would literally taste cigarette smoke in my mouth for weeks. My husband often complained that my breath smelled like I had been chewing on cigarettes or like an ashtray. … I had used up all my sick time … I had no choice but to fly when I was sick. … I worked with blocked ears. I worked with laryngitis. Only on the occasions when I lost my voice, which happened a couple of times a year, would I take sick leave. … Finally in May 1988, I totally lost my voice and could not fly. … I had surgery on my vocal cords. … The doctor blamed the dry air in airplanes, speaking above environmental noise … and bad air quality, especially smoke. I was advised by two doctors and a voice therapist that [unless my work environment changed] I would never get better." … It is frightening to me that I am no longer a healthy person. … I am not alone with these problems either. My doctor told me that he is seeing a lot more flight attendants with throat problems. … It is time that we have a total smoking ban on aircraft.[9]" Several others testified in the same vein.

Subsequently, in October of 1989, a House and Senate Conference Committee enacted a permanent smoking ban on all domestic continental flights and flights of 6 hours or less to or from Alaska or Hawaii, encompassing 99.9% of all domestic flights. It was signed into law by President George H.W. Bush in November, and took effect on February 25, 1990.[60] By 2000, the ban was extended to international flights.[9]

The Cheney Litigation

In 2015, a lawsuit in the State of Florida by the Estate of Kathleen-Sprowl-Cheney was filed against four tobacco companies for compensatory damages incurred alleging that the secondhand smoke that she inhaled while employed as a flight attendant for Eastern Airlines was a causative factor. This paper illuminates the deleterious effect of chronic workplace exposure of nonsmoking flight attendants to secondhand smoke and for the first time, applies pharmacokinetic modeling for forensic purposes to evaluate the risk of secondhand smoke in an aircraft cabin in this case. The author of this report has served as an expert witness in this and other flight attendant litigation.

Ms. Cheney was employed by Eastern Airlines, a U.S. carrier, from July 1968 to August 1988, serving as a Flight Attendant for 18 of the 20 years. From Jan 1971 - Jan 1973, she worked in the office as a Flight Services Analyst, returning to aircraft until being placed on permanent disability in 1988 (Figure 1). Her work environment involved smoke-filled cabins 100% of the time when flying. In October 1987, Ms. Cheney was diagnosed with throat cancer, and retired on medical disability in 1988. She stated that "my doctor informed me that, 'you have a smoker's throat cancer; in my opinion, your cancer came from inhaling other peoples' smoke. It is not common in women, and when it [occurs], it is found in women who are heavy smokers and heavy alcohol drinkers.' I am neither."[10] During her career, Ms. Cheney suffered from multiplicity of ailments, including asthma, breast cancer, carotid artery stenosis, cataracts, cervical cancer, chronic obstructive pulmonary disease, coronary artery disease, laryngeal cancer, pneumonia and leukemia. Ms. Cheney's in-flight exposure to toxic and carcinogenic tobacco smoke in Eastern Airline's passenger cabins was posited as the major risk factor leading to her premature death (Figure 1). She died from leukemia at age 68 in 2014.

Cancer of the head and neck organs, particularly the pharynx and the larynx from secondhand smoke exposure has been suggested by multiple reports.[11] For example, Zhang et al.[12] observed a dose-response relationship between the degree of exposure and risk of head and neck cancer. Adjusted ORs were 2.1 (95% CI, 0.7–6.1) for those with moderate exposure and 3.6 (95% CI, 1.1–11.5) for individuals with heavy exposure (P for trend = 0.025) in comparison with those who never had secondhand smoke exposure. Crude odds ratios were 1.8 for those with moderate secondhand smoke exposure and 4.3 for individuals with heavy secondhand smoke exposure among nonsmoking cases and controls (P for trend = 0.008).

Ms. Cheney developed leukemia. According to the International Agency for Research on Cancer,[39] "There is sufficient evidence in humans for the carcinogenicity of benzene, a component of tobacco smoke. Benzene causes acute myeloid leukemia/acute non-lymphocytic leukemia. A positive association has been observed between exposure to benzene and acute lymphocytic leukemia, chronic lymphocytic leukemia, multiple myeloma, and non-Hodgkins lymphoma. Ms. Cheney also suffered from breast cancer and throat cancer, as well as asthma and altered vascular properties. All of these have been related to tobacco smoke exposure, from high dose or low dose exposure due to active and passive smoking.[14,15]

Figure 1. Ms. Kathleen Sproul Cheney, in the doorway of an Eastern Airlines DC-9.[10]

During her career she flew on several different passenger airliners, including The Electra, DC9 various sizes, DC10, L1011, B727 various sizes, and B757.[10] She flew on both domestic and international routes.

Passenger Aircraft Characteristics

Ms. Cheney's primary workstations were aboard short-haul Boeing 727s and long-haul Lockheed L-1011's (Figure 2, a,b). Table 1[1] gives relevant parameters for various aircraft, updated in this report to include the L-1011 TriStar and the DC-9. The range in ventilation rate per person for the L-1011 depends upon whether one, two or three ventilation packs are operating. The L-1011 has a cabin length of 33 meters, width of 5.77 meters and height of 2.7 meters. It can fit 256 passengers in a mixed-class seating and up to 400 passengers in a high density configuration. Its cabin volume is 514 m^3. The DC-9-30 has a cabin volume of 146 m^3.[56] Note the low space volume per person, ranging from 1.2 to 1.9 m^3 for all types of passenger aircraft (Table 1).

Figure 2a. Eastern Airlines Boeing 727 Jetliner seated 120 passengers.[56]

Figure 2b. Eastern Airline's Lockheed L-10ll seated 242 passengers.[56]

Table 6 Cabin volumes, percentage air recirculation, and air exchange rates[1 3 11]

Body type (W, wide; N, narrow)	Cabin volume (m^3)	% Air recirculation	Air exchange rate (/h)	Estimated average seating*	Volume per person (m^3)	Ventilation rate per person (litre/s)
Boeing 727-200[N]	165	0	26.4	120	1.4	6–8
Boeing 747[W]	790	26	14.7	452	1.7	7–10
Boeing 767-200[W]	319	52	10.4	250	1.3	4
MD DC10-10[W]	419	0	22.8	280	1.5	7–9
MD DC10-40[W]	419	35	14.9	310	1.4	5
Airbus A-310[W]	334		9.7	250	1.3	4
DC-9	146	0	13.7	127	1.2	6.5
Lockheed L-1011	450	0	20.0	242	1.9	3-10

The B-747 has a passenger capacity of 331–550 persons, and the DC-10 from 250–380 persons.[1]
*At 100% load factor.[3]

Table 1. Aircraft Characteristics for a variety of commercial aircraft (from Table 6 in reference),[1] updated here to include the DC-9-30 and Lockheed L-1011.

