Airborne Infection Risk Calculator

User's Manual

Version 1.0

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DISCLAIMER

The Airborne Infection Risk Calculator (AIRC) is made available on an as-is basis without guarantee or warranty of any kind, express or implied. Neither the authors nor reviewers accept any liability resulting from the use of AIRC or its documentation. This is a preliminary decision-support tool that will be revised as the science surrounding airborne transmission of SARS-CoV-2 and other pathogens advances. **Implementation of AIRC and interpretation of its calculations are the sole responsibility of the user.**

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For additional information and resources on SARS-CoV-2 infection risk modeling, the authors refer readers to a modeling tool developed by Prof. Jimenez and available at:
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SECTION 1. INTRODUCTION

The Airborne Infection Risk Calculator (AIRC) is an airborne contagion modeling tool programmed in Microsoft Excel and designed to assist facility managers, building engineers, and public and occupational health professionals in prospectively evaluating individual infection and community transmission risks associated with specific indoor environments. AIRC can help users address two primary questions related to the risks associated with occupying an indoor space when community transmission of an infectious airborne pathogen, such as SARS-CoV-2, is occurring:

1. What is the potential infection risk associated with varying lengths of stay in the space?
2. What number of occupants helps maintain a basic reproduction number (R_0) less than one to prevent the exposure from further contributing to disease spread in the population?

AIRC is directly based on the novel risk modeling approach developed for SARS-CoV-2 by Buonanno et al. (2020a) and Buonanno et al. (2020b). As stated by Buonanno et al. (2020a):

"This approach, based on the principle of conservation of mass, represents a tool to connect the medical area, concerned with the concentration of the virus in the mouth, to the engineering area, dedicated to the simulation of the virus dispersion in the environment."

While AIRC and its underlying methods were created in direct response to the SARS-CoV-2 pandemic, the hope is that AIRC becomes a useful risk management tool for other airborne pathogens such as influenza, tuberculosis, and rhinovirus. The foundation for AIRC was provided by quantification of the quanta emission rate data of SARS-CoV-2 as a function of different respiratory activities, respiratory parameters, and activity levels. A quantum is the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons (Buonanno et al., 2020a). AIRC applies this quanta emission rate in an acknowledged infection risk model to simulate the individual infection risk associated with customized exposure scenarios, and the average number of infected people resulting from this scenario, i.e. R_0 (the basic reproduction number).

AIRC calculates individual infection risks and design occupancies for up to eight hours of total exposure under the following conditions:

- One infectious individual entering and leaving an indoor space at specified times,
- Two infectious individuals entering and leaving an indoor space at different or overlapping times,
- One exposed susceptible individual entering and leaving the indoor space at specified times,
- Exposed susceptible individuals occupying the indoor space for the entire duration of the model (up to eight hours),
- The viral emission rate for each infectious individual, and the inhalation rate for susceptible individuals, can be selected based on a list of activities, and
- The user can specify the dimensions of the occupied indoor space and an infectious viral removal rate term accounting for three mechanisms: particle deposition, viral inactivation, and site-specific ventilation rate.

Data input and results presentation were simplified to facilitate ease of use by non-quantitative professionals, while also providing some flexibility for more advanced users.

Limitations

The primarily limitation of AIRC is its adoption of a completely mixed box model approach to simplify extremely complex indoor fluid dynamics processes. The result of this simplification is a viral exposure concentration that is uniform across the room, instead of a three-dimensional, spatially variable plume with higher exposure concentrations closer to the source of the viral emissions. Additional limitations include the adoption of uniform values representing particle deposition and viral inactivation rates that do not vary according to site-specific environmental conditions, and the maximum simulation length of 8 hours. Secondary engineering and administrative controls, such as air filtration, UV disinfection, and mask-wearing, are not explicitly included in AIRC, but more advanced users can adjust input parameters to account for these interventions. Additional discussion of AIRC concepts and their limitations are provided in Section II, with specifics surrounding the useful scale of AIRC applications. Lastly, a major epidemiological limitation is the requirement to specify the number of infectious occupants in a space (limited to two) and their constant emissions-generating activity, rather than adopting a probabilistic approach taking into considering the overall prevalence of the virus in the community and the likelihood of infectious person occupancy times and activities. Additionally, the selected dose-response model does not consider variation in host sensitivity to the pathogen of interest, for example immunity from prior exposure or vaccination.

