BRUJOS SCIENTIFIC INC.
Industrial Hygiene and Toxicology

505 Drury Lane
Baltimore, Maryland 21229
(410) 566-1177
(410) 566-1178 Fax

The Risk of Tuberculosis Infection on a Commercial Aircraft

by
Robert Olcerst Ph.D., CIH, DABT
Brujos Scientific Incorporated
505 Drury Lane
Baltimore, Maryland 21229

ABSTRACT

The cabin of a commercial aircraft is a high density environment in which occupants are potentially at risk of airborne transmission of Mycobacterium tuberculosis. Trans-continental and trans-oceanic flights are routinely undertaken with hundreds of passengers. During these long flights there is an increased duration of potential exposure. to airborne contaminants and bioeffluents. This paper determines a "worst case" risk of tuberculosis infection for the passengers and flight attendants based upon typical design and ventilation parameters of a commercial aircraft. The model demonstrates that the "worst case" risk for a general passenger is 71.8/100000 for a ten hour flight. The risk for flight attendants over a year of occupational exposure is orders of magnitude greater. The concentration of micro droplet nuclei can be minimized by increasing the ventilation rates. The use of HEPA filtration by the aircraft manufactures reduces the risk by a factor of 2. Increasing the fraction of outdoor air above the present design level of 50% would not result in significant additional risk reduction.

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TERMS

C=Concentration of TB quanta $\left[\frac{quanta}{ft^3}\right]$
C_o=Concentration of TB quanta outdoors $\left[\frac{quanta}{ft^3}\right]$
V=Volume of Room $[ft^3]$
Q=Ventilation flow rate$\left[\frac{ft^3}{\min}\right]$
Q_{OA} = Outdoor air flow rate $\left[\frac{ft^3}{\min}\right]$
Q_R = Recirculated air flow rate $\left[\frac{ft^3}{\min}\right]$
H= Room height $[ft]$
F_g =Gravitational force $[N]$
m=Mass of particle $[g]$
ρ_g =Density of air; at normal temperature and pressure= 0.001192$\left[\frac{g}{cm^3}\right]$
ρ =Density of particle
ρ_o =Particle with a unit density
v= Velocity $\left[\frac{ft}{\min}\right]$
d=Distance $[cm]$
d_p =Particle diameter
υ_p =Volume of particle
g = Gravity acceleration
η =Dynamic gas viscosity=1.833x10^{-4} $\left[\frac{dyne-sec}{cm^2}\right]$
I= Number of infectious tuberculosis individuals
S=Number of susceptible non-infected individuals
q=Quanta of TB necessary to result in an infection
p= Respiration minute volume $\left[\frac{ft^3}{\min}\right]$
TB=the number of new infection cases
R=Risk=New cases/passenger
l= length of Mycobacterium tuberculosis
χ= Shape factor

INTRODUCTION

In 1986, the United States experienced the fewest number of new tuberculosis cases in it history. Since then, there has been a resurgence of tuberculosis because of associated with increasing risk factors of drug abuse, AIDS, and the advent of multi-antibiotic resistant strains of the organism. In 1991 there was an increase of 16 percent in the U.S. number of new tuberculosis cases. In 1992, there were 26000 cases with major outbreaks in New York and Miami. That year, the World Health Organization estimated that there were more than 16 million cases of tuberculosis. (1) During this time the number of international air travelers and domestic air travelers has steadily increased. It has been estimated that more than 13 million non-immigrants enter the United States by air annually.(2) Many of these air travelers come from areas of high prevalence of tuberculosis located in Asia, Africa, the Caribbean, Central and South America. In 1992, an air traveler with cavitary multidrug-resistant tuberculosis flew by commercial flight from London to Minneapolis. Although there were 343 people on board, no airborne transmission was identified during a three month follow up investigation. (2) In 1992, a commercial airline crew member with active tuberculosis potentially exposed 212 colleagues and 59 passengers during flights over a six month infectious interval. In this case investigators concluded that two crew members were infected with tuberculosis but they could not rule out transmission to passengers. (3) From January 1993 to February 1995, the Centers for Disease Control has investigated four other instances of air travel with infectious tuberculosis cases on the commercial flights.(4) In April, 1994 a passenger with pulmonary tuberculosis flew from Honolulu to Chicago and then on to Baltimore for a month long visit and then returned home by the same route. The four flights involved potential exposures to 925 passengers and crew members. Tuberculosis skin testing was found to be positive in one U.S. born and two foreign-born passengers of the 113 persons flying from Baltimore to Chicago. The flight from Chicago to Honolulu had a duration of 8 hours and 38 minutes with 257 persons aboard.. Fifteen positive tuberculin skin tests were found including six newly sera converted individuals, four of whom were seated in the same section as the index patient. The demonstration of positive tuberculin skin test conversions among U.S. borne passengers indicated that passenger to passenger transmission of Mycobacterium tuberculosis had probably occurred.

Consider a commercial airliner having a seating capacity for 290 occupied by 289 susceptible passengers (S=289) and one actively infectious occupant with laryngeal tuberculosis. Assume no air exchange or ventilation, i.e. steady state conditions. If there is an actively infectious occupant (I=1) then the number of new cases can be estimated by the following relationship: (5)

$$TB = rIS \tag{0.1}$$

where TB= the number of new cases per unit time
r= The fractional effective contact rate
I= The number of Infectious individuals
S= The number of susceptible individuals

Furthermore, consider

q= the quanta of airborne Tuberculosis mycobacteria emitted per infectious person per minute.