The Air Canada Study: Cotinine Dosimetry in Flight Attendants.

Nicotine and its metabolite, cotinine, are respectively the pre-eminent atmospheric and biomarkers for secondhand smoke exposure and dose. Mattson et al.[18] measured cabin air nicotine exposure and urinary cotinine dose in four flight attendants and five passengers on two international (San Francisco to Toronto and back) and two transcontinental (Toronto to Vancouver) smoking flights on Air Canada in May 1988. All subjects were non-smokers with no regular exposure to smoke, and were free of respiratory disorders. The first two flights were on B-727 narrow body jets with 100% fresh air. The latter two flights were on B-767 wide bodies, with 50% of the air recirculated. The same subjects were monitored in all flights (five passengers who sat in the smoking section or on its border, and four flight attendants who rotated assignments to smoking for half the flights and to non-smoking for the other half). Air nicotine exposure via personal monitoring pumps and filters was assessed during the flight. Cigarettes were counted at intervals during the flights, and the extent and duration of between flight exposure to SHS was monitored by passive monitors and recorded in diaries. Mattson et al.[18] found that attendants assigned to work in non-smoking areas were exposed to secondhand smoke. Self-reported eye and nasal symptoms and perception of a smoky atmosphere were significantly related to nicotine and cotinine. Mattson et al[18] concluded that SHS exposures on aircraft create a health risk, acute irritation, and annoyance to non-smokers.

Analysis of the Air Canada study indicated that the level of secondhand smoke in the cabins of both narrow and wide-body passenger aircraft caused doses of tobacco smoke that greatly exceed that of the typical worker and the general population, placing flight attendants at risk of the diseases of tobacco smoke exposure.[1] Figure 3 overlays the cotinine distribution for a statistical sample of the U.S. population showing the geometric mean cotinine level of 2.88 ng/mL from the Air Canada study. This Air Canada subjects' level is six times the level for the average worker and 14 times the average adult in 1999-2000 reported in the NHANES study. Moreover, the Air Canada subject', cotinine exceeded the 95th percentile of secondhand smoke dose for the U.S. adult population (Table 2).

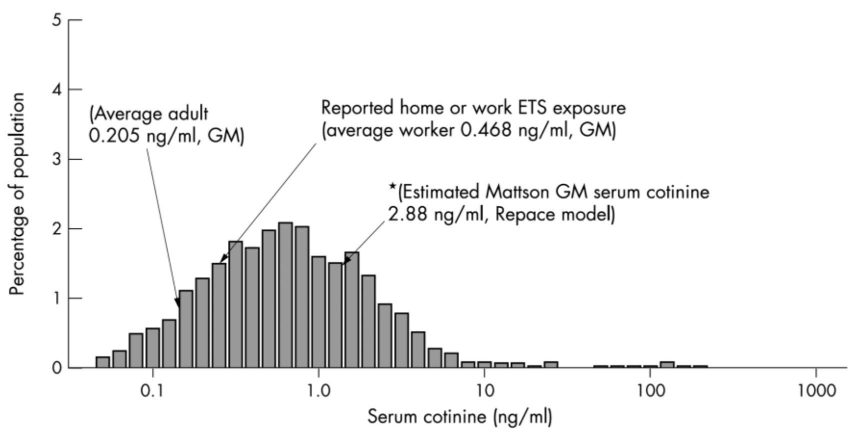

Figure 3 NHANES III distribution of cotinine in the US population versus the Mattson study. The median serum cotinine equivalent to the urinary cotinine level of 18.72 ng/ml is 2.88 ng/ml, which is six times the geometric mean (GM) serum cotinine level of the average US worker and 14 times that of the average adult, demonstrating that flight attendants have had abnormally heavy SHS exposure. NHANES III cotinine data from Pirkle *et al.*[38] *Repace *et al.*[36 37]

Figure 3 plots the average cotinine level for the Mattson study[18] of flight attendants' serum cotinine against the cotinine distribution for a statistical sample of the U.S. population showing much higher levels than the average worker and the average adult.[1]

Aircraft Ventilation Systems[1]

Until 1996, U.S. Federal Aviation Administration (FAA) regulations provided only that the airliner cabin passenger compartment "must be suitably ventilated." In 1970, the typical passenger aircraft provided 15 ft^3/min (7 liters/s) or more of outside air per person, but by 1987, this had declined to where some new commercial aircraft provided barely 6 ft^3/min per person (2.8 liters/s per person) of outside air flow to their passenger cabins. Thus, aircraft ventilation rates declined by a third to half or more over a period of 17 years.[1] Moreover, at the pilot's discretion, aircraft manufactured during the 1970s could reduce outside airflows to 10 ft^3/min per person, and outside air delivery rates have been reduced to as low as 2.1 ft^3/min per person (1 liter/s per person), or 1/10 of that for office workers. For aircraft with particulate air filtration, nominal filter efficiency (90–99.98%) varied with airline policy; however, such efficiencies are not attained in practice.

Gaseous secondhand smoke (SHS) contaminants are not filtered.

Table 2. Serum Cotinine Doses from the NHANES III Study, 1999-2000.[19]

Table 60. Cotinine

Geometric mean and selected percentiles of serum concentrations (in ng/mL) for the non-smoking U.S. population aged 3 years and older, National Health and Nutrition Examination Survey, 1999-2000.

	Geometric mean (95% conf. interval)	Selected percentiles (95% confidence interval)						Sample size
		10th	25th	50th	75th	90th	95th	
Total, age 3 and older	*	< LOD	< LOD	.059 (<LOD-.070)	.236 (.180-.310)	1.02 (.740-1.27)	1.96 (1.64-2.56)	5999
Age group								
3-11 years	*	< LOD	< LOD	.109 (.064-.180)	.500 (.290-1.02)	1.88 (1.19-3.09)	3.37 (1.79-4.23)	1174
12-19 years	*	< LOD	< LOD	.107 (.080-.163)	.540 (.371-.762)	1.65 (1.25-2.11)	2.56 (2.35-3.23)	1773
20 years and older	*	< LOD	< LOD	< LOD	.167 (.137-.200)	.630 (.520-.863)	1.48 (1.23-1.77)	3052
Gender								
Males	*	< LOD	< LOD	.080 (.060-.100)	.302 (.220-.390)	1.20 (.890-1.56)	2.39 (1.78-3.06)	2789
Females	*	< LOD	< LOD	< LOD	.179 (.135-.250)	.850 (.590-1.14)	1.85 (1.41-2.37)	3210
Race/ethnicity								
Mexican Americans	*	< LOD	< LOD	< LOD	.139 (.107-.182)	.506 (.340-.813)	1.21 (.813-1.84)	2242
Non-Hispanic blacks	*	< LOD	< LOD	.131 (.110-.150)	.505 (.400-.625)	1.43 (1.22-1.66)	2.34 (1.89-2.97)	1333
Non-Hispanic whites	*	< LOD	< LOD	.050 (<LOD-.070)	.210 (.150-.313)	.950 (.621-1.40)	1.92 (1.54-2.74)	1949

< LOD means less than the limit of detection, which is 0.05 ng/mL.