It is reiterated that AIRC is a risk screening tool that approximates more complicated processes occurring in reality. As such, conservative assumptions should be used for input parameters, with attention given to the all-important quanta emission rate, where conservatively high 85th percentile values are recommended for use. AIRC is a preliminary decision-support tool that will be revised as the science surrounding airborne transmission of SARS-CoV-2 and other pathogens advances. More sophisticated numerical models should be applied for situations where high-resolution, spatially representative results are required, or where needed for detailed design of secondary engineering controls in high-risk, complex settings. For CFD examples, see Vuorinen et al. (2020), Hosotani et al. (2013), and Chen et al. (2012).

Target Users

The target users of AIRC are building managers, engineering consultants, and public, occupational, and environmental health scientists. Users should be proficient in Microsoft Excel and have a basic understanding of building systems and indoor air quality. Users would also benefit from a basic understanding of human health risk assessment (see https://www.epa.gov/risk/conducting-human-health-risk-assessment for an overview). More generally, the target users are the technical professionals working to minimize the risk of airborne disease transmission by implementing the five-step framework outlined by Morawska et al. (2020):

1. Use engineering controls to reduce the risk of airborne infection;
2. Use existing systems to increase ventilation rates (outdoor air change rate) and enhance ventilation effectiveness;
3. Eliminate air-recirculation within ventilation systems so as to just supply fresh (outdoor) air;
4. Supplement ventilation with filtration systems to capture airborne microdroplets; and
5. Avoid over-crowding

SECTION II: AIRC CONCEPTUAL MODEL

To understand the airborne transmission pathway, it is helpful to advance the conceptual model presented in Morawska and Cao (2020), Morawska (2006), and Li et al. (2005). For purposes of AIRC, "airborne transmission" refers to inhalation of airborne droplet nuclei, or aerosols, at separation distances that can be greater than 2 meters away from an infectious emission. This conceptual model represents the concentration of virus-laden small droplets as a plume, where expired viral content is diluted immediately upon expiration and as it travels in the air carried by the air flow. As a result, the concentration of the virus does not increase uniformly in the interior environment of the enclosed space but is found at higher concentrations closer to the infectious subject.

Unfortunately, due to the complexity of indoor computational fluid dynamics (CFD), modeling this spatiotemporal plume presents a challenge to the broader public and occupational health community. As with other environmental contaminants in air and water, it is helpful instead to simplify the spatial component of fate and transport and use a completely mixed box model approach for risk calculation purposes. AIRC adopts this completely mixed box modeling approach, directly following the process outlined in Buonanno et al. (2020a) and Buonanno et al. (2020b). The emission of virus-laden small droplets is assumed to be instantaneously and completely mixed into a box representing an enclosed indoor environment or room, creating a time-dependent exposure concentration to susceptible occupants inside the box.

A conceptual representation of airborne transport and the box-model simplification for AIRC is presented as Figure 1 on the following page.