One quanta is the minimum quantity of TB that will lead to an infection.

qI= the TB quanta emitted from (I) infectious individuals per minute

qI/Q= the airborne concentration of tuberculosis quanta contaminating the "fresh" outside air

Q=the ventilation rate of outside "fresh" uncontaminated air in cubic feet per minute

p= the volume of air inhaled by susceptible individuals per minute

pS= the volume of air inhaled by susceptible people per minute

D= Dose per minute= The quanta of TB inhaled by a susceptible occupant=

$$D = \frac{qIp}{Q} \tag{0.2}$$

Inhalation by a susceptible individual of one quanta by definition is the dose that will result in infection of the susceptible person.

TB=the number of new infection cases per minute=

$$TB = S \text{ x } Dose = \frac{pq \text{ x SI}}{Q} \tag{0.3}$$

which is of the form of equation #1 where

$$r = \frac{pq}{Q} \tag{0.4}$$

The first term on right side of equation 3 is a more revealing definition of the effective contact rate described above. The number of new cases is dependent on the quanta of airborne organisms inhaled by susceptible occupants and the amount of fresh uncontaminated outside air.

The number of new infections over a time interval , (time=t) is then:

$$TB(t) = D \text{ x } t = \frac{SpqI}{Q} \text{ x } t = \frac{pqSIt}{Q} = C \text{ x } pS \text{ x } t = S \text{ x } Cpt \tag{0.5}$$

Where C= the quantal concentration=$\frac{qI}{Q}$

The risk of tuberculosis infection can be calculated as the number of quanta inhaled where one quanta will yield one infection. A quanta may contain 1 Mycobacterium tuberculosis or more. Often micro droplet aerosols that desiccate upon emission as they fall will agglomerate a number of bacilli together because of their sticky outer coating. Herman and Streifel have found that in general tuberculosis patients with an active laryngeal infection release 60 quanta per hour.(6)

According to Riley (5,7), the presence of a quanta of TB in room air is a rare event when the total number of air molecules are considered. Thus it is appropriate to use a Poisson statistical probability density function to describe the probability of inhaling 1 quanta.

The probability of getting x # of cases=

$$\Pr(X = x\# \text{ new cases}) = \frac{m^x e^{-m}}{x!} \tag{0.6}$$

Where m= the mean or expected dose= $\frac{pqSIt}{Q}$

$$\Pr(X = x\# \text{ new cases}) = \frac{(\frac{pqSIt}{Q})^x e^{-\frac{pqSIt}{Q}}}{x!} \tag{0.7}$$

Consider the case where there is 1 quanta of infectious TB in an indoor space. The Dose=1 quanta which is by definition sufficient to cause TB infection. In this case the probability of an individual getting 1 infection is

$$\Pr(X = 1 \text{ new cases}) = \frac{D^1 e^{-D}}{1!} = \frac{(1)e^{-1}}{1} = e^{-1} \tag{0.8}$$

Then the probability of NOT getting infected is

$$\Pr(X=0) = 1 - PR(X=1) = 1 - e^{-1} \tag{0.9}$$

The Wells-Riley Equation can be expressed in the following form when ventilation is added to the model presented above:(6,7)

$$TB = S \text{ x } (1\text{-e}^{-\frac{Iqpt}{Q}}) = S \text{ x } (1\text{-e}^{-Cpt}) \tag{0.10}$$

Where TB= the number of infections predicted
S= the number of exposed susceptible adult persons
I= the number of infectious individuals
q= the infector's emission rate (q=60 quanta per hour)
t= time (hours)
p= adult respiration rate (cfm)= 18.75 liters/hr x ft^3/28.32 liters= 0.662 ft^3/hr
Q= ventilation rate ($feet^3$/hour)
C=the quantal concentration

PARTICLE SETTLING

Mycobacterium tuberculosis are rod shaped bacteria with a length between 1-4 microns and a diameter ranging from 0.3 to 0.6 microns.(8) Micro droplets containing one or more Mycobacterium tuberculosis particles will be released into the air by an infectious individual. The droplets will desiccate as they move through the air. When such a particle falls through a gas, the motion of the particle and the flow pattern of the gas are determined by the gravitational and drag forces. For a falling particle in still air, the gravitational force is countered by the buoyant force of the viscous gas. The flow pattern is governed by the ratio of the inertial force of the gas to the frictional force of the gas moving over the particle. This ratio is designated as the Reynolds number which can be expressed as follows:

$$Re_p = \frac{\rho_g v d}{\eta} \tag{0.11}$$

When the inertial force pushing the gas aside due to the difference in velocity between the particle and the gas, is much smaller than the viscous resistance force, the drag coefficient C_{drag} is expressed in terms of the gas flow parameters

$$C_{drag} = \frac{24}{Re_p} = \frac{24\eta}{\rho_g v d} \tag{0.12}$$

When $\mathrm{Re}_p < 0.1$
The particle drag force is

$$F_{drag} = \frac{\pi d^2}{8} C_{drag} \rho_g v^2 \tag{0.13}$$

Combining equation 11 and 12 with 13 yields Stokes law of viscous drag forces neglecting slip

$$F_{drag} = 3\pi\eta v d \tag{0.14}$$

Consider a small particle in air acted on only by gravitational forces.

$$F_g = mg = \rho v_p g \tag{0.15}$$

The volume of a spherical particle is:

$$v_p = \frac{\pi}{6} d^3 \tag{0.16}$$

then substituting

$$F_g = \rho \frac{\pi}{6} d^3 g \tag{0.17}$$

If the spherical particle has unit density (i.e. $\rho = \rho_0 = 1$) then d is referred to as the Stokes diameter (d_{st}). The aerodynamic diameter (d_A)of a non spherical particle falling at terminal velocity (v) that has a density (ρ) can be defined as being equivalent to a spherical particle of unit density that has the same terminal settling velocity. Thus

$$d_A = d_{st} \sqrt{\frac{\rho}{\rho_o}} \tag{0.18}$$

The terminal settling velocity can be determined by equating the drag force with the gravitational force provided in equation 17 and solving for the gravitational settling velocity, (v) yields: (9,10)

$$3\pi\eta v d = \rho \frac{\pi}{6} d^3 g \tag{0.19}$$

$$v = \frac{\rho \frac{\pi}{6} d^3 g}{3\pi\eta d} = \frac{\rho d^2 g}{18\eta} = 0.003\rho d^2 \tag{0.20}$$

