ASHRAE VIRTUAL ANNUAL CONFERENCE

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SEMINAR 9
Is More Better? Air Change Rate for Health Hazard Control in Critical Environments

Tuesday, June 29, 2021 from 12:00 PM to 2:00 PM

COVID-19 and Beyond:
ACH: The Wrong Infection Control Parameter
Low RH: Too Long Ignored

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Learning Objectives

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- Describe strategies for enhancing contaminant removal at a given ACH and methods of measurement
- **Explain how relative humidity, ACH, and airborne virus transmission might be related**
- **Understand the interaction of variables: occupancy density, space volume, ACH, and ventilation rate**
- Describe the difference between air change rate and exposure control effectiveness in an industrial environment with point sources

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Acknowledgments and Bias

- The support of **Dr. James Bennett**, CDC/NIOSH, and **Mr. Raymond Horstman**, Fellow ASHRAE, is gratefully acknowledged.

- Re bias, I have co-developed technologies which circulate and **filter air in aircraft cabins near the breathing zones** of passengers and crew, and **prevent loss of cabin air humidity** to condensation on the cold fuselage behind the cabin insulation.

Human Generated Virion:
Respiratory Infection Mechanisms & Measures

- **Fomites**: surfaces carrying infectious virions, bacteria

  Measures: hand sanitizer; wet wipes; masks; UV on surfaces; HVAC - relative humidity (RH).

- **Cough and sneeze droplets** (> 5 microns).

  Measures: Cover your mouth if you cough or sneeze; masks; social distance 6 ft. HVAC - RH.

- **Breath, cough & sneeze aerosols** (≤ 5 microns) that move about by Brownian motion and remain airborne for hours.

  Measures: masks; HVAC - RH, virus-free air ventilation.

Low Relative Humidity: Too Long Ignored

Respiratory Infections & Humidity

- **RH Guideline.** The United States Environmental Protection Agency recommends maintaining 30% to 50% RH is optimal to maintain thermal comfort, air quality, & reduce mold growth in homes.[1]

- **RH norms.** These guidelines are not met at times on the ground and in the air in all settings both for condensation and equipment reasons (e.g. not using a dehumidifier as well as an air conditioner). For example, in buildings and homes in winter in cold climates with the heating system operating, RH normally is in the 20% – 35% range if there is no humidification. In summer, vehicles and buildings with A/C but without dehumidifiers normally are in the 50% – 65% RH range. Aircraft RH 15 minutes into the flight are typically 10% RH.

- **Low RH infection risk.** In terms of the quantifiable increased viral infection risk at low RH, all we know for sure is that influenza in the United States and Canada occurs primarily in the fall and winter seasons when indoor RH is lowest.[2]

Respiratory Infections & Low RH Research

- **Droplet dehydration to aerosols.** Low RH turns droplets into aerosols that can stay aloft for hours. E.g. Droplets dehydrate within a few seconds to aerosols at relative humidity (27%) and temperature (23°C).[3]

- **Mucociliary pathogen clearance inhibited.** Inhalation of dry air damages epithelial cells that protect against viral infections, increases mucin production and impairs mucociliary clearance (MCC) of pathogens trapped in the mucous layer of the airways.[5]

- **Infections are more severe.** At low RH (10-20% vs 50%), with nasal mucociliary clearance is impaired, aerosol particles (< 5µm) carrying virus are more likely to reach and inoculate (infect) the lower respiratory system where the minimum dose requirement to inoculate is lower and the symptoms more severe than if the inoculation occurs in the nasal system by droplets (> 5µm).[4, 6]

Respiratory Infections, Humidity & Masks

- **Masks prevent infections and reduce infection severity.** If an infection occurs while wearing a mask as filtration is not perfect, the infection is most likely to be asymptomatic (i.e. not severe).[23]

- **Masks raise inhaled air humidity**. Wearing masks humidifies the inhaled air and since masks do not filter the smallest particles that can cause the most severe infections, this humidification could be an alternative explanation as to why wearing a mask lowers the severity of COVID-19 infections.[7]

Public Transportation and Humidity

- **Occupancy density (OD)** is high in public transportation vehicles i.e. low spatial volume per occupant, which creates high ACH.

