Aerosol Dispersion in Commercial Aircraft Cabins

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The Team, Sponsors and Collaborators

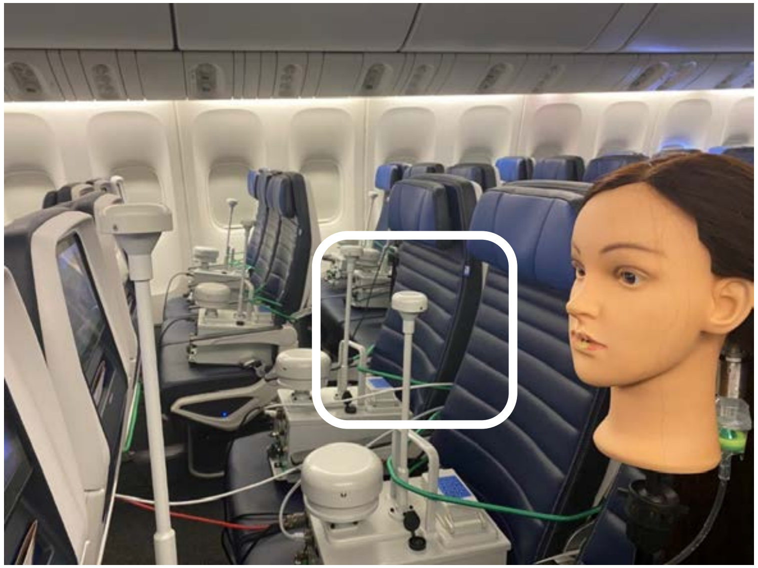
- **Test Team:** Sean Kinahan, David Silcott, Blake Silcott, Ryan Silcott, Peter Silcott, Braden Silcott, Steven Distelhorst, Vicki Herrera, Danielle Rivera, Kevin Crown, Gabriel Lucero, Wayne Bryden, Mike McLoughlin, Russell Accardi
- USTRANSCOM for sponsorship
- DARPA for technical direction and assistance
- Boeing for technical questions and engineering support
- United Airlines for donating airframe, engineering support, and test time and crew support

Background

- One of largest aircraft aerosol experimental tests to date – quantitative study to better understand potential SARS-CoV-2 exposure risks during long-haul flights
- Completed for United States Transportation Command (USTRANSCOM) to investigate exposure risk for SARS-CoV-2 on contracted Patriot Express flights
- Main objectives:
  - Provide quantitative aerosol dataset measuring levels of aerosol penetration into breathing zones of passengers seated near simulated infected passenger
    - In multiple seats across multiple rows distributed throughout the airframe
  - Provide recommendations on transport CONOPS
  - Provide data for modeling teams to determine efficacy of models (CFD, etc.)
- Over 300 aerosol tests performed: 15,500 breathing zone seat measurements using 40+ real-time sensors & 46 simulated infected passenger release locations

Reliance on the data and the scientific methods used to derive the data are at the risk of the user. The views, statistics, and data presented herein neither represent nor reflect the official views of USTRANSCOM or the Federal Government.

Tracking Aerosol Movement Using Tracer Particles



Approach/Methods:

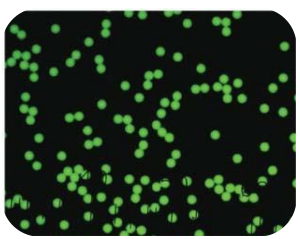
- Large-scale release of 1 μm fluorescent tracer particles
  - 2s on and 2s off breathing pattern – 1.43 m/s at mannequin lips
  - Approximately 2000 people breathing for 10 minutes
  - Approximately 3000 coughs/sneezes/loud-talking events

Characterization of Total Particles in a Chamber

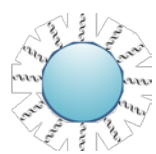
		Sample (n)	Mean (Total Particles)	Std Dev (Total Particles)	Standard Error of Mean
Chamber	Breathing w/o Mask	3	**1.8E+008**	1.7E+007	1.0E+007
Characterization	Breathing w/ Mask	3	**1.7E+008**	8.5E+006	4.9E+006
Statistics	DNA-tagged Release	3	**2.4E+007**	4.3E+006	2.5E+006

- Tracked using FLIR Instantaneous Biological Analyzer and Collector (IBAC)
  - 3.5 lpm aerosol spectrometer with fluorescent interrogation channel
- Mannequin with integrated aerosol nebulizer (mask/no mask)
- Each test is ~6-minutes; sampling monitored in real-time
- IBAC inlet in passenger breathing zone & typically completed in triplicate
- Coupled with DNA-tagged tracers (3 μm) for surface deposition and validation using additional methodology

IBAC
(FLIR Systems Inc.)