In a similar fashion the motion of a rod shaped or cylindrical particle can be described in terms of an inscribing prolate spheroid of density $=\rho$ having a major axis, b , and a minor axis or diameter, a, and an aspect ratio,

$$\beta = \frac{b}{a} \tag{0.21}$$

Then equating the gravitational force to the drag forces yields:

$$3\pi\eta v d\chi = 6\pi\eta v a\chi = \frac{4}{3}\pi a^2 b\rho g \tag{0.22}$$

where χ is a numerical shape factor. Where χ is the shape factor for the average random orientation of the prolate spheroid. If the terminal velocity for the inscribing prolate spheroid approximation of a cylinder is identical to the stokes unit density spherical particle then

$$v = \frac{\rho_p d_{st}^2 g}{18\eta} = \frac{2a^2\beta\rho g}{9\eta\chi} \tag{0.23}$$

and

$$d_A = d\sqrt{\frac{\rho\beta}{\rho_o\chi}} \tag{0.24}$$

solving for the shape factor χ :

$$\chi = \frac{d^2\rho\beta}{d_A^2\rho_0} \tag{0.25}$$

Griffiths and Vaughan have considered numerical shape factors for oblate and prolate spheroids whose motions are parallel or perpendicular to the major axis.(10) For the case of a prolate spheroid moving parallel to its major axis

$$\chi\| = \frac{4\left(\beta^2 - 1\right)}{3\sqrt{\left(\frac{2\beta^2-1}{\sqrt{(\beta^2-1)}}\right)\ln\left(\beta + \sqrt{(\beta^2 - 1)}\right) + \beta}} \tag{0.26}$$

For a prolate spheroid moving perpendicular to its major axis:

$$\chi_{\perp} = \frac{8\left(\beta^2 - 1\right)}{3\sqrt{\left(\frac{2\beta^2-3}{\sqrt{(\beta^2-1)}}\right)\ln\left(\beta + \sqrt{(\beta^2-1)}\right) + \beta}} \tag{0.27}$$

Two refinements have been proposed for the parallel and perpendicular shape factor to achieve a more accurate model. The first approach is based upon the fact that the volume of the prolate spheroid is 2/3 that of the cylinder or rod it inscribes.. To correct for this the spheroid must be given a diameter and length $(1.5)^{\frac{1}{3}}$ times that of the cylinder. The aspect ration, β, remains unchanged. Thus

$$d_A = d\sqrt{\frac{\rho\beta}{\rho_o\chi}}(1.5)^{\frac{1}{3}} \tag{0.28}$$

The second refinement considers the weight of the inscribed spheroid as 2/3 of that of the rod shaped particle. To compensate for this weight difference, the density of the spheroid can be increased by 3/2 times that of the rod or cylinder. Thus

$$d_A = d\sqrt{\frac{\rho\beta}{\rho_o\chi}}(1.5)^{\frac{1}{2}} \tag{0.29}$$

Prodi has approximated the aerodynamic diameter of a cylinder whose motion is perpendicular or parallel to its polar or major axis as equations 30 and 31: (9,11)

$$d_{A\perp} = \frac{3d\sqrt{\frac{\rho(\ln 2\beta+0.5)}{2\rho_0}}}{2} \tag{0.30}$$

$$d\| = \frac{3d\sqrt{\frac{\rho(\ln 2\beta-0.5)}{\rho_0}}}{2} \tag{0.31}$$

Cox (12) has undertaken a direct computation of the aerodynamic diameter of rods or cylinders. Based upon his analysis the aerodynamic diameter in the perpendicular direction to the major axis is

$$d_{A\perp} = d\left(\frac{9\rho\left[\ln(2\beta) + 0.193\right]}{8\rho_0}\right)^{\frac{1}{2}} \tag{0.32}$$

and the aerodynamic diameter parallel to the major axis is

$$d\| = d(\frac{9\rho\,[\ln(2\beta) + 0.807]}{4\rho_0})^{\frac{1}{2}} \tag{0.33}$$

When the range of the aerodynamic diameter of the cylinder or rod is greater than or equal to 2 microns but less than or equal to 8 microns Cox's treatment is equivalent to the prolate spheroid shape factor with or without either refinement. (10)

If the rod or cylinder are not preferentially oriented by any forces but are free to randomly orient themselves as they move through the aircraft cabin then a single average shape factor $\overline{(\chi)}$ that is a function of the perpendicular and parallel shape factors can be used to describe the motion of a randomly moving rod or cylinder. (13)

$$\frac{1}{\overline{\chi}} = \frac{1}{3\chi_{\|}} + \frac{2}{3\chi_{\perp}} \tag{0.34}$$

solving for $\overline{\chi}$

$$\overline{\chi} = \frac{9\chi_{\|}\chi_{\perp}}{3\chi_{\perp} + 6\chi_{\|}} \tag{0.35}$$

substituting Cox's direct calculational shape factors:

$$\chi = \frac{d^2\rho\beta}{d_A^2\rho_0} \tag{0.36}$$

$$\chi_{\perp} = \frac{8d\beta}{9\,[\ln(2\beta) + 0.193]} \tag{0.37}$$

$$\chi_{\|} = \frac{4d\rho\beta}{9\rho\,[\ln(2\beta) + 0.807]} \tag{0.38}$$

to simplify this equation let d=a=0.6 micron and $\beta = 4/0.6 = 6.667$

$$\chi_{\perp} = \frac{8 * (0.6) * (6.667)}{9 * [\ln(2 * (6.667)) + 0.193]} = 1.2775 \tag{0.39}$$