- **Air travel requires spatial pressurization** which creates low RH.

Bus: High OD, normal RH, high CO_2 [22]

Subway car with A/C: High OD, normal RH

Modern Train with A/C: High OD, normal RH

Narrow body aircraft cabin requires pressurization with outdoor air at 30,000 ft: High OD, low RH

A320 photograph courtesy L. Michael Roberts

Wide body aircraft cabin requires pressurization with outdoor air at 30,000 ft: High OD, low RH

Public Transportation

- **Intercity and international travel** is 10 times higher by air than all other public transportation modes for intercity travel (table below[13]) and is the primary mode for transoceanic travel.

- **Respiratory Infection Research.** As a result, air travel has received the most respiratory illness research attention.

U.S. Passenger-kilometer travel				
	1960	1990	2010	2019
Motor bus		33, 766	33,104	26,373
Transit (bus, rail, other)		66,213	84,695	87,061
Intercity, Amtrack	27,462	9,748	10,332	10,332
Air (intercity)	50,049	542,695	892,720	1,213,933

Passenger Aircraft Relative Humidity (RH)

- **Cabin RH = 10%.** The air in passenger aircraft cabins typically reduces to 10% RH after ~ 15 minutes flying due to 50% ventilation with low moisture content outside air.[8]

- **Breath and body moisture.** All cabin humidity after a short time is generated by the passengers only.[9]

- **Condensation.** Some cabin air humidity is lost to condensation on the cold fuselage behind the cabin insulation.[9]

Passenger Aircraft Insulation Envelope Condensation: Liner leakage reduces RH by 30%

- **RH with no condensation would be 14%** when ventilated with 10 cfm/p of outside air (i.e. meet the FAA requirement of 0.55 lb./min/p of outside air)

- **RH with condensation loss being 10%** for a 10 cfm/p outdoor air supply indicates 25% of cabin air leaks through the cabin liner to behind the insulation.

Cabin Humidity vs Ventilation Rate & Liner Leakage

Air Leakage rate behind insulation	25%	25%	25%	0%	0%	0%
Human moisture generation rate, lb./hr.	0.1	0.1	0.1	0.1	0.1	0.1
Human moisture generation rate not lost to condensation, lb./hr.	0.075	0.075	0.075	0.1	0.1	0.1
Cruising flight ventilation air moisture at 70F, lb./hr.	0	0	0	0	0	0
Ventilation air weight at 70F & 3/4 atm, lb./ft3	0.056	0.056	0.056	0.056	0.056	0.056
Ventilation rate, outdoor air, cfm/p	15	10	7.5	15	10	7.5
Weight of air, Lb./hr.	50.4	33.6	25.2	50.4	33.6	25.2
Lb. moisture per lb. air	0.0015	0.0022	0.0030	0.0020	0.0030	0.0040
Cabin RH at 72F and7500 ft.* ASHRAE Psychrometric Chart No. 5	7%	10%	14%	9%	14%	18%

Offsetting liner stack pressures is the first step towards cabin humidification

- **Stack pressures across the cabin insulation** of less than 10 Pascals cause this condensation humidity loss. For aircraft engineers, this pressurization is miniscule compared with the 8.2 psi (56,500 Pascals) cabin pressurization required when cruising at 40,000 ft to provide a cabin air density equivalent to that at an 8000 ft altitude.

- **Sealing, flow blocking and pressurizing the insulation envelope** with ~ 100 cfm of dry air will prevent this condensation and ventilation air loss. [10, 11]

- **Humidification.** With cold fuselage condensation eliminated, cabin humidification to raise cabin air from 14% RH to the 30% RH EPA guideline becomes a possible option.

