


AMCA COVID-19 Guidance for Large- Diameter Ceiling Fans

Over a 12-month period, Air Movement and Control Association, in collaboration with an international team of scientists, engineers, and researchers, executed a series of numerical simulations to investigate the impact of large-diameter ceiling fans on COVID-19 exposure in a warehouse.

Photograph courtesy of Greenheck Fan Corp.



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Numerous studies of airflow and performance characteristics of circulating fans have been undertaken.^{1,2,3,4,5,6} Relatively few, however, are focused on aerosol transmission of airborne pathogens in large industrial spaces, a shortage all the more noticeable during the coronavirus disease 2019 (COVID-19) pandemic.

To contribute to and improve the body of COVID-19-prompted guidance for the operation of circulating fans, Air Movement and Control Association (AMCA) International commissioned numerical-simulation studies of airborne-particle and aerosol transmission with large-diameter (greater than 2.1 m [7 ft]) ceiling fans (LDCF). The focus of the studies was warehouses in the United States, in which LDCF commonly are used for comfort cooling and destratification. The results, however, also are applicable to many manufacturing/industrial facilities.

To promote integrity in the design and execution of the research and ensure the conclusions drawn from the study are valid, AMCA assembled “industry” and “science” teams (Table 1). Consisting of representatives of AMCA member companies and members of the AMCA

staff, the industry team provided expertise in the application and performance of products, while the science team, made up of authorities in infectious diseases, indoor-air quality, fans, and computer modeling, including two leading members of the ASHRAE Epidemic Task Force, advised on the project setup and reviewed the intermediate and final results. Because COVID-19 infection rates are poorly understood and varying with mutations, the study focused on particle concentrations as an indicator of exposure risk.

Following is a high-level summary of the project’s findings and resultant guidance. For information on the simulation methodology, setups, assumptions, validations, and results, see the final report, “AMCA COVID Guidance for UNDUCTED Fans – Modeling Ceiling Fans,” prepared by Liangzhu (Leon) Wang, PhD, P.Eng.; Senwen Yang; Runzhong (Alvin) Wang; Mohammad Mortezaadeh, PhD; Jiwei Zou; and Chang Shu of Concordia University, at https://bit.ly/COVID_LDCF.

The Building

Based on the U.S. Department of Energy (DOE) commercial reference building for warehouses (Figure 1a), the warehouse in the study measured 100 m (330 ft) long by 46 m (150 ft) wide by 8.5 m (28 ft) tall with two AMCA-certified 6.1-m- (20 ft) diameter ceiling fans installed 36.6 m (120 ft)

apart in the bulk-storage area (Figure 1b). The warehouse was modeled with (Figure 1c) and without racks, with the racks oriented to provide the most beneficial airflow performance across most aisles. Simulation results are reported mostly at the whole-warehouse-breathing-zone horizontal plane (Figure 1d), at the vertical plane crossing the two LDCF centers (Figure 1e), and inside the working zone (Figure 1f).

The warehouse was assumed to be located in Chicago. Simulations using the DOE’s EnergyPlus whole-building energy-modeling program were performed to determine air and surface temperatures during winter and summer, respectively.

Scenarios

A variety of arrangements and locations of the packing line relative to the ceiling fans and workers were simulated (Figure 2). The U-H-D-3 (packing line directly under the right-side fan and oriented horizontally, two rows of workers 0.9 m [3 ft] apart) combination in Figure 2 is the scenario used for most of the discussion.

Figure 3 shows steady-state airflow distribution for a case of U-H-D-3 at three air speeds exiting the fans (i.e., average air speeds through the area swept by the fan blades): 3 m/s (10 fps) (100-percent fan speed) (FS-3), 0.6 m/s (2 fps) (20-percent fan speed) (FS-0.6), and 0 m/s (0 fps) (fans off) (FS-0). When the fans blow air downward