$$\chi_{\|} = \frac{4 * (0.6) * (6.667)}{9 * [\ln(2 * (6.667)) + 0.807]} = .52333 \tag{0.40}$$

$$\overline{\chi} = \frac{9\chi_{\parallel}\chi_{\perp}}{3\chi_{\perp} + 6\chi_{\parallel}} = \frac{9 * (0.52333) * (1.2775)}{3 * (1.2775) + 6 * (0.52333)} = .86296 \quad (0.41)$$

$$v = \frac{2a^2\beta\rho g}{9\eta\overline{\chi}} = \frac{2 * (0.00006)^2 * (6.667) * (1.1) * 980.7\frac{cm}{\sec^2}}{9 * (0.0001832\frac{g}{cm\,\sec}) * (0.86296)} = 0.036394\frac{cm}{\sec} \quad (0.42)$$

$$v = 0.036394\frac{cm}{\sec} * \frac{60\sec}{\min} * \frac{inch}{2.54cm} * \frac{ft}{12inch} = 0.072\frac{ft}{\min} \quad (0.43)$$

This is the terminal velocity for a randomly oriented rod shaped bacteria that an infectious air traveler would emit into the cabin whose height is H and net volume is V. Clayton and colleagues have performed a study measuring aerosolized bacteria and air current indicator tubes in a Boeing 707. (14) Their studies determined that the ventilation design of typical commercial aircraft provide conditions of stirred mixing once the craft is airborne and pressurized. The particle will experience stirred settling induced by the action of the cabin ventilation system and passenger's adjustable overhead air vents.(14) The concentration at any time=t will be determined by the stirred settling velocity in the following manner: (13)

$$V\frac{dC}{dt} = -C\left(\frac{v}{H}\right) \quad (0.44)$$

Exact solution is :

$$C(t) = e^{-\frac{v}{VH}t}C\mid_{t=0}^{t=\infty} = C_0e^{-\frac{v}{VH}t} \quad (0.45)$$

The solution of equation #45 is based upon the premise that the initial concentration is equal to the outdoor concentration. The particle concentration in the aircraft will be determined by the rate of particle generation plus the rate of infiltration from external or extra compartmental sources minus the removal rates for stirred settling, electrical plating out of particles on surfaces and agglomeration etc. For purposes of this model, all these removal rates will be assumed to be zero except stirred settling and there will be no resuspension of micro droplets. In this case the mass balance equation for cabin particle concentrations can be expressed as the following differential equation::

$$V\frac{dC}{dt} = qI + C_oQ - CQ - C\left(\frac{v}{H}\right) \quad (0.46)$$

The outdoor tuberculosis quantal concentration C_0 is = 0. Rearranging equation #46 yields:

$$V\frac{dC}{dt}+\left(Q+\frac{v}{H}\right)C=qI \tag{0.47}$$

Laplace solution is :

$C(t)=\frac{1}{QH+v}qIH-VH^2\frac{e^{-t\frac{QH+v}{VH}}}{QH^2V+vVH}qI+VH^2\frac{e^{-t\frac{QH+v}{VH}}}{QH^2V+vVH}C(0)\,Q+VH\frac{e^{-t\frac{QH+v}{VH}}}{QH^2V+vVH}C(0)\,v$

When t=0 then C(t=0)=0 and

$$C(t)=\frac{1}{QH+v}qIH-VH^2\frac{e^{-t\frac{QH+v}{VH}}}{QH^2V+vVH}qI \tag{0.48}$$

$$C(t)=\left[\frac{1}{QH+v}\right](qIH-qlHe^{-t\frac{QH+v}{VH}}) \tag{0.49}$$

$$C(t)=\left[\frac{qIH}{QH+v}\right](1-e^{-t\frac{QH+v}{VH}}) \tag{0.50}$$

$$C(t)=\left[\frac{qI}{Q+\frac{v}{H}}\right](1-e^{-t\frac{QH+v}{VH}}) \tag{0.51}$$

Exact solution to equation #47 including outdoor concentrations of contaminants can also be obtained by directly solving the ordinary differential equation . The exact solution is :

$$V\frac{dC}{dt}+\left(Q+\frac{v}{H}\right)(C-C_o)=qI \tag{0.52}$$

$$\frac{dC}{dt}+\frac{(Q+\frac{v}{H})}{V}C=\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o \tag{0.53}$$

Equation #53 is a simple first order linear differential equation of the form:

$$y'+a(x)y=b(x) \tag{0.54}$$

Where where a(x)=$\frac{(Q+\frac{v}{H})}{V}$and b(x)=$\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o$ Multiplying both sides of equation #54 by an integrating factor e$^{\frac{(Q+\frac{v}{H})}{V}t}$ yields:

$$e^{\frac{(Q+\frac{v}{H})}{V}}(\frac{dC}{dt}+\frac{(Q+\frac{v}{H})}{V}C)=e^{\frac{(Q+\frac{v}{H})}{V}t}(\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o) \tag{0.55}$$

$$\int\frac{d}{dt}(Ce^{\frac{(Q+\frac{v}{H})}{V}t})=\int(\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o)e^{\frac{(Q+\frac{v}{H})}{V}t}dt+\text{constant} \tag{0.56}$$

$$Ce^{\frac{(Q+\frac{v}{H})}{V}t}=\int(\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o)e^{\frac{(Q+\frac{v}{H})}{V}t}dt+constant \tag{0.57}$$

$$Ce^{\frac{(Q+\frac{v}{H})}{V}t}=(\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o)\int e^{\frac{(Q+\frac{v}{H})}{V}t}dt+\text{constant} \tag{0.58}$$

$$Ce^{\frac{(Q+\frac{v}{H})}{V}t}=(\frac{qI}{V}+\left(\frac{Q+\frac{v}{H}}{V}\right)C_o)\left(\frac{V}{Q+\frac{v}{H}}\right)e^{\frac{(Q+\frac{v}{H})}{V}t}+\text{constant} \tag{0.59}$$

$$Ce^{\frac{(Q+\frac{v}{H})}{V}t}=(\frac{qI}{Q+\frac{v}{H}}+C_o)e^{\frac{(Q+\frac{v}{H})}{V}t}+\text{constant} \tag{0.60}$$

$$C(t)=e^{\frac{-(Q+\frac{v}{H})}{V}t}\text{constant }+(\frac{qI}{Q+\frac{v}{H}}+C_o) \tag{0.61}$$