* Not calculated. Proportion of results below limit of detection was too high to provide a valid result.

In addition to low per person air exchange rates, aircraft cabins have the smallest available airspace per person of any social venue, and occupants of a fully loaded aircraft typically have about 35–70 ft^3 (1–2 m^3) of available airspace per person, 1/10th that of a typical office worker or a spectator in an auditorium. Moreover, aircraft cabins have an abnormal respiratory environment relative to most human habitats: they typically are pressurized to only 75% that at sea level, equivalent to an altitude of 8000 ft (2440 m); at such a pressure, there is a lower oxygen partial pressure than at sea level. In addition, the upper limits on carbon dioxide concentrations in aircraft are five times higher than in buildings. The combination of lower partial pressure of oxygen, high carbon dioxide concentrations, and very low humidity in aircraft cabins may increase respiratory system stress and irritation for persons in aircraft cabins aloft relative to those at or near sea level, especially for non-sedentary flight attendants.[1]

Repace[1] assessed the contribution of secondhand smoke (SHS) to aircraft cabin air pollution and flight attendants' SHS exposure relative to the general population by reviewing published air quality measurements, modelling studies, and dosimetry studies. In summary, this review noted that flight attendants reported suffering greatly from SHS pollution on aircraft. Both government and airline sponsored studies concluded that SHS created an air pollution problem in aircraft cabins, while tobacco industry sponsored studies yielding similar data, concluded falsely, that ventilation controlled SHS, and ludicrously claimed that SHS pollution levels were low. Between the time that non-smoking sections were established on US carriers in 1973, and the two hour US smoking ban in 1988, commercial aircraft ventilation rates had declined three times as fast as smoking prevalence.

Concentrations of tobacco smoke in enclosed spaces are directly proportional to the density of active smokers, and inversely proportional to the air exchange rate in units of air changes per hour (ACH).[13,17,20] The maximum seating occupancy of a 727-200 is 145 persons per 1000 ft^2 (~145 persons/100m^2), comparable to a standup bar. By comparison, according to ASHRAE Ventilation Standard 62-1973,[21] the occupancy of a stand-up bar is 150 persons/1000 ft^2 or (~150 persons/100m^2), and the recommended design ventilation rate ranges from 40 to 50 cfm/occupant (19 to 24 L/s-occ), compared to at most 26 cfm/occupant (12 L/s-occ) for the 727-200. By comparison, for the Lockheed 1011, the cabin area is 840 ft^2, yielding a maximum occupancy of 288 persons per 1000 ft^2 (~288 persons/100 m^2) with a design ventilation rate of 20 ACH. So, the L-1011 had almost twice the occupancy of a standup bar, but just half the ventilation rate per occupant.

Despite the high air exchange rates in the B-727 and L-1011, the small space volume, the high cabin occupancy, coupled with a high percentage of smokers, can lead to very high secondhand smoke concentrations. With an average of 33% of the population being smokers during the years that Ms. Cheney flew on Eastern, some L-1011 flights might have had as many as (0.33)(242) = 80 smokers on board and some B-727 flights might have had as many as (0.33)(120) = 40 smokers on board.

The U.S. Dept. of Transportation study of Airliner Cabin Air Quality.[23,24]

During the mid-1980s the Committee on Airliner Cabin Air Quality, assembled by the National Academy of Sciences, performed a systematic review of existing information relating to health and safety aspects of the airliner cabin environment aboard civil commercial aircraft. The committee's report recommended that smoking be banned on all commercial flights to lessen irritation and discomfort of non-smoking passengers and cabin crew members, to reduce potential health hazards from exposure to [secondhand smoke] and to eliminate the possibility of fires caused by cigarettes. Subsequently, Public Law 100-200, enacted in 1987 and effective for 2 years beginning in April 1988, prohibited smoking by passengers on any scheduled domestic commercial flight of 2 hours or less. At the same time, the U.S. Department of Transportation (DOT) conducted a study to develop information to estimate health risks from exposures to ETS for nonsmoking airliner occupants, as well as risks from other pollutants of concern for all airliner occupants.[23] The author was part of an inter-agency federal panel assigned to plan the study, evaluate submitted proposals, and select the contractor. The DOT (1989) study was the first comprehensive investigation of airliner cabin air quality.[24]

Measured Respirable Suspended Particulate (RSP) Levels on 8 international Flights.[24]

The DOT study reported selected SHS contaminants (nicotine, RSP, CO) as well as CO_2, ozone (O_3), microbial aerosols, cabin pressure, relative humidity, and temperature were measured in 92 randomly selected smoking and nonsmoking flights. About 39% of the flights monitored were on the B727 and the L1011, of the type on which Ms. Cheney was exposed. Both RSP and nicotine correlated strongly with observed smoking rates for all smoking flights, domestic and international, the average number of passengers in the smoking section was 18, and ranged from 2 to 63; the average percentage of passengers in the smoking section was 13.7%, and ranged from 1.4 to 41.9%, and the average number of cigarettes smoked per passenger hour was 1.5 (range 0.2 to 6.5). There was evidence for migration of SHS-RSP into the non-smoking sections. Using area monitors, respirable suspended particulate (RSP) concentrations averaged 175 micrograms per cubic meter ($\mu g/m^3$) in the coach smoking section compared to background levels of 35 to 40 $\mu g/m^3$ on nonsmoking flights. Nicotine levels were 13.4 $\mu g/m^3$ in smoking and below 0.3 $\mu g/m^3$ in no-smoking sections and on nonsmoking flights. Measured CO_2 levels averaged 1500 ppm, well above the ASHRAE Standard 62 comfort criterion of 1000 ppm.