Air Change Rate: the Wrong Infection Control Parameter

Dose via airborne virions [14, 15, 16, 17]

$$D = \int ICdt = p\{NI/VV_e\}\{t+OD/VV_e[\exp(-VV_e t/OD)-1]\} \text{..........}(1)$$

- D = Average dose number (# of virus inhaled by an exposed group of persons shed by an ill person, virions
- I = Inhalation rate, L/s
- p = Fraction of exposed persons
- N = Rate of bioeffluent infectious airborne shed by an ill person in the space, virions/s
- t = Duration of infectious aerosol generation, s
- OD = Spatial volume/person, L/person
- V = Infectious aerosol-free ventilation rate per person (HVAC outdoor air + virus-filtered recirculation air + envelope infiltration air), L/s per person
- Ve = Effectiveness of supply the ventilation air to each occupant's breathing zone. Ve=1 in a uniformly mixed system.

High change rates may increase the risk of airborne infections

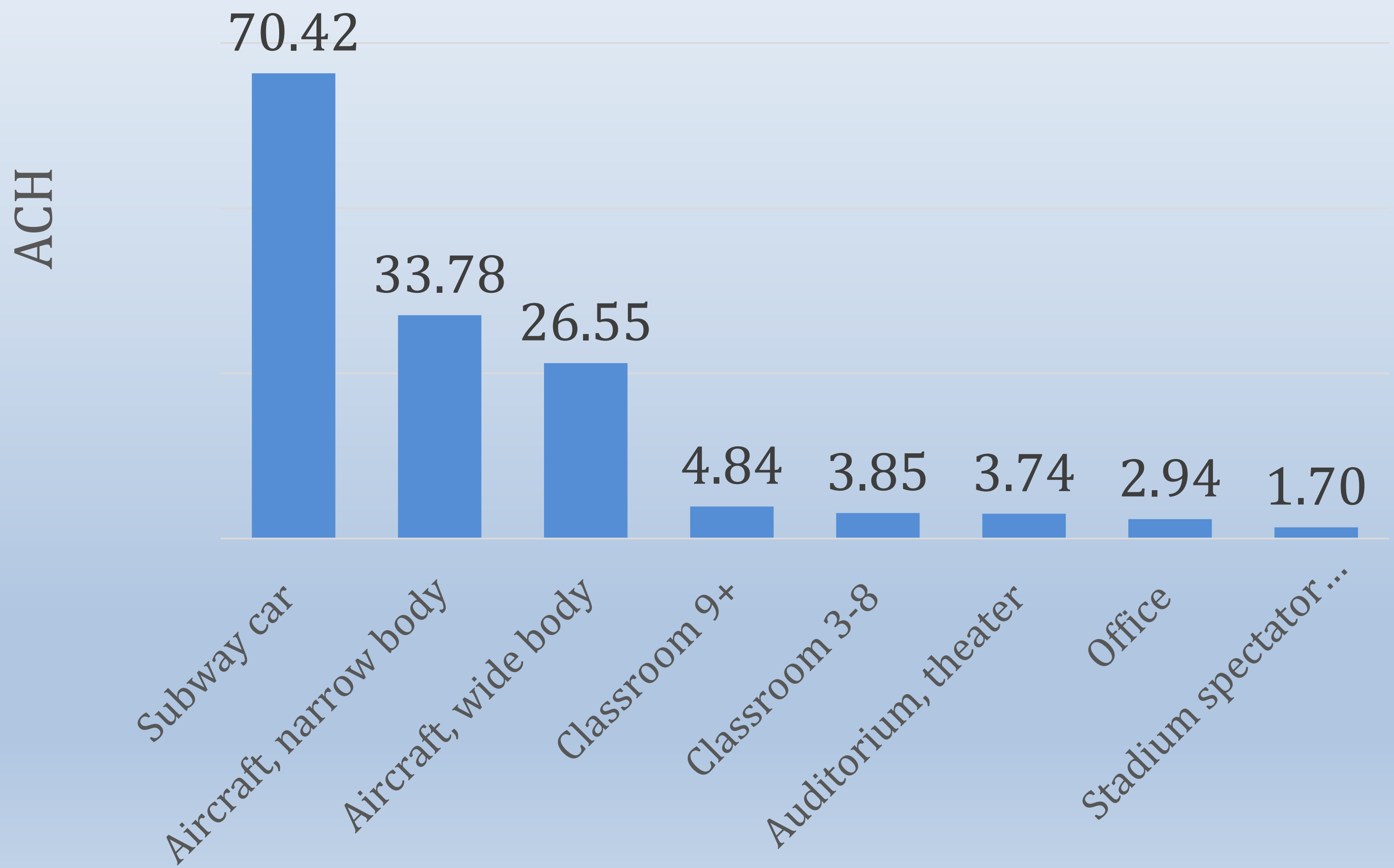
- **The Equation:** The higher the virus-free airflow per person, V, and the closer the Ve is to 1, the lower the infection risk. ACH is not in the equation governing exposure to ill person generated aerosols.
- **Why is ACH high?** A high ACH could be a result of a high occupancy density as is the case in transportation systems, rather than a high virus-free air flow per person such as in a hospital operating room.
- **Mixing effect.** High air flow velocities such as those from gaspers create better mixing and therefore lower the infection risk. [12]
- **Ve < 1 and high ACH.** High ACH rates in settings such as in aircraft cabins have air velocities lower than those of gaspers but may be high enough to cause stratification of particles in narrow body aircraft and result in a lower effective ventilation rate and a higher risk of infection.
- **Age of Air.** The higher the ACH the shorter the time airborne virions remain in the setting. But this is not a positive as it increases the likelihood of the airborne virions inhaled still being viable and also not having deposited on surfaces.
- **Lag effect to reach equilibrium in steady state shedding**