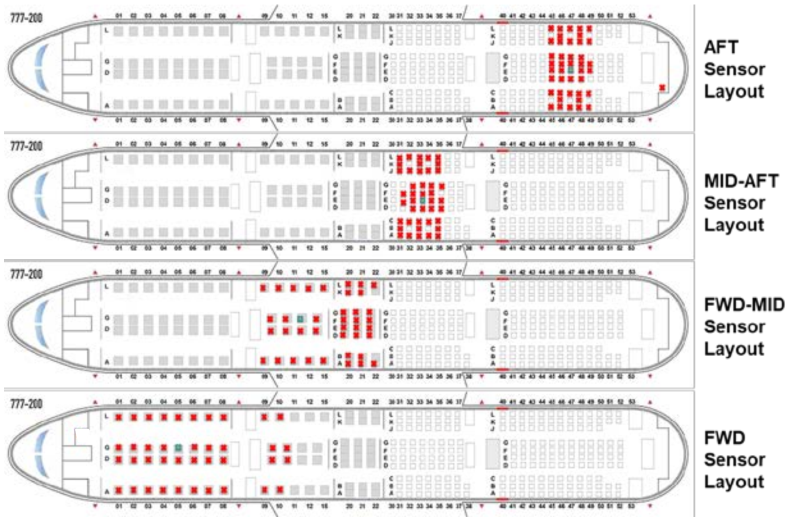
Monodisperse Fluorescent PSL Beads (Thermo Fisher)



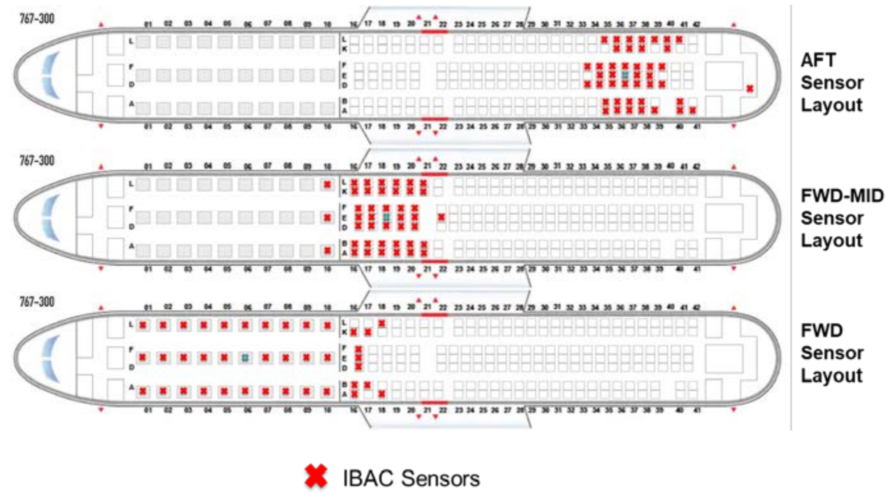
Biotinylated-DNA tagged PSL microspheres