Levels of CO, O_3, and microbial aerosols were generally quite low. Estimated lifetime cancer risks due to ETS (environmental tobacco smoke) exposure were 12 to 16 premature lung cancer deaths per 100,000 nonsmoking cabin crewmembers and 0.06 to 0.83 deaths per 100,000 nonsmoking passengers. These risks added to risks from cosmic radiation, ranging from 5 to 60 premature cancer risks per 100,000 for cabin crew and passengers who fly frequently. The report noted that "The health effects of radiation are often augmented by other factors that tend to increase overall risk, these include tobacco smoking and dietary factors." The report estimated that the increased risk for typical domestic flights from Tampa to St. Louis for 20 years increased cancer risk by 21 deaths per 100,000, and from non-circumpolar routes from New York to London of 29 deaths per 100,000 per 10 years.

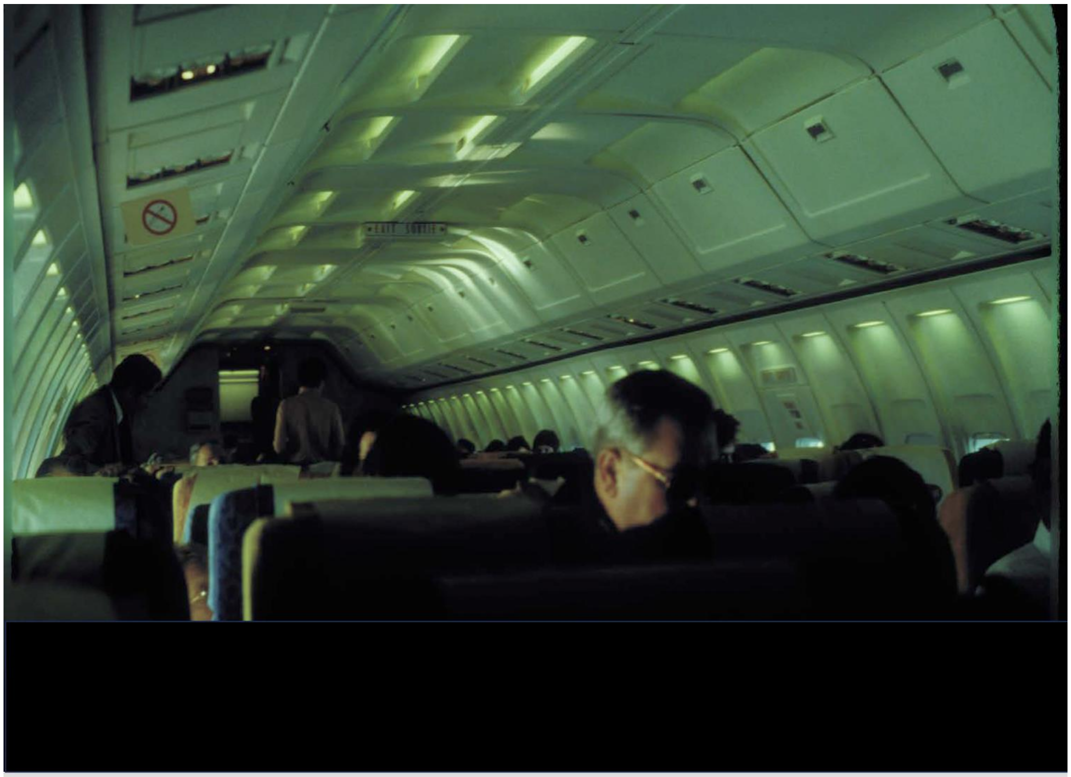

Figure 4. Author's photo of a passenger cabin with smoking/nonsmoking sections.

Thus, assuming that Ms. Cheney flew domestic flights for 9 years and international flights for 9 years, her estimated increased risk of cancer (leukemia and solid tumors) would approximate 9 deaths per 100,000 for domestic flights, and 14 deaths per 100,000 for international flights, totaling 23 deaths per 100,000. To this risk, secondhand smoke exposure would add another estimated 14 deaths per 100,000, or an increase by (14/23) = 61% over a non-SHS exposure case.

The DOT study generalized their area measurements by mathematical modeling, and conducted a carcinogen risk assessment using two exposure–response models, one by Repace and Lowrey (1985), and the other by Armitage and Doll.[24] It concluded that a total or partial ban on smoking was indicated, as the measured values…were well within the range associated with irritancy response and unacceptable cancer risk for the general population.[24]

For a subset of eight randomly selected international flights, respirable particle (RSP) results reported in DOT (1989) are given in Figure 5.[1] Figure 5 plots RSP concentration on smoking and non-smoking flights as a function of seating position with respect to the smoking section in the aircraft. These involved widebody aircraft, including five B747s, one B-767, and two MD DC10s. The average load factor (per cent of seating capacity filled by passengers) was 64%. Figure 5 shows that relative to the level measured on nonsmoking flights, smoking elevated peak RSP levels by 100-fold, and average RSP levels by 15-fold in the smoking section, and that the non-smoking section (boundary, middle, and seats most remote from smoking) on smoking flights is considerably contaminated with fine particle pollution relative to non-smoking flights. Multiple studies on aircraft reported peak levels of fine particles ranged from 750–1200 $\mu g/m^3$. Such peaks assume even greater importance when flight attendants' activity patterns are taken into account: peaks appear to occur after meals while flight attendants may be servicing the cabin, increasing proximity to smoking and elevating attendants' SHS doses beyond what area monitors of SHS concentrations would suggest. Such peaks assume greater import when acute irritating effects of tobacco smoke are considered.[1]

The cigarettes smoked per hour measured by DOT during active smoking ranged from 15.8 to 22 (ave. 19.5), and the cigarettes smoked per passenger per hour ranged from 0.9 to 1.9 (ave. 1.52) (DOT, Table 4.9). The length of time that smoking was permitted on these flights ranged from <2.5 to ≥ 5.0 hours.[24]

Table 3 shows the U.S. EPA Air Quality Index[25] used to alert the public to current fine particle air pollution. Figure 5 shows that peak levels in the DOT (1989) smoking sections where flight attendants served passengers were polluted well beyond Code Purple, (Very Hazardous) into the Significant Harm zone. The average level in the smoking zone at 175 $\mu g/m^3$ or **Code Purple** levels, Very Unhealthy leading to "serious health effects."