Input Data for 8 settings [14]

Location	Subway car	Aircraft narrow body	Aircraft wide body	Class-room 9th+	Auditor-ium, theater	Class-room 3rd-8th	Stadium spectat-or area	Office
Spatial vol.,v/p, (m^3)	0.7	1	1.6	8.1	10.2	11.3	26.6	28.3
Group design exposure time (h)	0.5	6	14	6	4	6	4	8
Ve	0.65	0.65	1	1	1	1	0.9	1
Infection-free ventilation air V*Ve (L/s/p)	8.9	6.1	11.8	10.9	10.6	12.1	11.3	23.1
V/v, ACH	70	34	27	4.8	3.7	3.9	1.7	2.9

Typical Air Change Rates (ACH) = V/v

ACH = total virus free air supply plus recirculation air supply for 1 hour, V/ spatial volume, v



Influenza Input Data

- **At rest inhalation rate** [18]

  I = 0.28 cfm = 0.132 L/s

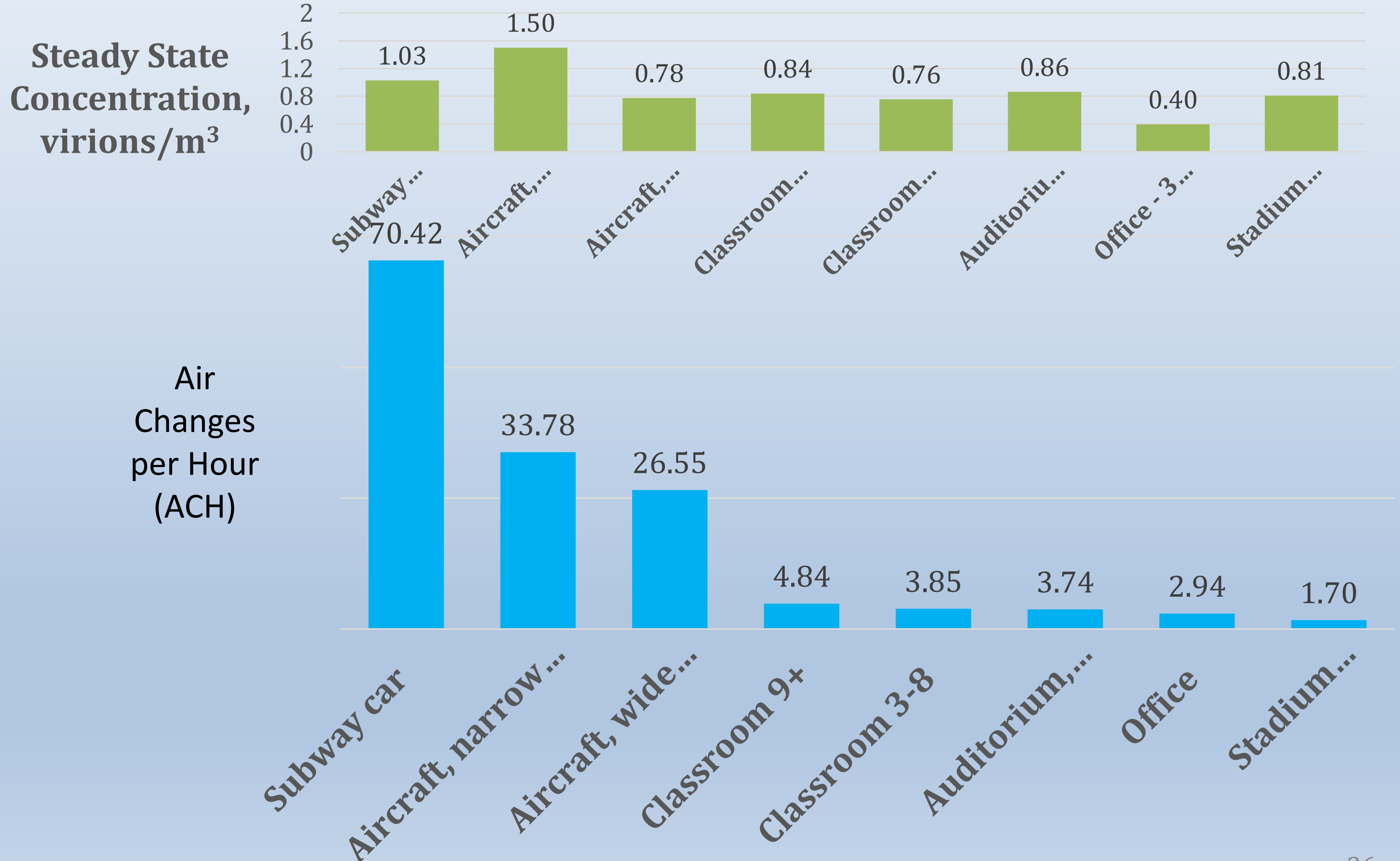
- **Influenza aerosol virus shedding rate used in the example dose calculations** [19]