SCIENCE TEAM			
Name	Title	Affiliation	Project role/contribution
Liangzhu (Leon) Wang, PhD, P.Eng.	Associate professor, Department of Building, Civil, and Environmental Engineering	Concordia University	Principal investigator
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Edward A. Nardell, MD	Professor, departments of Environmental Health and Immunology and Infectious Diseases	Harvard T.H. Chan School of Public Health	Infectious diseases and study of ceiling fans for control of infectious diseases
Jovan Pantelic, PhD	Research scientist, building science	Well Living Lab Inc.	Infectious diseases
Paul Raftery, PhD	Professional researcher	Center for the Built Environment, University of California, Berkeley	Ceiling-fan modeling
Geoff Sheard, DSc	President	AGS Consulting LLC	Computational-fluid-dynamics modeling and fan engineering
Pawel Wargocki, PhD	Associate professor, departments of Civil Engineering and Indoor Environment Chair, ASHRAE Epidemic Task Force Science Applications Committee	Technical University of Denmark	Indoor-air-quality expertise
INDUSTRY TEAM			
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Aaron Gunzner	Senior manager, advocacy	AMCA International	Staff liaison
Mark Stevens	Executive director	AMCA International	Member relations
Christian Taber	Principal engineer, codes and standards	Big Ass Fans	Warehouse model, LDCF modeling
Mike Wolf, PE	Director, regulatory business development	Greenheck Fan Corp.	Regulatory communications

TABLE 1. The science and industry teams for AMCA’s LDCF research.

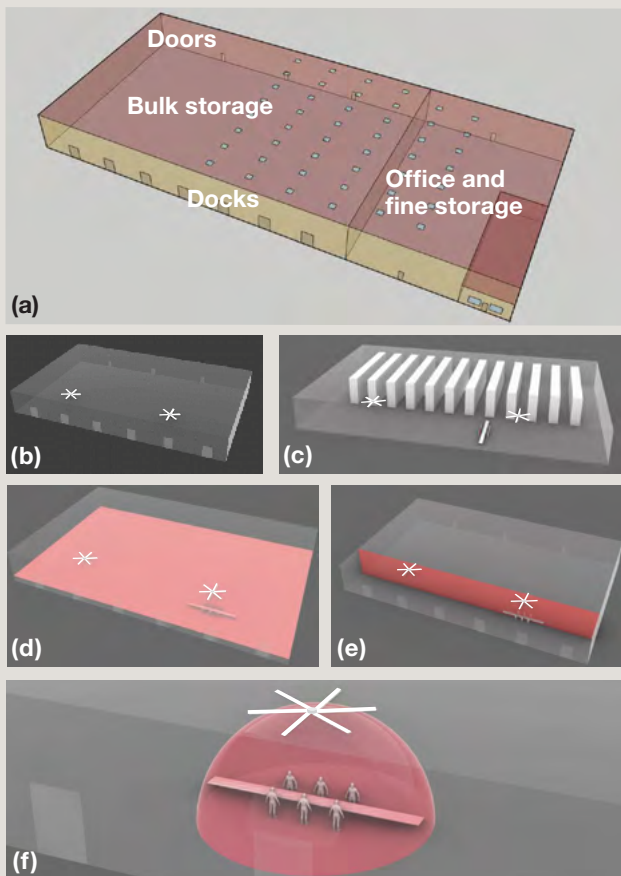


FIGURE 1. (a) DOE warehouse commercial reference building; (b) computational-fluid-dynamics (CFD) bulk-storage model with two LDCE; (c) CFD model with racks; (d) whole-warehouse-breathing-zone horizontal plane; (e) vertical plane; (f) working zone.

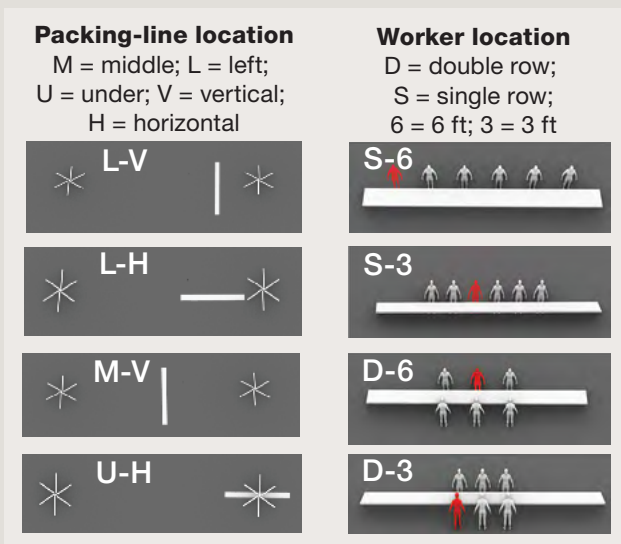


FIGURE 2. Parametric case scenarios. The person colored red is the infector.

at FS-3 and FS-0.6, circular high-speed regions form below the fans, with lower-speed cores directly under the fans. FS-3 has an air speed exiting the fan of 3.0 m/s (591 fpm), and most of the warehouse seems well-mixed, especially in the horizontal plane. FS-0.6 shows low speed at the horizontal breathing-zone plane everywhere except close to the fans, indicating less air mixing in the whole warehouse than with FS-3. When the fans are off, most air speed is less than 0.2 m/s (0.7 fps), and, aside from airflow through open doors and docks, the thermal plumes account for most of the local airflow from the worker group.