Figure 6 shows that the area-monitored peak levels of SHS measured in the aircraft cabin in Figure 7 were comparable to area-monitored levels in a smoky bingo hall (T), and much higher than smoky bars.[7,26]

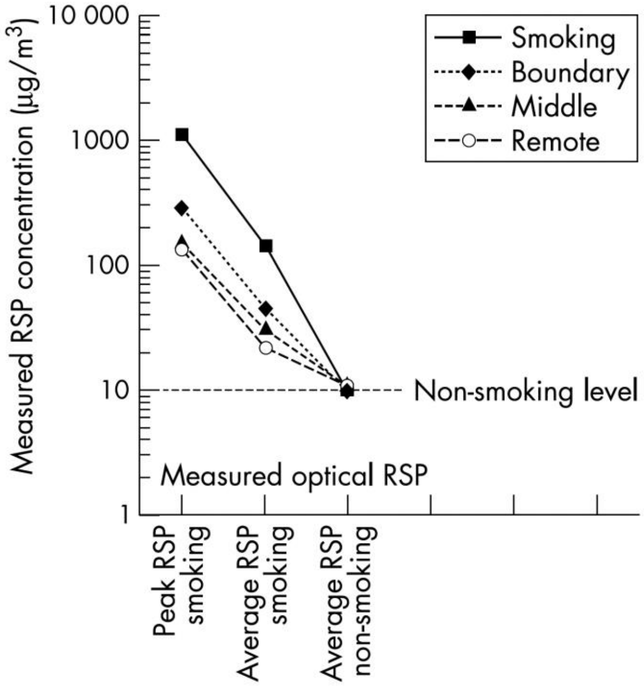

Figure 1 Measured RSP concentrations on eight international flights by seat location (Nagda *et al*[3] table 5-2; table 4–22). "Smoking" refers to seats in the smoking section, while "Boundary", "Middle", and "Remote" refer to seats in the non-smoking section, and describe their proximity to the smoking section. The dotted line indicates the RSP level on non-smoking flights.

Figure 5. A plot (Figure 1 in reference)[1] of area-monitored RSP levels in 8 international flights in the DOT (1989) study[24] of smoking effects on passenger aircraft.

Liu et al.[27] performed Monte Carlo simulations integrating historical trends and distributions of influence factors to simulate 10,000 flight attendants' exposure to area concentrations of secondhand smoke in the smoking section of passenger aircraft on commercial flights from 1955 to 1989. These models indicated that annual mean SHS $PM_{2.5}$ concentrations to which flight attendants were exposed in smoking sections of passenger cabins steadily decreased from approximately 265 $\mu g/m^3$ in 1955 and 1960 to 93 $\mu g/m^3$ by 1989, and airborne nicotine exposure among flight attendants also decreased from 11.1 $\mu g/m^3$ in 1955 to 6.5 $\mu g/m^3$ by 1989.

Fig. 7-1. RESPIRABLE PARTICLE DENSITY vs ACTIVE SMOKER DENSITY

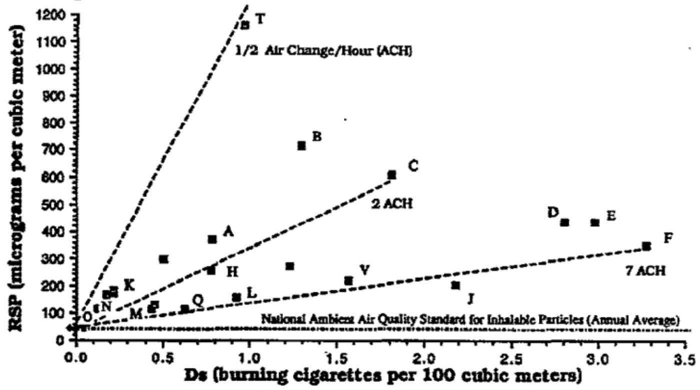

Fig. 7–1 Respirable particle density (RSP) vs. active smoker density (Ds). *Source:* Repace and Lowry 1980, 1982.

Figure 6. Fine particle concentration (RSP) plotted vs. burning cigarette density (D_s) Data points, E, H, K, L, M, and N are typical restaurants; B and V are reception balls; J is a hospital waiting room; I is a bowling alley; D, G, and T are bingo games; while O is a sports arena; B is a lodge hall dinner-dance; C and Q are bars; F is a nightclub; and A is a private home during a party.) The dashed lines show the calculated air exchange rates in units of air changes per hour (ACH) [Figure 7-1 in reference].[7,26]

Liu et al.[27] noted that both the concentrations measured in the literature and those simulated in their study confirm that flight attendants were exposed to very high concentrations of SHS in commercial aircraft when smoking was allowed. A flight attendant could be exposed to SHS concentrations greater than 800 µg/m³ of RSP and 29 µg/m³ of nicotine in passenger cabins in 1955, and to greater than 250 µg/m³ of RSP and 17 µg/m³ of nicotine in passenger cabins in 1989.[27] As Table 3, shows, these exposure concentrations range from Hazardous to Significant Harm as judged by the EPA Air Quality Index. By 1985 more than 40 000 flight attendants in the United States worked an average of 900 hours each year.[27] Note that these modeled exposure estimates are conservative, in that they do not incorporate proximity of the flight attendants to the smokers, respiration rates during exposure, or work activity patterns during the flight. This is why dosimetry studies are vital in estimating true risk. This is addressed later in this report in the discussion of absorbed dose.

Prevalence of Smoking among U.S. Adults[16]

U.S. smoking prevalence varied from about 39% in 1968 to about 27% in 1988, and averaged about 33% in 1980.[17]

Discussion:

Tobacco smoke inhaled during active smoking, i.e. high dose exposure to tobacco smoke causes lung cancer, asthma, breast cancer, cataracts, laryngeal cancer, carotid artery stenosis, cervical cancer, chronic myeloid leukemia, coronary artery disease, atherosclerosis, cardiovascular disease, chronic obstructive lung disease, pneumonia, and airway inflammation. Passive smoking, i.e. low dose exposure of nonsmokers due to secondhand smoke inhalation causes lung cancer, cervical cancer, breast cancer, asthma induction and aggravation, cardiovascular effects, heart disease morbidity and mortality, pneumonia, and altered vascular properties.[28-31]

Exposure: Ms. Cheney was exposed to secondhand smoke for 20 years as a flight attendant, 18 of which were spent in the aircraft cabin and 2 years in Eastern Airline's smoky offices. Assuming she experienced 900 flight-hours per year,[27] over an 18 year period, Ms. Cheney would have spent 16,200 flight-hours inhaling secondhand smoke exposure in Eastern's aircraft cabin.