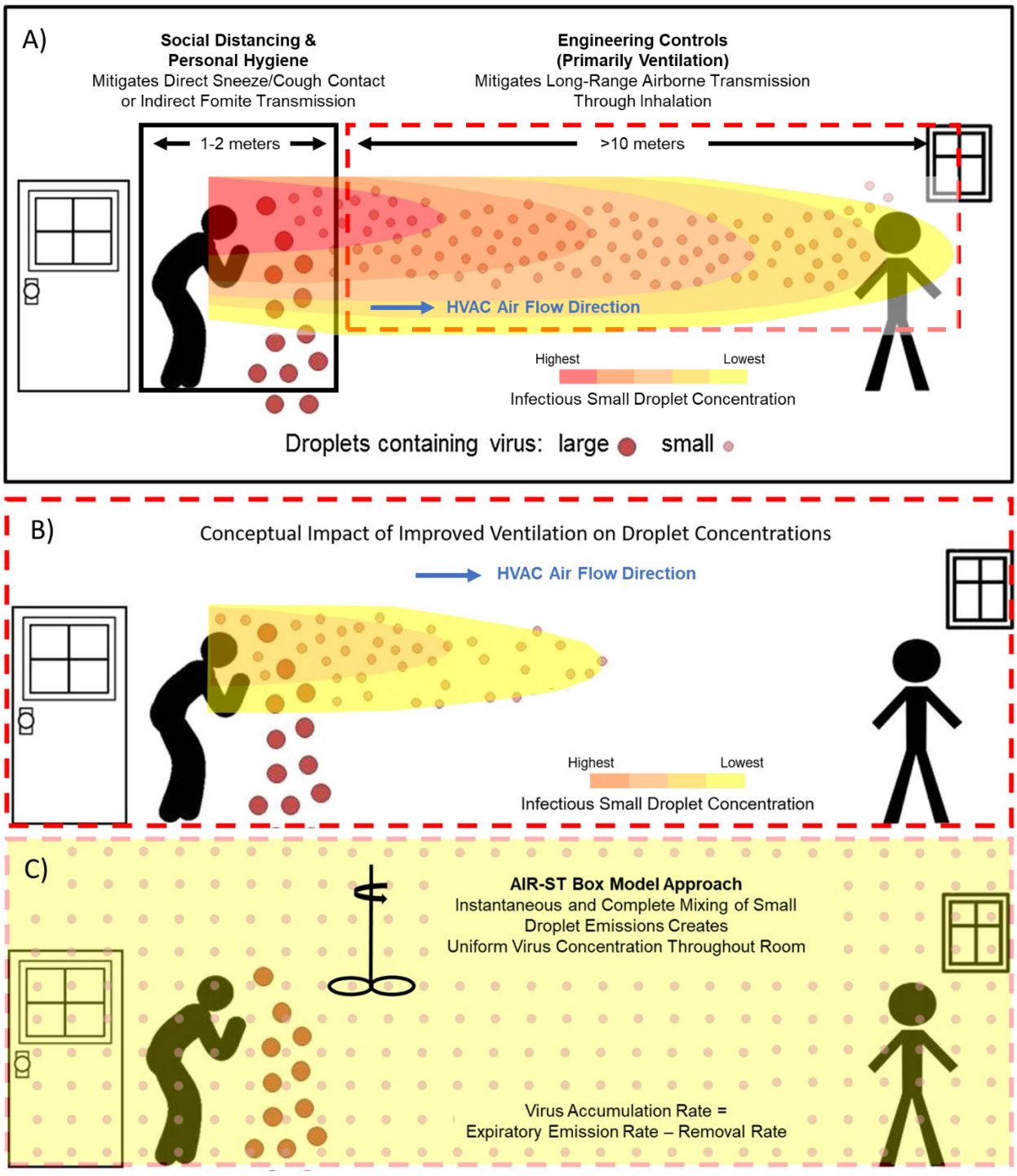


Figure 1: Conceptual Diagrams of Small Droplet Transport and AIRC Box Model Approach Modified from Morawska and Cao (2020)

Figure 1 (A) illustrates the creation of an infectious droplet plume extending far beyond the "social distancing" range of 1-2 meters. Concentrations are higher closer to the emission source and decay moving further away and will reach a pseudo steady-state profile in time if conditions are held approximately constant. Figure 1 (B) shows the conceptual effect of increasing the ventilation rate in

the room. The plume is reduced in intensity and extent, and the susceptible occupant is exposed to lower viral concentrations and consequentially has reduced infection risk. Figure 1 (C) illustrates adoption of the box model approach used by AIRC, where the concentration in time becomes uniform across the room, and susceptible individuals are therefore exposed to the same concentration regardless of their position in the room. Differences in exposure risk between susceptible occupants in the room is therefore reduced to a function of exposure duration rather than spatial location.