  N = 11 influenza virus ribonucleic acid (RNA) copies/minute

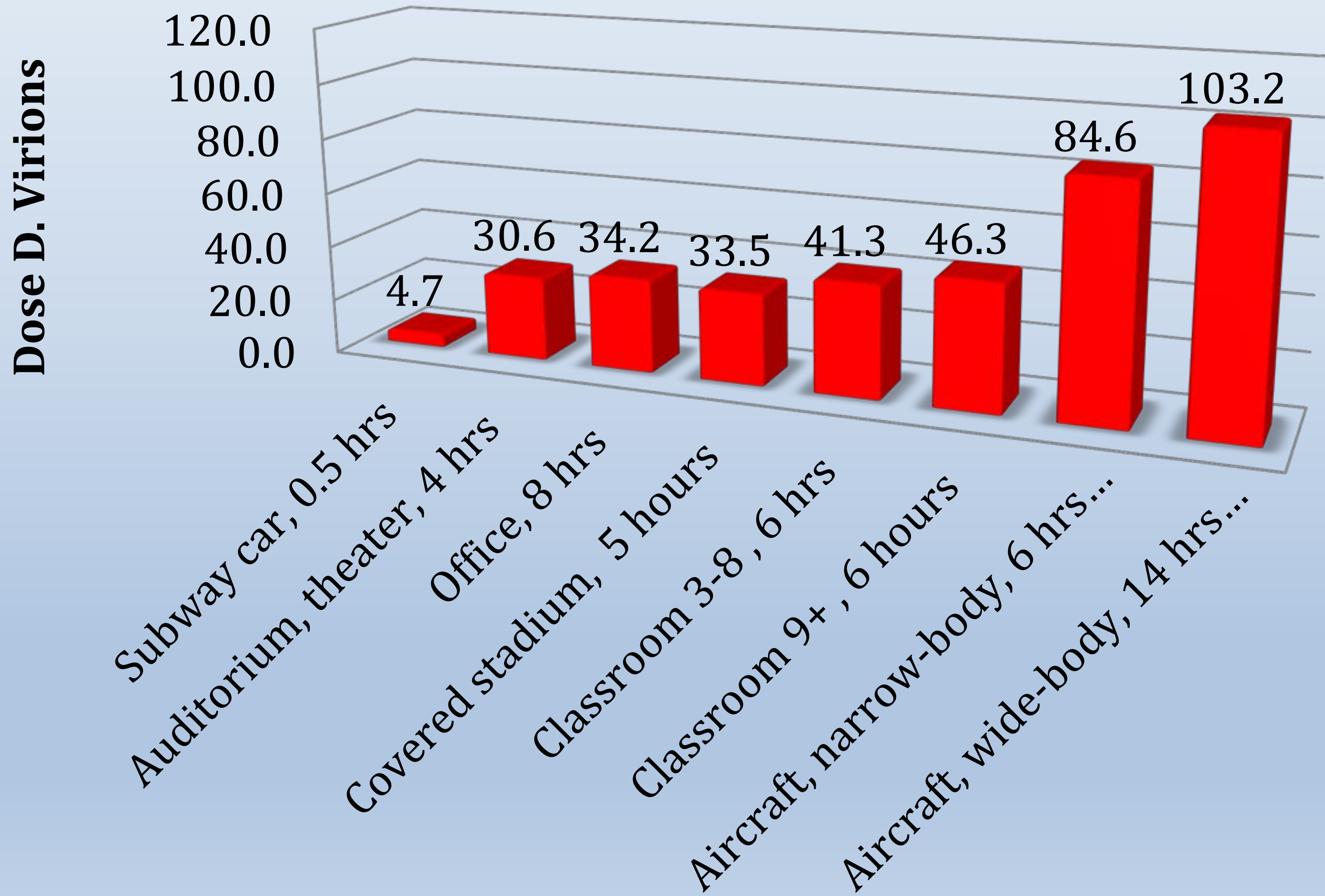
- **A later study** measured virus RNA shed by ill influenza patients as [20]

  N = 1267 virus RNA copies/minute from $\leq$ 5 micron particles
  N =   400 virus RNA copies/minute from > 5 micron particles