Air Quality Index Levels of Health Concern	$PM_{2.5}$ (µg/m³) AQI Break-points	Air Quality Index (AQI) Values	Air Quality Conditions
Air quality satisfactory, air pollution poses little or no health risk.	0.0 - 15.4	0 - 50	Good
Air quality acceptable; however a moderate health concern for small numbers of persons unusually sensitive to air pollution.	15.5- 40.4	51 - 100	Moderate
Sensitive persons may experience health effects. General public not likely to be affected.	40.5 - 65.4	101 -150	Unhealthy Sensitive Groups
Everyone may begin to experience health effects; sensitive groups may experience more serious health effects.	65.5 - 150.4	151 - 200	Unhealthy
Health alert: everyone may experience more serious health effects.	150.5 - 250.4	201 - 300	Very unhealthy
Health warnings of emergency conditions. The entire population is more likely to be affected.	250.5 - 350.4	301 - 400	Hazardous
Air Pollution Emergency	350.5 - 500.4	401- 500	Very Hazardous
Increased Mortality	> 505	500	(Significant Harm)*

*Proposed 2007 (http://www.epa.gov/ttn/caaa/gen/aqi_issue_paper_020707.pdf).

Table 3. Breakpoints of the U.S. Air Quality Index (USEPA, 1999)* Levels of fine particulate ($PM_{2.5}$) air pollution and corresponding U.S. health advisory descriptors with accompanying simplified color code (US EPA, 1999)[25].

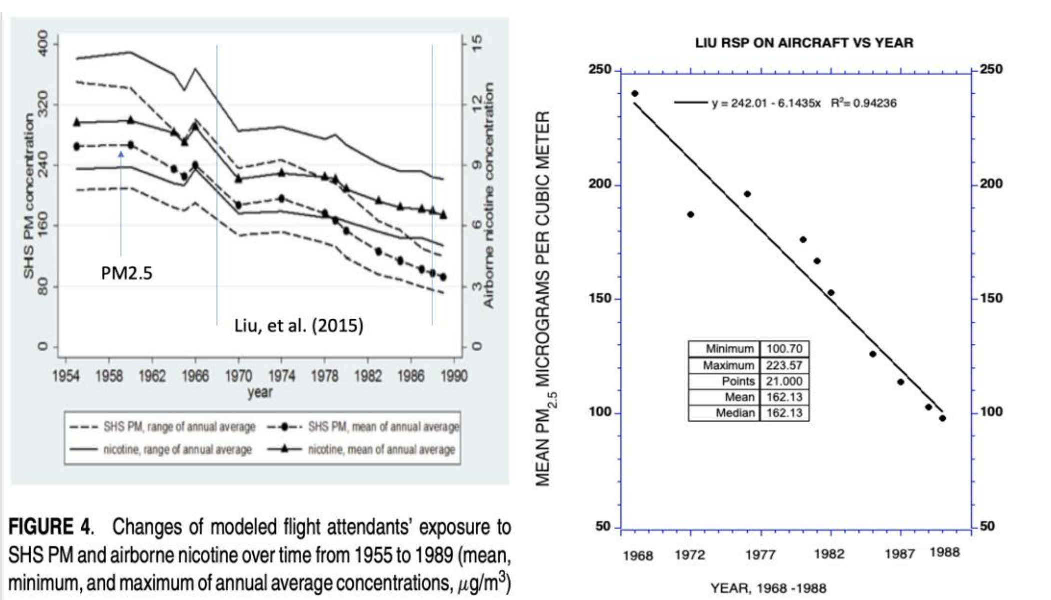

Figure 7. Left: [Figure 4 in reference)[27] showing Monte Carlo simulations of flight attendants' exposure in smoking section of passenger cabins from 1955 to1989. Right, a curve fit plotted from their data from 1968 to 1988, covering the period when Ms. Cheney flew on Eastern, yielding an average aircraft cabin exposure concentration of 162 µg/m³, consistent within ~7% of the 175 µg/m³ measured in the DOT (1989) study[24], indicating an average Code Purple (Very Unhealthy) level of exposure to $PM_{2.5}$ air pollution from secondhand smoke.

Table 5. Comparison of Ms. Cheny's Diseases with those caused by exposure to tobacco smoke over the dose spectrum from passive to active smoking.[36-55]

Kathleen Cheney's Diseases	Diseases Caused by inhaling Tobacco Smoke
asthma	asthma
breast cancer	breast cancer
carotid artery stenosis	carotid artery stenosis
cataracts	cataracts
cervical cancer	cervical cancer
chronic myeloid leukemia	chronic myeloid leukemia
chronic obstructive pulmonary disease	chronic obstructive pulmonary disease
coronary artery disease	coronary artery disease
laryngeal cancer	laryngeal cancer
pneumonia	pneumonia

Absorbed Dose: Repace et al.[32] developed the *Rosetta Stone Equations*, based on pharmacokinetic modeling, used for mapping absorbed cotinine dose into personal secondhand smoke fine particulate (SHS-$PM_{2.5}$) exposure and vice versa (Table 6). Using these equations, the Mattson study[18] of urine cotinine, when converted to its serum cotinine equivalent, shows that a flight attendant on the transcontinental 727 narrow body and 767 widebody flights studied absorbed doses that were six times the average worker and 14 times the average U.S. adult, indicating very heavy secondhand smoke exposure, consistent with the highest atmospheric measurements in the DOT study[24] that measured Very Unhealthy exposures to secondhand smoke.[32] How does this translate into the equivalent inhaled dose of SHS-RSP? Mattson et al.[18] measured an average serum cotinine dose of P = 2.88 ng/mL.

The personal SHS-$PM_{2.5}$ exposure equivalent of serum cotinine dose, P = 2.88 ng/mL, is calculated as follows: From Table 6 below, from Repace et al.,[32] $P = 0.006\ \rho HN$, where ρ is the respiration rate of the flight attendant, H is the duration of exposure, and N is the personal nicotine concentration in cabin air. For P = 2.88 ng/mL, H = 4 hours, and a respiration rate $\rho = 1\ m^3/hr$, and R = SHS-RSP = 10 N. Substituting N = 10/R. and solving for R, yields P = (0.006)(1 m^3/hr)(4 hr flight)(10/R) or R = (10)(2.88)/[(0.006)(1)(4)] = 1200 $\mu g/m^3$. This dosimetrically-estimated exposure is double the Significant Harm Level of the AQI (Table 3). It is also far above the average exposure derived from area monitors, but is comparable to the peak exposure concentration measured in the DOT study in the smoking section (Figure 5). Dosimetric estimates of inhaled exposure incorporate source proximity, respiration rate, and personal activity patterns, and thus are a more accurate way of estimating true exposure. This is why both NIOSH and OSHA use personal monitoring to determine workplace exposures to toxic chemicals.