Conclusions

Based on 223 parametric CFD simulations—each with 14.6 million grids and an average of six hours of computing time for airflow calculations and eight hours for transient-particle models—the following major conclusions were reached:

- Of the options (speed, direction) for operating the fans, running the fans at the highest feasible speed to produce downward flow consistently yielded the best performance.
- Operating the fans at maximum speed generated high air speeds in occupied zones, which is not always practical, as it may cause thermal discomfort amid cold indoor conditions. Where lower air speeds are preferred, 3 m/s (10 fps) with reverse flow is a good option, though not as good as 3 m/s (10 fps) with downward flow.
- Reversing fans at high fan speed (e.g., 3 m/s [10 fps]) reduces performance compared with running fans at high fan speed with downward flow.
- Reversing fans at low fan speed (e.g., 0.6 m/s [2 fps]) may reduce whole-warehouse air speed and, thus, lower diluting effect, increasing the whole-warehouse concentration at the breathing zone.

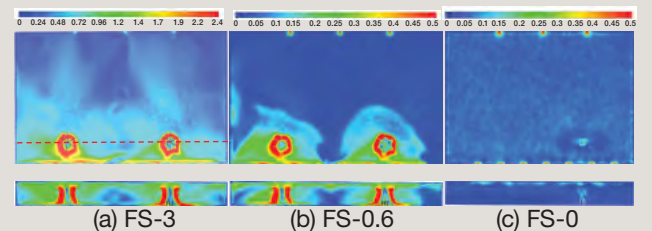


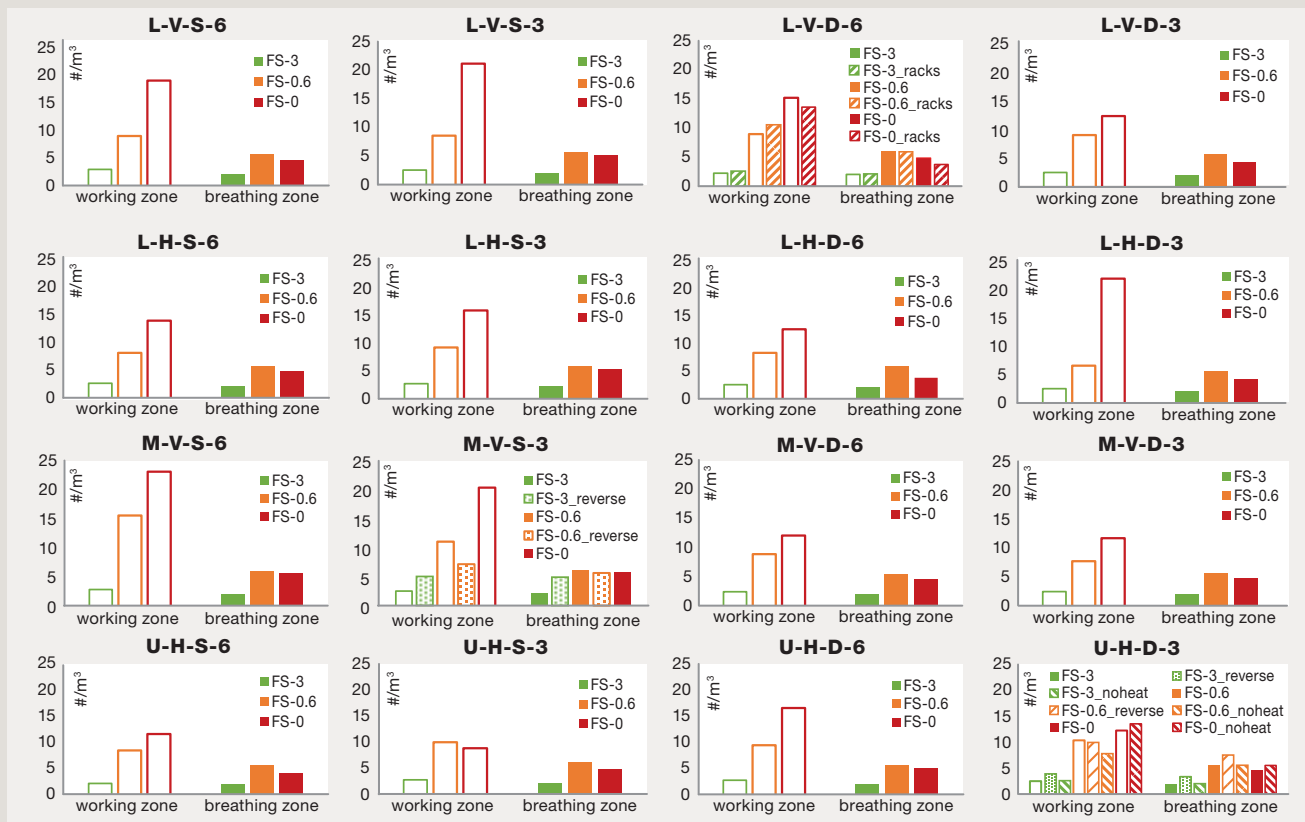
FIGURE 3. Steady-state airflow distribution for a selected case of U-H-D-3 at three fan speeds, meters per second. The dashed line is the location of the vertical plane.