With the box model simplification, it becomes straightforward for AIRC to calculate changes in room concentration over time. Depending on the strength and duration of the emission rate and the ventilation rate in the room, the viral droplet concentration profile versus time will assume a predictable curve shape. Three common concentration curves are presented in Figure 2.

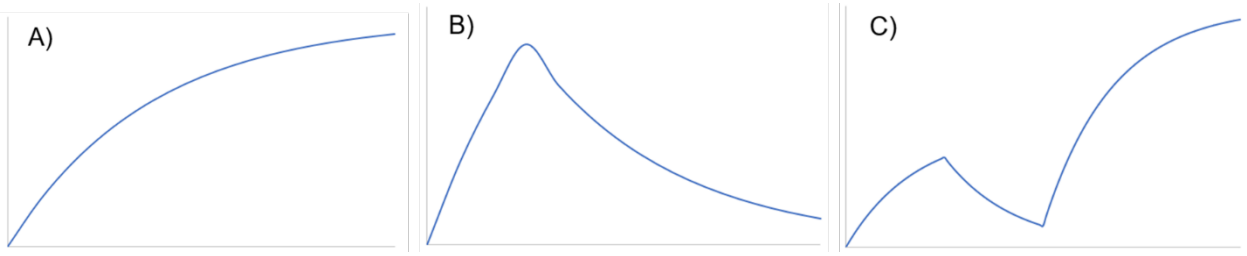


Figure 2: Common concentration versus time curves for different contaminant source scenarios on a linear scale, based on concept presented in NEEC (2015). Figure 2 (A) represents the concentration profile in a room with a constant emission source and constant ventilation rate, showing how the concentration approaches a steady-state asymptote. Figure 2 (B) presents a scenario where the same emission is eliminated and concentrations decay accordingly due to constant ventilation. Figure 2 (C) shows a more dynamic scenario where there are two separate, non-overlapping emission periods, with the second period resulting in higher concentration either due to a higher emission rate or a lower ventilation rate.

With its simplifying assumptions, the accuracy and utility of AIRC becomes a question of scale. In general, the smaller the enclosed space and the more completely mixed the air, the more the results will approximate reality. An upper limit to the appropriate room size for AIRC cannot be definitively provided at this time, but applications to indoor spaces that are thousands of square meters in area with complex HVAC zoning are unlikely to produce useful risk predictions. Alternatively, a room of approximately 500 square meters or less comprising a single HVAC zone is more likely to be a good candidate for AIRC application. A practical way to accommodate larger buildings or spaces with complex zoning is to divide the area into sub-zones, each represented by an AIRC model. The process is conceptually illustrated in Figure 3, which depicts a multi-zone modeling approach to characterize the March 2003 outbreak of SARS-CoV-1 in Ward 8A at the Prince of Wales Hospital in Hong Kong (Li et al., 2005 and Xiao et al., 2017).