When t=0 then Constant= $-(\frac{qI}{Q+\frac{v}{H}}+C_o)$. Assuming that qI, Q and V are constants and that at t=0 $C=0$, equation #61 results in the following:

$$C(t)=-e^{\frac{-(Q+\frac{v}{H})}{V}t}(\frac{qI}{Q+\frac{v}{H}}+C_o)+(\frac{qI}{Q+\frac{v}{H}}+C_o) \tag{0.62}$$

$$C(t)=(\frac{qI}{Q+\frac{v}{H}}+C_o)\left[1-e^{\frac{-(Q+\frac{v}{H})}{V}t}\right] \tag{0.63}$$

Upon inspection of equation #63 it should be noted that, in a well mixed vacant cabin the only source of tuberculosis micro droplets is the outside air. At equilibrium, when t$\rightarrow\infty$, the exponential factor in the second term will approach zero and the concentration will equal the first term .

$$C(t\rightarrow\infty)=(\frac{qI}{Q+\frac{v}{H}}+C_o) \tag{0.64}$$

If it is assumed that there is no outdoor source of infectious micro droplets or re-entrainment of infectious micro droplet aerosols then $C_o = 0$ and the equilibrium concentration equation #64 simplifies as follows:

$$C(t \rightarrow \infty) = \frac{qI}{Q + \frac{v}{H}} \tag{0.65}$$

If high efficiency particulate air filtration is used to remove aerosols from the outdoor and return air streams then equation #46 can be modified as follows:

$$V\frac{dC}{dt} = qI + C_o(1 - E)FQ + C(1 - E)(1 - F)Q - CQ - C\left(\frac{v}{H}\right) \tag{0.66}$$

where:

E= the fractional HEPA efficiency (0.9997 at 0.3 microns.)

F= the fraction of Outdoor Air=0.5

$$V\frac{dC}{dt} = qI + C_o(1 - E)FQ + C(((1 - E)(1 - F))Q - Q - \left(\frac{v}{H}\right)) \tag{0.67}$$

$$V\frac{dC}{dt} = qI + C_o(1 - E)FQ + C(Q((1 - E)(1 - F) - 1) - \left(\frac{v}{H}\right)) \tag{0.68}$$

$$V\frac{dC}{dt} + \left(Q(1 - ((1 - E)(1 - F))) + \frac{v}{H}\right)C = qI + C_o(1 - E)FQ \tag{0.69}$$

When C_o is= 0 the equation simplifies :

$$V\frac{dC}{dt} + \left(Q(1 - ((1 - E)(1 - F))) + \frac{v}{H}\right)C = qI \tag{0.70}$$

Typical commercial aircraft supply 10 cfm/passenger of outside air and combining it with 10 cfm/passenger of recirculated air.(15) The total supply air is HEPA filtered. In this case, equation #70 becomes

$$V\frac{dC}{dt} + \left(Q(1 - ((0.0003)(0.5))) + \frac{v}{H}\right)C = qI \tag{0.71}$$

$$V\frac{dC}{dt} + \left(Q(a) + \frac{v}{H}\right)C = qI \tag{0.72}$$

Laplace solution is :

$C(t) = \frac{1}{QaH+v}qIH - VH^2\frac{e^{-t\frac{QaH+v}{VH}}}{QaH^2V+vVH}qI + VH^2\frac{e^{-t\frac{QaH+v}{VH}}}{QaH^2V+vVH}C(0)Qa + VH\frac{e^{-t\frac{QaH+v}{VH}}}{QaH^2V+vVH}C(0)v$

where

a=$1-((1-E)(1-F)) = (1-((0.0003)(0.5)) = 0.99985$

$$C(t) = \frac{1}{QaH+v}qIH - VH^2\frac{e^{-t\frac{QaH+v}{VH}}}{QaH^2V+vVH}qI \tag{0.73}$$

$$C(t) = \frac{qIH}{QaH+v}(1-e^{-\frac{(QaH+v)t}{VH}}) \tag{0.74}$$

$$C(t) = \frac{qIH}{QaH+v}(1-e^{-\frac{(QaH+v)t}{VH}}) \tag{0.75}$$

$$C(t) = \frac{qIH}{0.99985QH+v}(1-e^{-\frac{(0.99985QH+v)t}{VH}}) \tag{0.76}$$

In the case of a commercial airliner seating 290 passengers (16)

The gross cabin volume including galley = 483.9 m^3 = 17088 ft^3

Assuming 6 cfm displacement for each cabin occupant and their luggage then the

V=Net cabin volume= $17088 - (290 * 6) = 15348$ ft^3

H=2.87 m=9.41667 feet

t=10 hour flight duration

qI=$60\left[\frac{quanta}{hr}\right] = 1\left[\frac{quanta}{\min}\right]$

No outdoor TB micro droplet particulate concentration $C_0 = 0\left[\frac{microdroplets}{ft^3}\right]$