Idealized thermal-plume assumptions had a substantial impact on results for the FS-0 cases. In the real world, occupant movement, passing traffic, and the like disrupt thermal plumes, making them less effective at transporting particles emitted by occupants to the upper region of a space. In other words, the FS-0 cases may underestimate particle concentrations in the region near occupants.

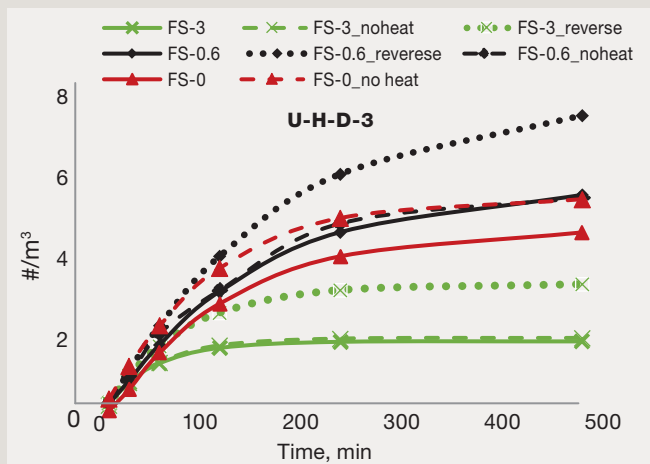
Both dilution and deposition were the major mechanisms by which high fan speeds reduced particle concentrations near occupants.

Figure 4a shows breathing-zone and working-zone concentrations for a variety of fan speeds and scenarios, with figures 4b and 4c focusing on U-H-D-3.

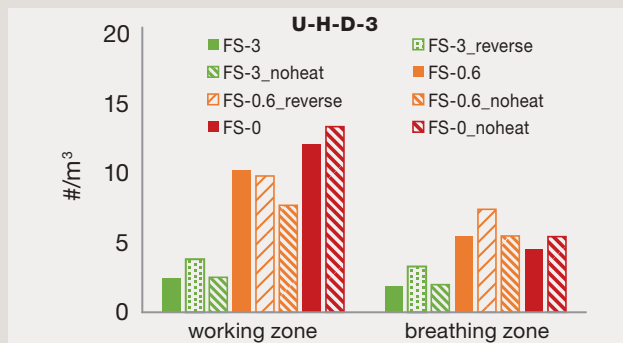
To better understand the impact of fan speed, the



(a)



(b)



(c)

Notes:

- Best case: FS-3 (green line) = full speed (3 m/s [10 fps]) in downward direction
- Worst case: FS-0.6 (black dotted line) = 20-percent speed (0.6 m/s [2 fps]) in upward direction

FIGURE 4. (a) Working-zone and whole-warehouse-breathing-zone concentrations at the end of eight hours; (b) transient concentrations; (c) concentrations at the eighth hour for U-H-D-3. “Noheat” indicates a simulation with thermal-buoyancy-driven flow disabled, while “reverse” indicates fan direction was reversed.