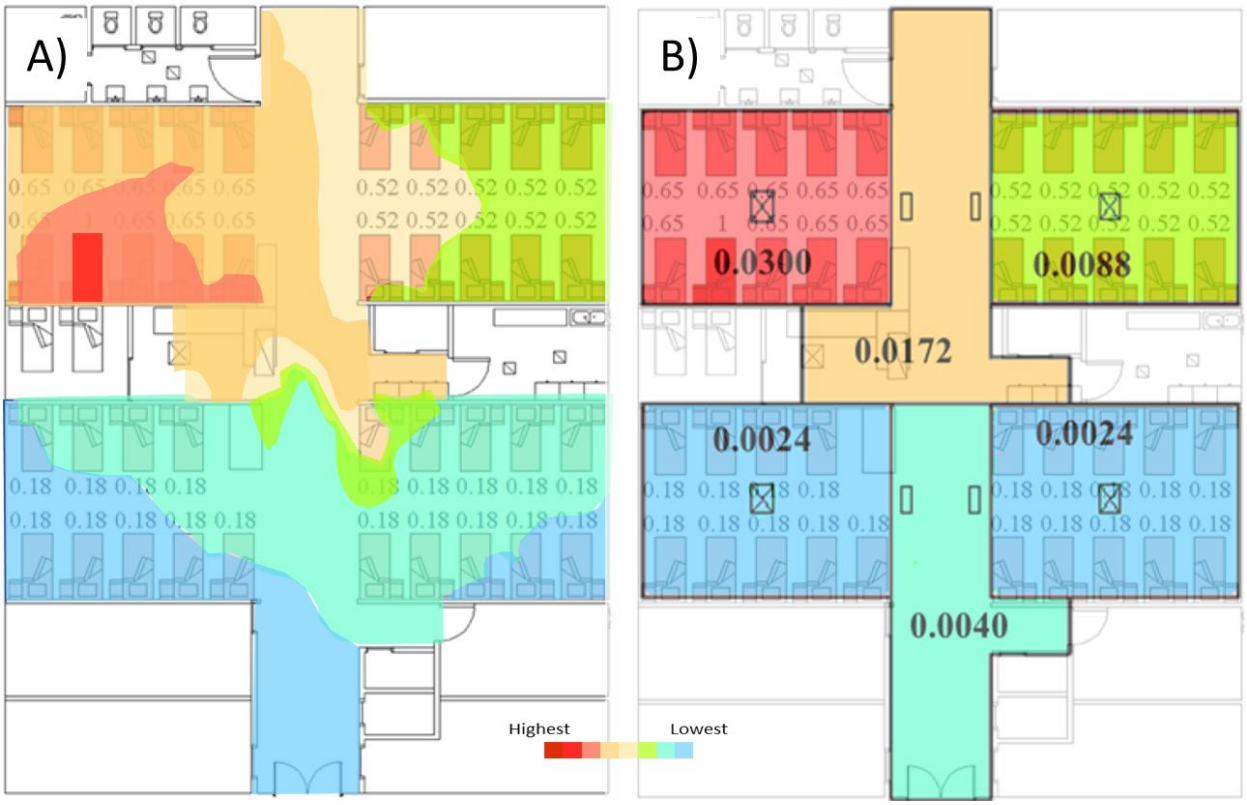


Figure 3: Simulated infectious aerosol distribution using a complex CFD model (A) and a simplified multi-zone approach (B), modified from Xiao et al., 2017. Predicted aerosol concentrations for each approach are overlaid on top of the reported SARS-CoV-1 attack rate in the zone. The index patient was located in the top left zone.

Figure 3 (A) presents a more realistic spatial representation of aerosol distribution, characterized by a plume emanating from the index patient. However, the multi-zone approach on Figure 3 (B) is likely sufficient to calculate infection risk, especially where conservative assumptions are used. Wagner et al. (2009) takes a similar approach by implementing a Sequential Box Model (SBM) that incorporates air exchange between zones.

Retrospective assessments of the AIRC risk modeling approach are provided in Buonanno et al. (2020b), simulating the outbreaks of SARS-CoV-2 at a restaurant in Guangzhou, China and a choir rehearsal in Skagit, WA, USA. The ability of the AIRC approach to reasonably reproduce these airborne "superspreading events" indicate its validity for risk screening purposes, especially when considering the urgent and time-critical need for quantitative tools to inform decision making during the SARS-CoV-2 pandemic. Furthermore, as noted in Buonanno et al. (2020a), in epidemic modeling quantifying community transmission, it is impossible to specify the geometries, the ventilation, and the locations of all infectious sources in each microenvironment. Therefore, adopting the completely mixed box model approach is generally more reasonable than hypothesizing about myriad complex environments because results must be interpreted on a statistical basis (Sze To and Chao, 2010).

SECTION III: THE INFECTION RISK MODEL

The detailed modeling approach implemented in AIRC and described in this section directly follows from Buonanno et al. (2020a) and Buonanno et al. (2020b).