Test Sections & Seats – 777 & 767 Airframes

777-200

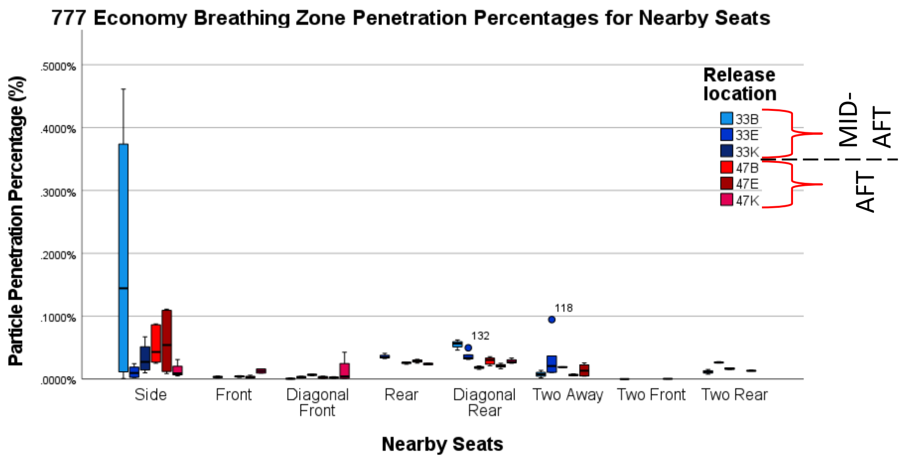


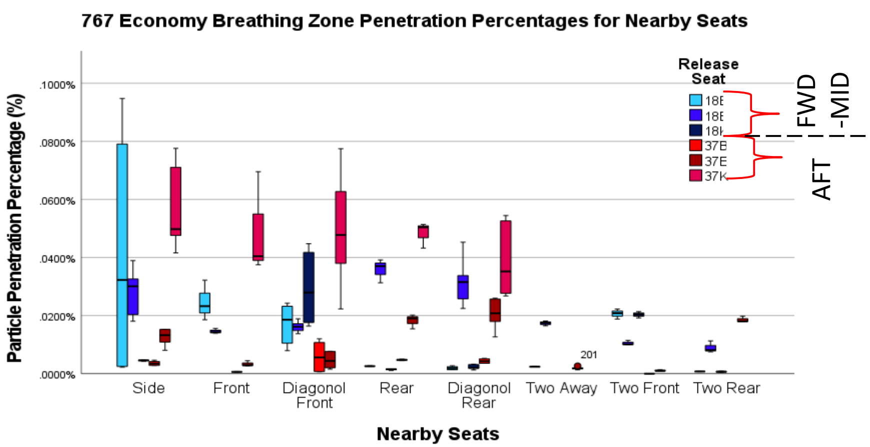
767-300



- Single seat indicated, but multiple seats tested in each row
- Releases using mannequin performed in 46 total seats
- Inflight, simulated inflight (hangar), and ground (loading and unloading) tests performed
- These results are from inflight tests