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TABLE 3

Rosetta Stone Conversion Equations for SHS Atmospheric Biomarker Estimation for Adults (as a Function of Respiration Rate ρ, Daily Hours of Exposure, *H*) and Between Hair Nicotine and Urine Cotinine in Infants

SHS Marker, Units	Conversion Equation
R = RSP, $\mu g/m^3$	R = 10 N
N = Nicotine, $\mu g/m^3$	$N = 21.7\ D_{hs}/C_v$
CO = Carbon monoxide, ppm_{mass}	CO = 0.004 R
PPAH = Particulate polycyclic aromatic hydrocarbons, $\mu g/m^3$	PPAH = R/2000
P = Plasma (Serum) cotinine, ng/mL	$P = 0.006\ \rho HN$
S = Saliva cotinine, ng/mL	S = 1.16 P
U = Urine cotinine, ng/mL	U = 6.5 P
$\Omega_{infants}$ = Hair nicotine, ng/mg	$\Omega_{infants} \approx 0.7\ U_{infants}$

Note that the units of N in the cotinine equations are $\mu g/m^3$.

D_{hs} indicates smoker density (no. of habitual smokers smoking 14 mg SHS-RSP/cigarette at the rate of 2 cigarettes/hr in the micro environment per 100 m^3 of space volume); C_v, air exchange rate of space volume in air changes per hour (hr^{-1}).

Table 6. The Rosetta Stone Equations summarizing the pharmacokinetic models relating atmospheric secondhand smoke exposure to Respirable Suspended Particulate (PM2.5) and airborne nicotine to the nicotine metabolite in body fluids and hair (Table 3 in reference).[32]

Dose-Response: Eisner et al.[33] investigated the dose-response relationship between secondhand smoke cotinine dose and COPD. They found that the highest tertile of cotinine dose (median cotinine 1.54 ng/mL) was associated with a five-fold mean increase in COPD severity, disease-specific degradation in quality of life, and dyspnea relative to the lowest tertile (median cotinine 0.054 ng/mL). The median level for the Mattson study of flight attendants was 2.88ng/ml, or 1.9 times the highest tertile in the Eisner COPD study[33], indicating that in-flight doses were consistent with very adverse COPD outcomes. Further, according to the Surgeon General, "Cigarette smoking is causally associated with cancer of the lung, larynx, pharynx, oral cavity, and esophagus" in both men and women (SG, 2004). Kasim et al.[34], using residential and occupational secondhand smoke exposure histories in a case-control study of 1068 histologically confirmed adult leukemia cases and 5039 population controls between the ages of 20 to 74, for a subset of 266 cases and 1326 controls, subjects who were lifetime nonsmokers with reported exposure history, the risk for chronic lymphocytic leukemia was clearly associated with secondhand smoke exposure with an adjusted odds ratio of 2.3 (95% CI 1.2-4.5) for more than 83 smoker-years of residential exposure, and more than 72 smoker-years of occupational exposure, with a dose-response relationship.

From Liu et al.,[27] taking an estimated average (occupancy) load factor of 0.5, the average number of passengers per 727 and L10ll as 150 to 288, for an average of 200, and a smoking prevalence of 33%, the average number of smokers per flight would be 33, assuming the average number of flights per day to be 3 for 200 days per year, or 600 flights per year, with 33 smokers per flight, then 600 flights x 33 smokers per flight = 19 800 smokers x 18 years of flying = 356 400 smoker-years, placing Ms. Cheney into the highest category of exposure for chronic lymphocytic leukemia.

Although the 2014 Surgeon General's Report concluded that the evidence was suggestive but not sufficient to infer a causal relationship between tobacco smoke and breast cancer, the 2006 California EPA report declaring secondhand smoke to be a "toxic air contaminant" did conclude that it was a cause of breast cancer in younger primarily pre-menopausal women. Further, Johnson (2005) noted that the overall premenopausal breast cancer risk associated with passive smoking among life-long non-smokers was 1.68 (95%CI 1.33–2.12), and 2.19 (95% CI 1.68–2.84) for the 5 of 14 studies with more complete exposure assessment. For women who had smoked, their breast cancer risk estimate was 1.46 (95%CI 1.15–1.85) when compared to women with neither active nor regular passive smoke exposure; 2.08 (95% CI 1.44–3.01) for more complete passive exposure assessment compared to an odds ratio of 1.15 (95% CI 0.92–1.43) for less complete passive exposure assessment. Studies with thorough passive smoking exposure assessment implicate both active and passive smoking as risk factors for premenopausal breast cancer. A case-control study of passive smoking and breast cancer risk in Chinese women by Li et al.[57] conducted in 2015 of passive smoking exposure showed statistically significant dose-response relationships with breast cancer risk, whether expressed in smoker-years, cigarettes/day or total pack-years (P_{trend}=0.003, 0.006 and 0.009, respectively). Li et al. found that an increase in total smoker-years for any passive exposure significantly elevated the risk of breast cancer ($P_{trend}<0.001$).

Liu et al.[27] estimated an average cabin exposure concentration over the 18-yr period that Ms. Cheney flew on US aircraft as 162 µg/m^3. The estimated risk from a daily inhaled absorbed dose of flight attendants to (162 µg/m^3) @ 6 hr/day x 1 m^3/hr resp rate = 0.972 mg/day. Using the risk model of Repace and Lowrey[34] for lung cancer deaths (LCDs) of passive smokers yields an estimated dose-response of RISK = {5 LCDs/[(100,000)(0.972 mg/day)]} = 5.14 LCDs/100,000 Person-Years. Using this dose-response relationship to estimate working lifetime risk for typical flight attendants (Table 7) yields an estimated risk that is 18 times OSHA'S SIGNIFICANT RISK OF MATERIAL IMPAIRMENT OF HEALTH Standard of 1 death per 1000 per working lifetime, at risk of multiple cancers. Ms. Cheney's working lifetime was 18 years.

Table 7. Estimated Passive Smoking Deaths[47], Mapped into an 18-yr Risk in from airline cabins secondhand smoke using a dose-response relationship.[34]

Cause[36-46]	U.S.A., Deaths/Year	% of Deaths	18-Yr Risk*
Lung Cancer	3100	5.12	1/1000
Heart Disease	47000	77.69	14/1000*
Breast Cancer	8700	14.38	3/1000*
Cervical Cancer	500	0.83	~2/10000*
Nasal Sinus Cancer	200	0.33	1/10000
Brain Cancer, Leukemia *& Lymphoma	1000	1.65	~1/10000*
Total	60,500	100	18/1000**

*Kathleen Cheney developed these diseases.** Kathleen Cheney: (15+3+2) = 18/1000 or 18 times OSHA'S SIGNIFICANT RISK level.