The model used to quantify airborne infection risk in AIRC was developed by Gammaitoni and Nucci (Gammaitoni and Nucci, 1997), and was successfully applied in previous papers estimating the infection risk due to different diseases (e.g. influenza, SARS, tuberculosis, rhinovirus) in various settings such as airplanes (Wagner et al., 2009), cars (Knibbs et al., 2011), and hospitals. The model calculates the quanta concentration (n) in an indoor environment over time, subject to a constant quanta emissions rate and removal rate. As a reminder, a quantum is the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons (Buonanno et al., 2020a). The full equation for n(t), including an initial concentration term (n_0), is presented below:

$$n(t)\ (\frac{quanta}{m^3}) = n_0 e^{-IVRR \cdot t} + \frac{ER_q \cdot I}{IVRR \cdot V}(1 - e^{-IVRR \cdot t})$$

where IVRR (hr^{-1}) represents the total infectious viral removal rate, I is the number of infectious subjects, V is the volume of the indoor air environment, and ER_q is the abovementioned quanta emission rate (quanta/hr) characteristic of the specific disease/virus under investigation. The IVRR term is the sum of three contributions, all expressed in hr^{-1}: the air exchange rate (AER) via ventilation (also commonly termed the number of air changes per hour), the particle deposition rate on surfaces (k, e.g. via gravitational settling), and the viral inactivation rate (λ) (Yang and Marr, 2011). Details on specification of these three parameters are provided in Section IV.

In addition to the constant ER_q and IVRR values, it is assumed that the latent period of the disease is longer than the time scale of the model, and the droplets are instantaneously and evenly distributed in the room, using the box model approach described in Section II (Gammaitoni and Nucci, 1997). Once again, the latter represents a key assumption for the application of the model as it considers that the air is well-mixed within the modelled space. The risk associated with an exposure is dependent on the dose of quanta and duration of exposure, as well as the probability of occurrence of this exposure condition. The dose of quanta (D_q) received by a susceptible subject can be obtained by integrating the calculated quanta concentration over the total exposure time (T), as follows:

$$D_q\ (quanta) = IR \int_0^T n(t)dt$$

where IR is the inhalation rate of the exposed subject (m^3/hr) which is a function of the subject's activity level. To determine the probability of infection (P_I, %) of exposed susceptible occupants, a simplified exponential dose-response model is used. Lastly, the individual infection risk experienced by an exposed subject can be simply calculated as the product of the probability of infection (P_I, %) and the probability of occurrence (P_P, %) of such a value. These two equations are presented below:

$$P_I\ (\%) = 1 - e^{-D_q}$$

$$R\ (\%) = P_I \cdot P_P$$

While Buonanno et al. (2020b) evaluated this probability of occurrence using a Monte Carlo simulation approach, for purposes of the simplified AIRC screening tool, a uniform probability of occurrence of 15% is assumed on the basis that the 85th percentile of the quanta emission rate (ER_q) is used in the model. The 85th percentile value was selected because Monte Carlo simulations for a range of exposure scenarios indicate that the maximum individual risk value occurs within a narrow range of 84th-90th percentile values. Therefore, AIRC conservatively attempts to estimate the maximum individual risk for an exposed individual. However, the user should consider that the problem of estimating respiratory emissions is inherently probabilistic, and that AIRC only presents one possible realization.

On a population level, the basic reproduction number R_0, representing the number of susceptible people infected after the exposure time, can be determined by multiplying the probability of infection (P_I, %) by the number of exposed individuals. For purposes of AIRC, however, reproductive effects are calculated differently to provide the maximum number of occupants that may keep the R_0 below 1 for the scenario in question. In this way the user can obtain a potential occupancy or crowding index that considers the need to reduce community transmission. It is critical for the user to note that in AIRC this occupancy is calculated for a specific exposure scenario up to a maximum of 8 hours (480 minutes). If this exposure scenario is expected to occur repeatedly, such as daily, the user may want to reduce the calculated occupancy further as R_0 would be expected to exceed 1 over time.