CASE 1: CABIN WITH NO HEPA FILTRATION

Q_{OA}=10 cfm per passenger x 290 passengers = 2900 [cfm]
Q_R=10 cfm per passenger x 290 passengers = 2900 [cfm]
Q=Q_{OA}+ Q_R = 5800 [cfm]
$C_0 = 0 \left[\frac{microdroplets}{ft^3}\right]$
v=$0.072\frac{ft}{\min}$

$$C(t) = (\frac{qI}{(1-((1-E)(1-F)))Q+\frac{v}{H}} + C_o)\left[1 - e^{\frac{-(1-((1-E)(1-F)))Q+\frac{v}{H})}{V}t}\right] \quad (0.77)$$

$$C(t) = (\frac{qI}{(1-(1-0.5))Q+\frac{v}{H}} + C_o)\left[1 - e^{\frac{-(1-((1-0.5)(1-F)))Q+\frac{v}{H})}{V}t}\right] \quad (0.78)$$

$$C(t) = (\frac{1}{2900+\frac{0.072}{9.41667}})\left[1 - e^{\frac{-(2900+\frac{0.072}{9.41667})}{15348}t}\right] \quad (0.79)$$

$$C(t) = \left[3.4483 \times 10^{-4} - 3.4483 \times 10^{-4} \exp\left(-.18895t\right)\right] \quad (0.80)$$

CASE 2: CABIN WITH HEPA FILTRATION

Q=5800 $[cfm]$
v=0.072$\frac{ft}{\text{min}}$
$\text{C}_0 = 0 \left[\frac{microdroplets}{ft^3}\right]$

$$C\left(t\right) = \frac{qI}{(0.99985Q + \frac{v}{H})}(1 - e^{-\frac{(0.99985Q+\frac{v}{H})t}{V}}) \tag{0.81}$$

$$C(t) = (\frac{1}{(0.99985)(5800) + \frac{0.072}{9.41667}}) \left[1 - e^{\frac{-((0.99985)(5800)+\frac{0.072}{9.41667})}{15348}t}\right] \tag{0.82}$$

$$C(t) = \left[1.7244 \times 10^{-4} - 1.7244 \times 10^{-4} \exp\left(-.37784t\right)\right] \tag{0.83}$$

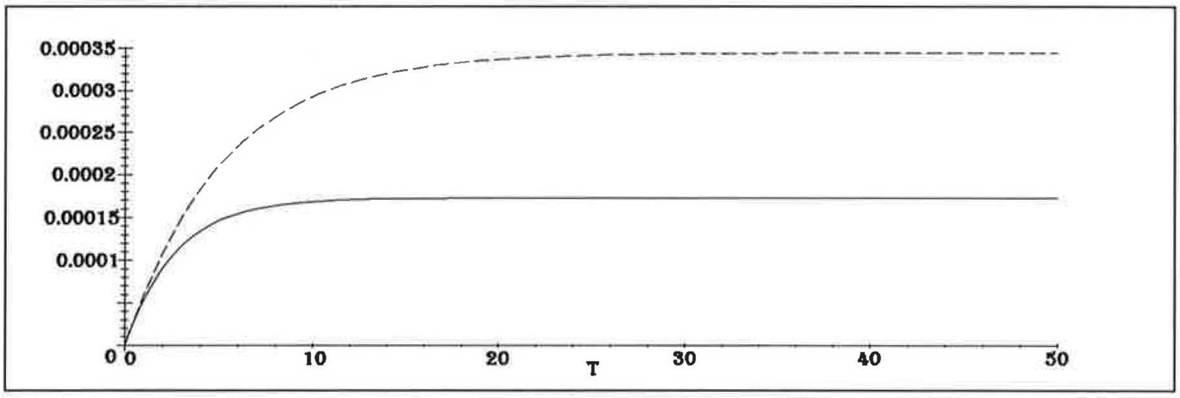

Figure 1: TB QUANTA CONCENTRATION VS TIME (HOURS)
Solid line=HEPA: Dashed line= no HEPA

$$TB = S \text{ x } (1\text{-e}^{-\frac{Iqpt}{Q}}) = S \text{ x } (1\text{-e}^{-Cpt}) \tag{0.84}$$

Where TB= the number of infections predicted
S= the number of exposed susceptible persons =289 adults
I= the number of infectious individuals=1
q= the infector's emission rate (q=60 quanta/ hr)

t= time (hours)=10 hours
p= respiration rate (cfm)= 18.75 liters/hr x ft^3/28.32 liters= 0.662 ft^3/hr
Q= ventilation rate (ft^3/hr) = 5800 cfm x 60 min/hr= 3.48×10^5 ft^3/hr
C=the equilibrium quantal concentration

Let (R) be defined as the new tuberculosis case rate per passenger (i.e. Risk). Then

R can be defined as

$$R = \frac{TB}{S} = (1\text{-e}^{-Cpt}) \tag{0.85}$$

For Case 1 C=3.4483×10^{-4}

$$TB = S \text{ x } (1\text{-e}^{-Cpt}) = (289)(1 - \exp^{-(0.00034483)(0.662)(10)}) \tag{0.86}$$

$$TB = (289)(1 - \exp(-2.282775 \times 10^{-3}) = 0.65897 \tag{0.87}$$

$$R = \frac{TB}{S} = (1\text{-e}^{-Cpt}) = \frac{0.65897}{289} = 0.0022802 \tag{0.88}$$

For Case 2 C=1.7244×10^{-4}

$$TB = S \text{ x } (1\text{-e}^{-Cpt}) = (289)(1 - \exp^{-(0.00017244)(0.662)(10)}) \tag{0.89}$$

$$TB = (289)(1 - \exp(-1.141553 \times 10^{-3})) = 0.32972 \tag{0.90}$$

$$R = \frac{TB}{S} = (1\text{-e}^{-Cpt}) = \frac{0.32972}{289} = 0.0011409 \tag{0.91}$$