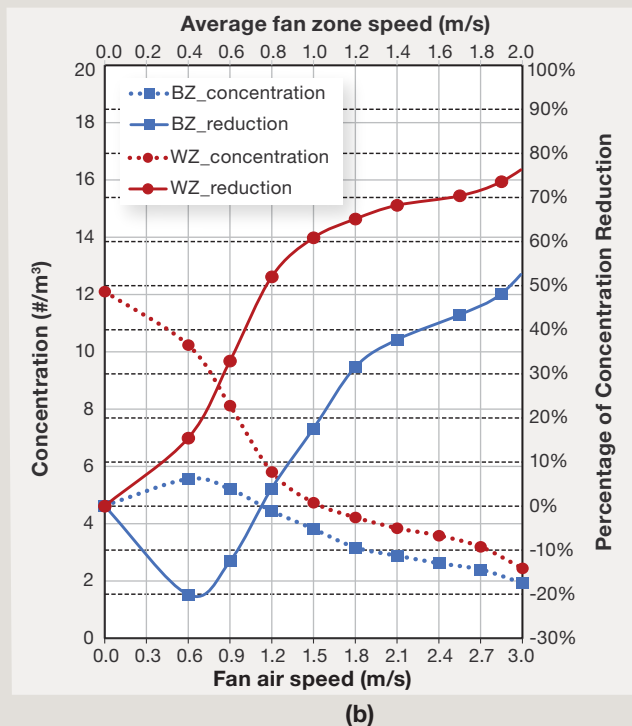
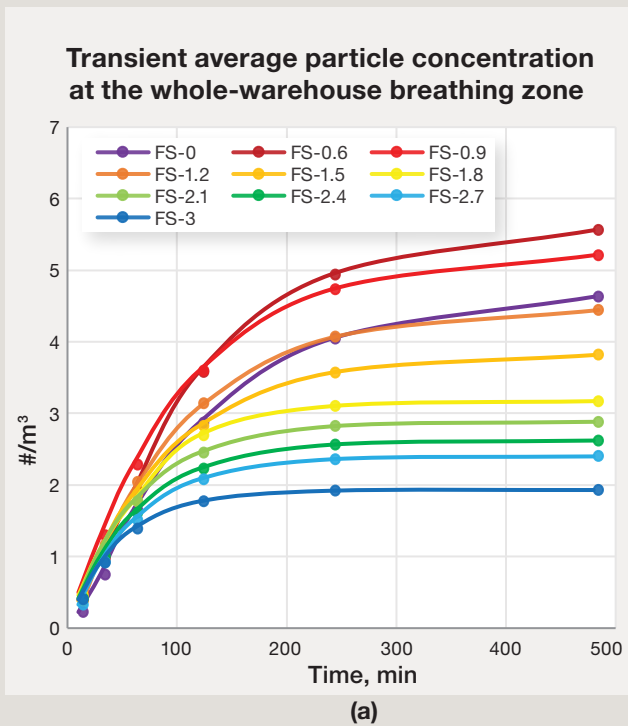
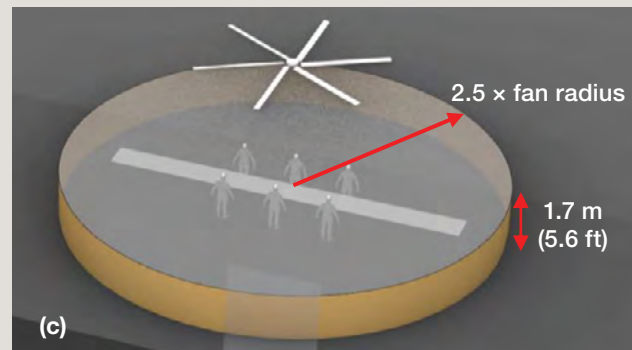


FIGURE 5. (a) Transient breathing-zone concentration, (b) eighth-hour breathing-zone and working-zone concentrations and relative concentration reduction (baseline: FS-0), and (c) the cylindrical shape of the “fan zone” (radius: $2.5 \times 3.05 \text{ m} = 7.6 \text{ m}$ [25 ft]) for the fan-velocity analysis of U-H-D-3.



researchers conducted simulations of the fan speeds 0.9 m/s (3.0 fps) (30-percent fan speed), 1.2 m/s (~4.0 fps) (40-percent fan speed), 1.5 m/s (5.0 fps) (50-percent fan speed), 1.8 m/s (6.0 fps) (60-percent fan speed), 2.1 m/s (7.0 fps) (70-percent fan speed), 2.4 m/s (8.0 fps) (80-percent fan speed), and 2.7 m/s (9.0 fps) (90-percent fan speed) (Figure 5). This modeling was limited to the U-H-D-3 arrangement.