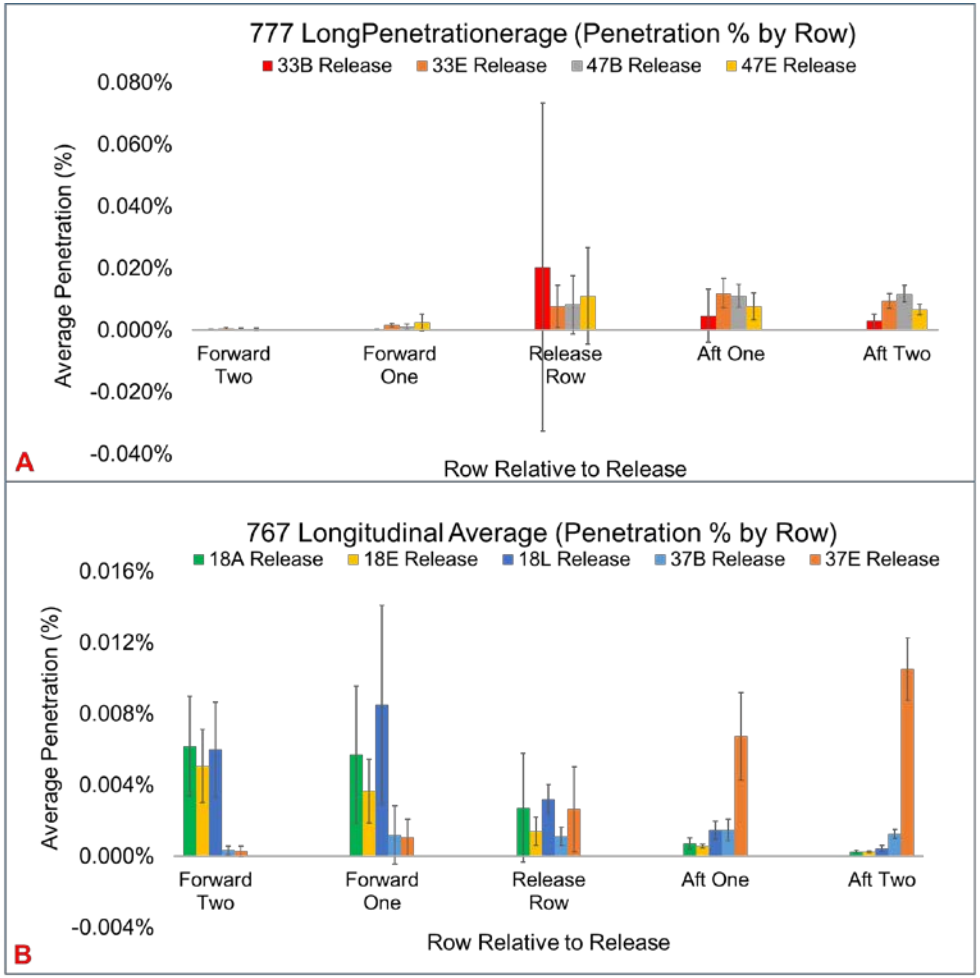
Economy Particle Exposure– Inflight





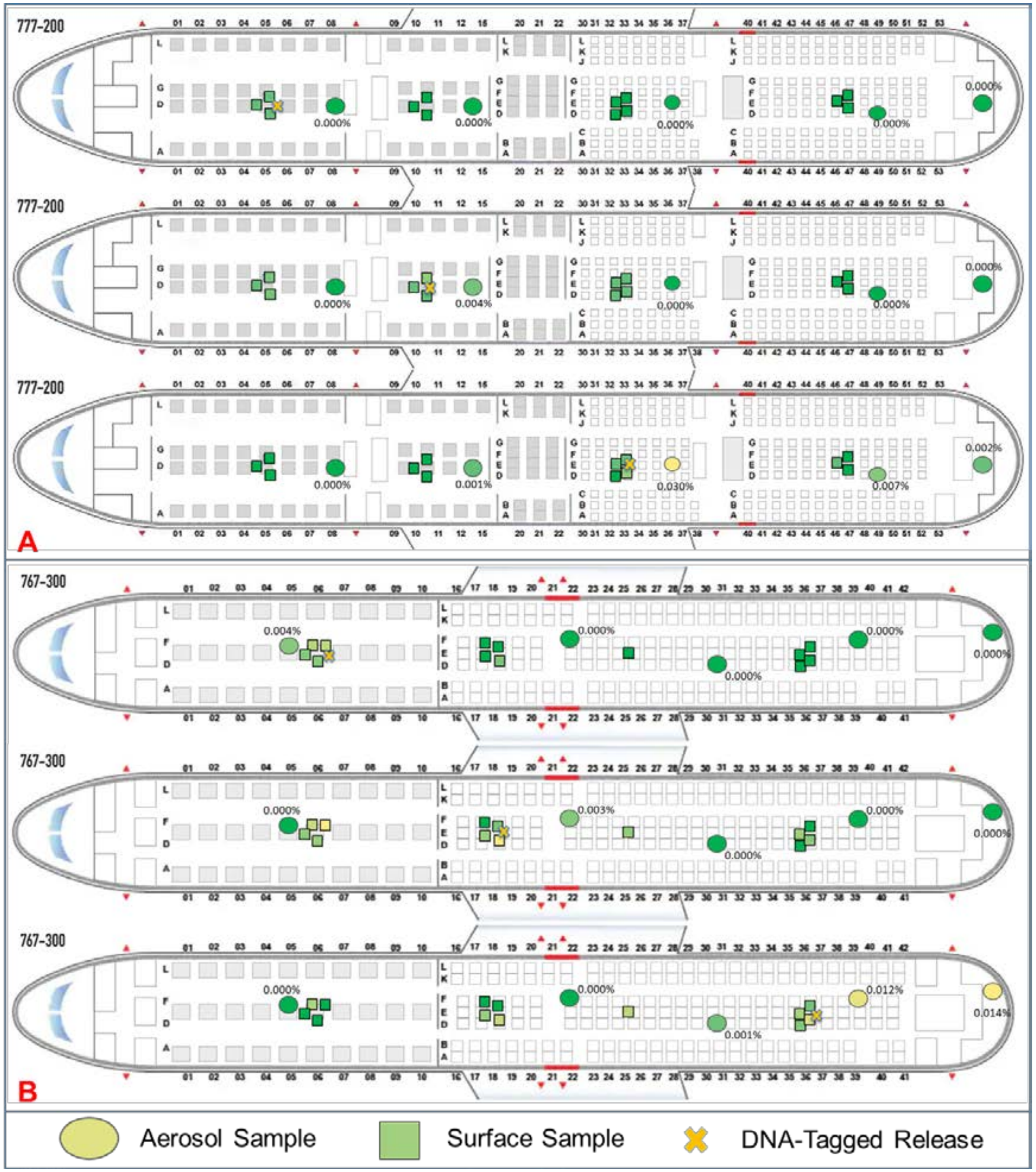
- For those closest economy seats:
  - Front (x2), Back (x2),
  - Left/Right (x2), Diagonal (x1)
- The 767 performed significantly better than the 777 for seats nearby ($p<.05$)
- 777
  - Particle Reduction 777 99.98-99.99%
  - Mean penetration %
    - AFT:0.0063% $\pm$ 0.0007% (n=375)
    - MID-AFT: 0.0060$\pm$ 0.0019% (n=312)
- 767
  - Particle Reduction 767 99.97-99.98%
  - Mean penetration %
    - AFT:0.0050% $\pm$ 0.0003% (n=366)
    - MID-AFT: 0.0052%$\pm$ 0.0003% (n=351)
- Extreme outliers in the case of a passenger seated directly next to an “infected” person for one seat on the 777 (33B)