Thus airframe industry's standard design utilizing HEPA filtration results in a risk reduction of 1.9986. The relationship between the new tuberculosis infection rate and the ventilation (Q) can be determined from equation #84 when the duration of the flight is 10 hours as follows. The number of new cases versus the ventilation rate is plotted as figure 2. It is obvious that the higher the rate of ventilation the lower the concentration of micro droplet aerosols and the lower the infection rate.

$$TB = (1 - \exp(-6.62/Q)) \tag{0.92}$$

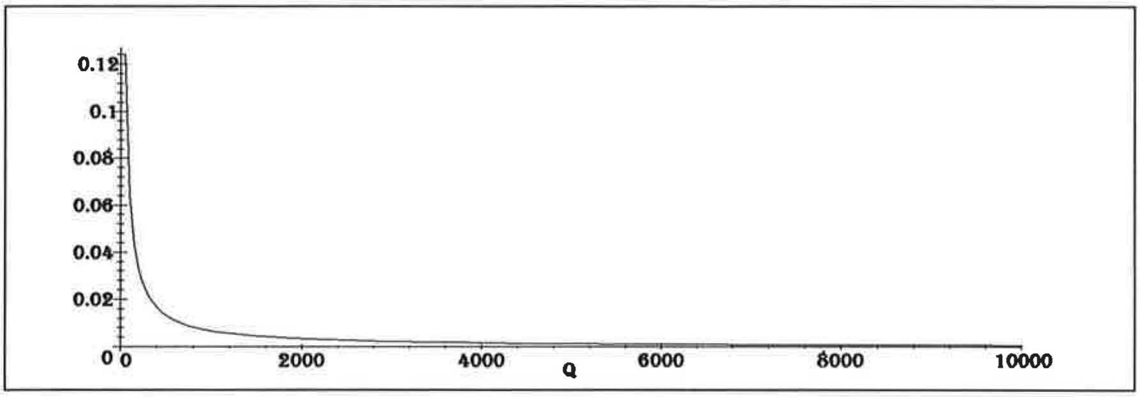

Figure 2: NEW TB INFECTIONS VERSUS VENTILATION

The relationship between the fraction of outside air and the number of new tuberculosis cases is determined by substituting the equilibrium concentration from equation #83 into equation #84 as follows:

$$TB = S \text{ x } (1\text{-e}^{-Cpt}) = S(1 - \exp(-(\frac{qI}{(1-((1-E)(1-F)))Q + \frac{v}{H}} + C_o)pt)) \tag{0.93}$$

For the specific case where there is a single actively infectious laryngeal tuberculosis case in the cabin, and the plane is equipped with the standard HEPA air filters described in case 2. When $C_0 = 0$

$$TB = S(1 - \exp(-(\frac{qI}{(1-((1-E)(1-F)))Q + \frac{v}{H}})pt)) \tag{0.94}$$

$$TB = S(1 - \exp(-(\frac{1}{(1-((0.0003)(1-F)))(5800) + \frac{0.072}{9.41667}})(6.62)) \tag{0.95}$$

$$TB = (289)(1 - \exp(\frac{-6.62}{5798.3 + 1.74F}) \tag{0.96}$$

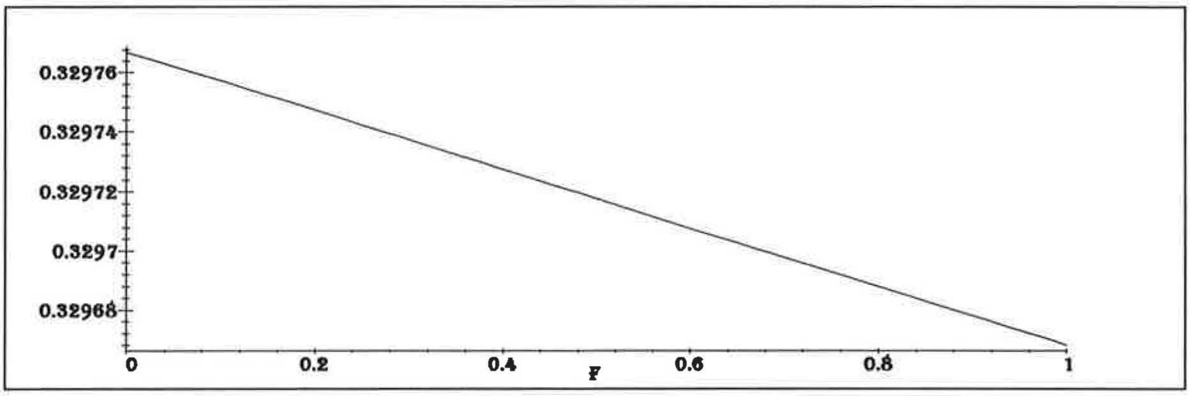

Figure 3:TB INFECTIONS VERSUS FRACTION OF OUTSIDE AIR

The new tuberculosis case rate per passenger can be determined as follows:

$$R = (1 - \exp(\frac{-6.62}{5798.3 + 1.74F}) \qquad (0.97)$$

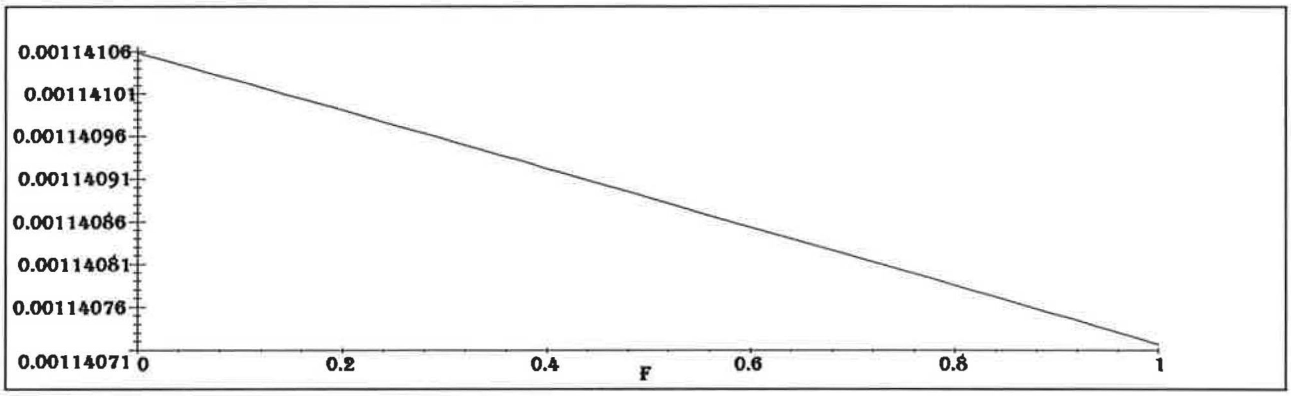

Figure 4: TB RISK VERSUS FRACTION OF OUTSIDE AIR

The risk can be minimized if the plane were to use 100% outdoor air in a single pass mode as can be seen in figure 4. The risk reduction gained by redesigning from the present design concept of 50% outside air to a 100% single pass mode is 0.99982. Thus it is apparent that further efforts to increase the percentage of outside air will have limited benefit. The HEPA filtration provides air that is quite similar to outdoor air with respect the particulate contaminants.

In 1993, the tuberculosis infection rate for the general population of New York State was 21.7/100000. The general population rates for California and New Jersey were 18.4 and 12.6 /100000 respectively.(17) If the general population rate for New York State is considered to be a worst case, then the risk of finding an as yet unidentified actively infectious laryngeal tuberculosis passenger on the plane out of 290 passengers is:

$$\left(\frac{21.7}{100000}\right)(290) = 0.06293 \tag{0.98}$$

The overall risk to a member of the general population can be found by multiplying the probability of having an infectious passenger with the probability of being infected during a flight of 10 hours duration. Thus from equations #91 and #98 :

$$(0.06293)(0.0011409) = 7.1797 \times 10^{-5} \tag{0.99}$$

The worst case risk to a flight attendant can be estimated by assuming that he or she flies 200 days per year and that each flight is 10 hours in duration. It is assumed that the ventilation rate is constant throughout the flight as well as during boarding and landing. Risk during ground operations can be determined in a similar manner if ventilation rates are available during those operations. It is assumed that the normal ground operations are an insignificant fraction of the total exposure duration. If it is assumed that the flight attendants have the same risk as the passengers per flight then their yearly rate can be calculated based upon a Poisson distribution as follows:(7)

$$\Pr(X = \#\text{ new cases per year}) = \frac{m^x e^{-m}}{x!} \tag{0.100}$$

where m=the mean or expected infection rate per year
$m = 7.1797 \times 10^{-5}$ x 200 flights/year
$m = 1.4359 \times 10^{-2}$

$$\Pr(X = 1 \textit{ new cases per year}) = \frac{m^x e^{-m}}{x!} = 0.014359 \exp(-0.014359) \tag{0.101}$$

$$\Pr(X = 1 \textit{ new cases per year}) = 0.014154 \tag{0.102}$$

DISCUSSION

Confinement of hundreds of passengers in a small volume cabin for extended durations is common for trans-oceanic or trans-continental commercial aviation. There is a concern that the indoor spaces of the commercial airliners may subject the occupants to elevated levels of airborne contaminants.(18,19) The Federal Aviation Administration (FAA) in the United States, regulates the airborne concentration of ozone, carbon monoxide, and carbon dioxide.(20) The FAA has not established a limit for outdoor supply air in the cabin. The Canadian Labor Code's Aviation and Occupational Safety and Health Regulations follow the American Conference of Governmental Industrial Hygienists Threshold Limit Values for carbon dioxide, carbon monoxide, formaldehyde, ozone and total dust.(21) The ANSI/ASHRAE Standard 62-1989 entitled "Ventilation for Acceptable Indoor Air Quality." provides a standard for outdoor supply air in transportation vehicles of 20 cubic feet per minute per person.(22) The commercial aviation industry designs to 10 cfm of outside air and HEPA filters an additional 10 cfm of recirculated air. O'Donnell and co-workers have reported on a study of 33 flights where 18 did not meet the manufactures' recommended 10 cfm of outside air.(23)

The resurgence of tuberculosis and the advent of multi-drug resistant strains has heightened the concern regarding the potential for the transmission of airborne diseases by micro droplet aerosols. There have been reported sera conversions associated with trains and aircraft flights. A flight from Baltimore to Hawaii resulted in passengers acquiring tuberculosis from an actively infectious carrier who died shortly after reaching her destination. Crew members have been infected by co-workers. This paper determines the "worst case" risk of tuberculosis infection by assuming that there is a rate in the general population that is similar to the peak rate found in a high risk New York State in recent years. This is a conservative over estimate because it is not typical for other areas of the country and even New York State's rate has been declining in recent years. It is also assumed that each flight is of a long ten hour duration. This is very conservative because the average flight is far less than ten hours and may be nearer to 1-2 hours. The model also conservatively assumes that flight attendants fly for 200 days per year and on each day spend ten hours in the cabin. The model assumes that the rate of ventilation is constant and that the efficiency of the filters does not change.

The model demonstrates that the "worst case" risk for a general passenger is 71.8/100000 for a ten hour flight. The risk for flight attendants over a year of occupational exposure is orders of magnitude greater. The concentration of micro droplet nuclei can be minimized by increasing the ventilation rates. The use of HEPA filtration by the aircraft manufactures reduces the risk by a factor of 2. Increasing the fraction of outdoor air above the present design level of 50% would not result in significant additional risk reduction.

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