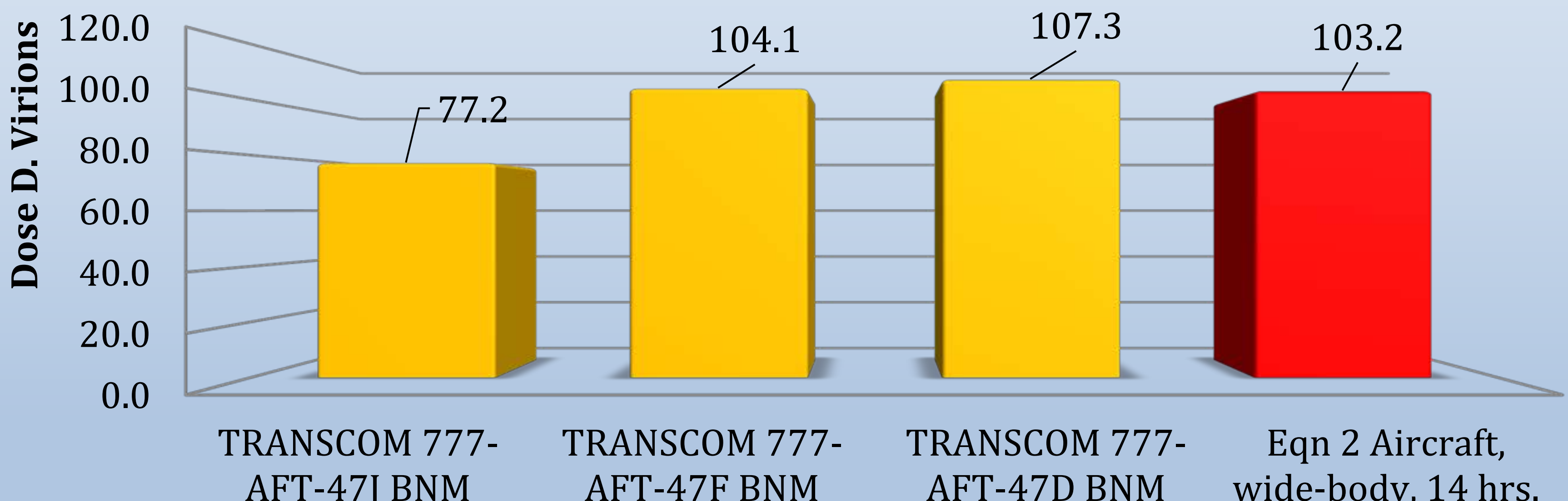
Example Steady State Virion Concentration {N/VVe} vs. Air Change Rate {V/v} in 8 settings



Eight (8) Setting Group Dose (p=1) for Design Travel Durations



Equation 1 comparison with the United States Transportation Command (US military) wide body aircraft experiments[21]



USTRANSCOM (United States Transportation Command) findings modified for the virion shedding rate, virus-free ventilation rate, inhalation rate, occupancy density and exposure times used in Eqn. 1 for the wide body cabin.

Humidity Conclusions

- **Target RH 30-50% in all settings** to optimize human resistance to serious viral infections.

- **Mask hydration of inhaled air** raises inhaled air humidity and could be a reason along with their particle filtration that wearing masks lowers the severity of COVID-19 infections and could be helpful in low RH settings for infectious aerosols in general as well as for ameliorating other health problems such as asthma.

Ventilation Conclusions

- **Equation (1)** accurately predicts group dose, p=1.

  $$D = p\{NI/VV_e\}\{t+OD/VV_e[\exp(-VV_e t/OD)-1]\}$$

- **The number of persons affected** by a single infector and therefore the average individual dose remains to be determined for many settings.

- **Standard setting bodies** need to bear in mind that an infectious dose can accumulate in several settings and that HVAC design criteria are needed for the number of infected persons shedding a particular virus in each space and that possible exposure time “t” plays an important role in setting HVAC design criteria.

Ventilation Conclusions

- **A high ACH can be both positive and negative** re the risk of airborne infections depending on whether it is high due to a high virus-free air supply rate per person or due to a high occupancy density.

- **A high ACH potentially increases the risk of infections** by:
  - **Lowering Ve** through stratification**,**
  - **Reducing age of air,** but not concentration, potentially increases the number of airborne virions remaining viable, and decreases the chance of virions plating out and not being inhaled.

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Questions?

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