Longitudinal Aerosol Movement



- Airfcraft are designed to mix air within a row, with airflow predominantly from top to bottom, minimizing longitudinal (front to back/back to front) flow
  - Outflow valves for pressurization and exhaust are located in aft (back)
- Average data for each row and look at forward and aft movement between rows
  - 767 demonstrated aftward mixing in the rear of the plane and forward mixing for releases towards front
    - Duplicated in first class (data not shown)
  - The 777 shows strong aftward mixing with very limited forward mixing in both economy sections
    - For the 777 first class – Row 11: Aftward; Row 5: Forward

Surface Contamination from Aerosol



- Surface deposition (**via aerosol route**) is minimal, even when assuming a square foot of surface area
- Deposition is typically highest on armrests and in seats nearest the point of release
- Aerosol collectors (Sartorius 50 lpm gel filters) agree well with real-time results

Mask Comparison

- Experiments not explicitly designed to test mask efficiency
  - Hope to observe a reduction compared to unmasked condition
  - Droplet size at outlet of mannequin (<5 μm) is not intended to be full distribution of coughing/breathing/talking
    - Likely best represents breathing (<4 microns) and not larger droplets that can also become aerosols
- Mean 15.6% reduction across all sensors in a given section for inflight testing with large range (-26.6% to 52.3% reduction)
  - Agrees reasonably with Chu, et al. (2020) @ 14.3%
  - Lower than Sickbert-Bennet (2020) @ 38.1%
- Alternative mask models can be applied to unmasked data sets, which have been the priority for analysis
- Increasing the velocity from 1.43 to 12.84 m/s drastically improved mask efficiency (coughing simulation)
- Often changes the direction of aerosolization, 13 sensors on average had a higher count with a mask than without

$$1 - \frac{\sum \int N_{Mask}(t)dt * n_{no-mask}}{\sum \int N_{No-Mask}(t)dt * n_{mask}}$$

Calculated by summing all triplicate integrated particle count releases with and without a mask, dividing, and then normalizing for any missing measurements

	Statistic	Result
Mask Effect	Sample Size (n)	14
	95.0% Lower CL for Mean	3.5%
	Mean	**15.6%**
	95.0% Upper CL for Mean	27.6%
	Standard Deviation	20.9%
	Standard Error of Mean	5.6%
	Minimum	-26.6%
	Median	17.7%
	Maximum	52.3%

Key Conclusions

- Rapid dilution, mixing and purging of aerosol from infected passenger zone likely due to airframe's high air exchange rate, downward ventilation design, and recirculated HEPA filtration
- Aerosol exposure risk minimal, under the conditions tested, on Boeing 777 and 767 aircraft with an average breathing zone penetration for nearby seats of 0.0176% and .0148%, corresponding to a 99.98% reduction in aerosol
- Maximum aerosol penetration (always in seats directly adjacent to a simulated patient) of 0.4614%
- Mask reduces the exposure risk (average 15.6%) when comparing replicates in the same seat with and without a 3-ply mask
- Helps explain why outbreaks on flights have been limited
  - IATA study - 44 identified potential cases among 1.2 billion travelers
  - 4/14 passengers seated within 3 rows infected in a well-studied flight from Dubai to Auckland
    - 18-hour flight with ~1.5 hour refueling layover in Kuala Lumpur

Key Limitations

- These tests are only relevant to transmission via the aerosol route
  - Contact transmission and transmission by ballistic droplets are not represented by this data
  - Seats with the highest penetration are also most likely to be affected by these modes
- This data assumes the aircraft HVAC is running in the same conditions as those tested
  - Only one, optimized, condition was tested
  - If the HVAC is turned off for any period of time, aerosol transport will be dramatically affected
- Mannequin always faced forward and movement in the aisles was minimal during testing
  - Limited follow-up testing indicates that turning the mannequin head can dramatically affect the seat immediately next to the source
  - Significant movement in the aisles could also disrupt airflow
  - Reality is meal-service, movement, and talking are likely, especially on longer flights – additional testing/analysis in progress
- These represent long-haul airframes, and we did not test more common 737 airframe as part of this effort

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