The U.S. Life Tables[35] indicate that at age 68 Ms. Cheney had only a 15% mortality probability, as Figure 8 illustrates graphically, with ~85% of the non-Hispanic White female cohort remaining alive, and that a non-Hispanic white female at age of 68 would have about an 18-1/2 year life expectancy remaining. Ms. Cheney succumbed to chronic myelomonocytic leukemia, whose risk factors include age, biologic sex (twice as common in males), and previous cancer treatment using chemotherapy. The average age at diagnosis is between 71 and 74 years old.[58] As noted earlier, benzene is a potent leukemogen; according the U.S. ATSDR, about half of benzene exposure in the U.S. comes from smoking tobacco or exposure to secondhand smoke.[59] In other words, at age 68, Ms. Cheney had a remaining statistical life expectancy of nearly 2 decades, absent her death from leukemia.

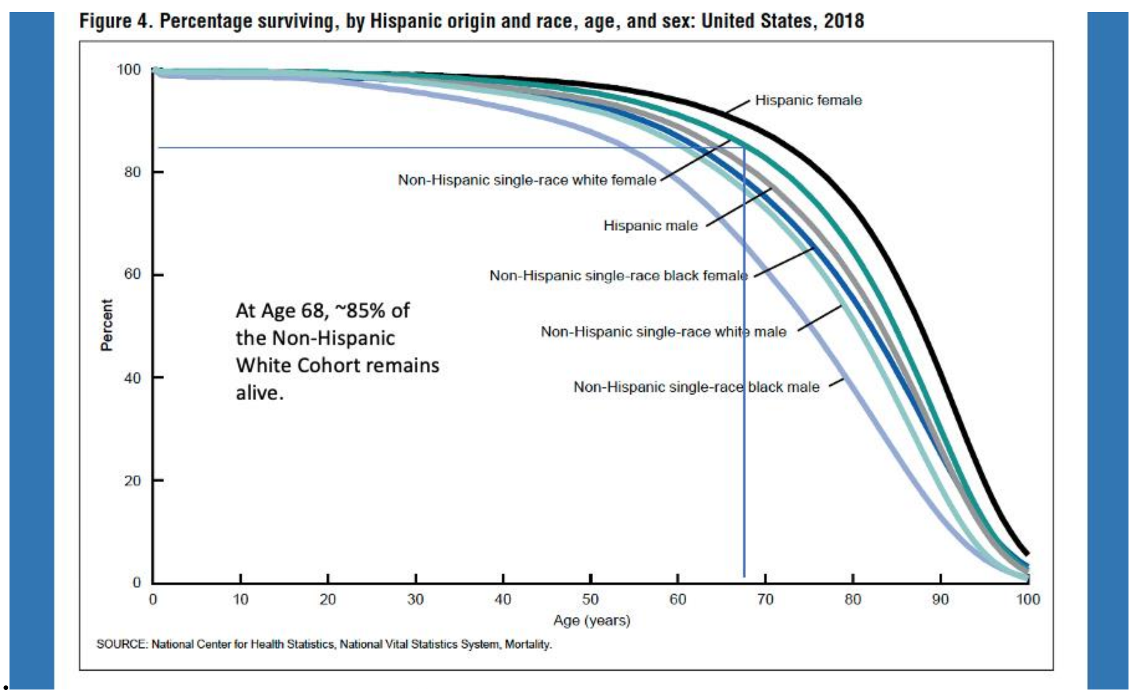

Figure 8. A U.S. Non-Hispanic White Female has approximately 18.5 years of life expectancy remaining (CDC Life Tables, Arias, et al.[35])

The foregoing methodology has implications for risk estimation for the class of ~60 000 flight attendants currently and formerly employed by U.S. airlines. In 1994, a group of 30 flight attendants brought a class action lawsuit against a group of tobacco companies, asserting that they suffered from health conditions allegedly due to continuous exposure to smoke emitted from the cigarettes of passengers during smoking flights. These plaintiffs sought damages for the injuries under common law consumer protection theories, including strict tort liability, breach of implied warranty, negligence, fraud, misrepresentation and conspiracy to commit fraud.[61,62] This dosimetric methodology of assessing risk has also proved to be useful in protecting children against secondhand smoke injury in child custody cases[63,64] as well as in casino worker litigation.[65]

CONCLUSIONS

Both area measurements and modeling of fine particle air pollution ($PM_{2.5}$) from smoking in aircraft cabins indicate that typical aircraft smoking sections were polluted to Very Unhealthy Levels according to the U.S. EPA AQI. Absorbed cotinine dose in Air Canada flight attendants manifested levels six times as high as the average U.S. worker and 14 times as high as the average U.S. adult. This placed Ms. Cheney and other nonsmoking flight attendants in a very heavily exposed category relative to the general population. Flight attendants' dosimetrically-estimated fine particle levels from secondhand smoke in aircraft cabins was double the Significant Harm Level of the U.S. EPA Air Quality Index.

Several studies of the health problems incurred by flight attendants flying during the smoking years concluded that flight attendants incurred elevated rates of chronic bronchitis, heart disease, skin cancer, breast cancer, melanoma, reproductive cancers, hearing loss, asthma, middle ear infections, pneumonia, and chronic obstructive pulmonary disease, and various pulmonary function abnormalities, as well as depression and anxiety. All of these were diseases relatable to secondhand smoke exposure.

Kathleen Sprowl Cheney flew in Eastern Airlines as a flight attendant for 18 years from 1968 to 1988 in smoky aircraft cabins, retired on disability in 1988, and died from leukemia in 2014, losing an estimated 18½ years of lifespan. To a reasonable degree of scientific certainty, Ms. Cheney's risks of cancer, respiratory disease, COPD and coronary heart disease were significantly increased due to her toxic and carcinogenic exposures to secondhand smoke in Eastern Airline's passenger cabins. By U.S. occupational health standards, Ms. Cheney's estimated risk from secondhand smoke exposure on Eastern Airline's smoky cabins was 18 times OSHA's Significant Risk of Material Impairment of Health. In-flight exposure to toxic and carcinogenic tobacco smoke in smoky passenger cabins appears to be a major risk factor leading to her multiple smoking-related diseases and premature death.

This risk assessment for an individual flight attendant, currently in litigation, has implications for the extant and future health of other flight attendants exposed to secondhand smoke on aircraft during the 20th Century Era, and given the long latency for carcinogenesis, will prove to be useful for future litigation and occupational injury claims. It is clear that banning smoking on passenger aircraft appears to have prevented significant morbidity and mortality.

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64. Brandon W. Melton v. Brandy Jean Melton Sevier County Circuit Court Case No. DR 2010-35-2. Arkansas, USA.

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