Table 2 summarizes airflow characteristics of the modeled fans for a variety of speeds with the U-H-D-3 arrangement.

Guidance

Based on the preceding conclusions, the guidance in Table 3, which combines particle-concentration considerations with thermal-comfort constraints, was developed. It is intended primarily for building operators and other individuals with control over the operation of fans in large, sparsely occupied spaces.

Summary

Building operators and other individuals with control over the operation of fans in large, sparsely occupied spaces are encouraged, where feasible, to operate fans with doors and/or windows open, as they will increase ventilation airflow through the openings. Additionally, they are advised to avoid locating occupants immediately downstream of each other for extended periods and to operate fans at the highest feasible speed while maintaining occupant comfort. The simulations showed a notable reduction in concentration at high fan speeds (e.g., summer conditions) and only a slight reduction in concentration close to the fan (e.g., within two fan diameters), with no practical difference outside of that region, at low fan speeds.

Fan-speed label	Fan speed	Fan speed	Air speed exiting fan	Airflow exiting fan	Average air speed at side surface ¹	Average fan-zone ² air speed	Maximum air speed in fan zone
	(% max. rpm)	rpm	m/s (fpm)	m ³ /s (cfm)	m/s (fpm)	m/s (fpm)	m/s (fpm)
FS-0.6	20	16	0.6 (118)	18 (38,400)	0.2 (39)	0.4 (79)	1.0 (197)
FS-0.9	30	23	0.9 (177)	27 (57,600)	0.3 (59)	0.6 (118)	1.3 (256)
FS-1.2	40	31	1.2 (236)	36 (76,800)	0.4 (79)	0.8 (157)	1.7 (335)
FS-1.5	50	39	1.5 (295)	45 (96,000)	0.5 (98)	1.0 (197)	2.2 (433)
FS-1.8	60	47	1.8 (354)	54 (115,200)	0.6 (118)	1.2 (236)	2.5 (492)
FS-2.1	70	55	2.1 (413)	63 (134,400)	0.7 (138)	1.4 (276)	2.9 (571)
FS-2.4	80	62	2.4 (472)	72 (153,600)	0.8 (157)	1.7 (335)	3.4 (669)
FS-2.7	90	70	2.7 (531)	82 (172,800)	0.9 (177)	1.9 (374)	3.8 (748)
FS-3.0	100	78	3.0 (591)	91 (192,000)	1.0 (197)	2.1 (413)	4.4 (866)

¹The side of the cylinder of the fan zone colored by yellow in Figure 5c.

²A cylinder around the fan center at a height of 1.7 m (5.6 ft).

TABLE 2. Fan air speed and airflow rate in the fan zone for a case of U-H-D-3.

Location of most occupants	Summer	Winter
Close to the fan(s)	Operate the fan(s) downward at high speed.	Operate the fan(s) at the highest speed that does not cause discomfort in either forward or reverse direction, whichever was used prior to the pandemic. ¹
Far from the fan(s) ²	Operate the fan(s) downward at high speed.	Operate the fan(s) at the highest speed in either forward or reverse direction, whichever was used prior to the pandemic. ³

1 Simulations show slightly lower concentrations with reverse flow than with forward flow at a given low speed, but this is based on a much smaller number of simulated scenarios (two as opposed to the 16 for a typical forward-direction scenario) and is a small effect given simplifications and assumptions in the model. For simplicity, retaining the pre-pandemic direction is advised—unless reversing the fan allows for substantially higher fan speeds while avoiding draft at the occupied level.

2 At locations more than three fan diameters from the center of a fan the majority of the day.

3 Although simulations show a slight increase in average whole-warehouse-breathing-level concentration with fans at low speed as opposed to off, the distribution is far more uniform across the entire warehouse (i.e., no “hot spots”). Based on feedback from the science team, this homogeneity likely is a net advantage, as more mixing (i.e., dilution) is beneficial for times when workers who may be far apart for much of the workday meet and interact more closely. Lastly, the still-air results depend highly on model assumptions and simplifications (e.g., plume effectiveness, lack of local mixing, the presence of racks, etc.), and this small difference could be an artifact of those.

TABLE 3. AMCA LDCF guidance. Note: The green/yellow/red color coding is an approximate indicator of how clear the effect was in the simulations.

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