This maximum occupancy calculation uses the following equation, rounded down to the nearest integer:

$$Max.Occupants\ for\ R_0(t) < 1 = \frac{1}{P_I(t)}$$

SECTION IV: AIRC DATA ENTRY & RESULTS

There are two tabs for the user to enter data in AIRC, the first tab entitled "Input and Results", and the second tab entitled "ERq IR Selector". For both sheets the user must enter a value into all cells with white fill and black text. All cells with black fill and white text are calculated by AIRC and are locked to the user. Cells with gray fill are informational and are not used by AIRC. In addition, drop-down lists are used on both tabs to include the second infectious occupant and to select the desired activities for infectious and susceptible occupants. Based on the assumption that users are most concerned with SARS-CoV-2, quanta emission rates associated with the selected activities are for SARS-CoV-2.

A description of each data input field is provided below, with recommended values.

1. Room Dimensions

The room dimension parameters for the user to enter are the floor plan area (in m^2) and the ceiling height of the occupied indoor space to be modeled (in m). The product of the area and ceiling height is the room volume (m^3).

2. Infectious Viral Removal Rate

As defined in Section III, the Infectious Viral Removal Rate (IVRR) is the sum of the air exchange rate (AER) via ventilation (also termed the number of air changes per hour), the particle deposition rate on surfaces (k, e.g. via gravitational settling), and the viral inactivation rate (λ). Entry details on these three parameters are presented below.

Parameter	Air Exchange Rate (AER)
Units	hour (hr^{-1})
Recommended Values	Use site-specific measured values, or design or estimated values if field measurements are unavailable. For natural ventilation (infiltration only), values of 0.2 – 0.5 hr^{-1} are recommended. For the opening of doors and windows on one side of a room, values of 1.0 – 5.0 hr^{-1} are suggested. It is noted that ventilation rates through windows are highly site-specific and the user is cautioned against making assumptions on the higher end of this provided range.
Notes/Estimation Methods	The AER is the most important site-specific parameter in the model and the largest contributor to virus removal. Therefore, site-specific measurements or design values are the best sources for parameter input. AER can be simply calculated as the total fresh outdoor airflow (OA) divided by the volume of the room. Recirculated airflow should not be included in the AER calculation as it represents fresh airflow only.

If actual total and outdoor airflows cannot be measured directly, the percent OA delivered to a space is commonly estimated using air handler carbon dioxide (CO_2) concentrations in parts per million (ppm) as follows:

$$\%\ \mathrm{OA} = \frac{CO_2\ \text{Return Air} - CO_2\ \text{Mixed Air}}{CO_2\ \text{Return Air} - CO_2\ \text{Outside Air}}$$

Note that the above calculation is also routinely performed using temperatures instead of CO_2 concentrations, but that it is less accurate, especially when temperature differences are small. Another common method of estimating ventilation rate is using "rule of thumb" values per person based on steady-state CO_2 concentrations achieved in offices and classrooms with ASHRAE 62n default occupancy rates, as follows (NEEC, 2015):

Zone CO_2 (ppm)	Outside Air (CFM per person)	Outside Air (Liters (L)/s per person)	Outside Air (m^3/hr per person)
2,500	5	2.4	8.5
1,400	10	4.7	17
1,000	15	6.9	25
750	30	14	51

AIRC follows the risk minimization framework outlined by Morawska et al. (2020), in which enhanced ventilation is the primary reliable and readily available line of defense against airborne transmission in indoor air environments. Secondary measures where ventilation alone may be insufficient, such as enhanced filtration, ultraviolet germicidal irradiation (UVGI), and/or room humidification, are not explicitly included in AIRC. Advanced users of AIRC can include filtration in the model by adding "equivalent" air exchanges to the AER term.

Azimi and Stephens (2013) provide a comprehensive review of infectious droplet nuclei filtration efficiencies (see Figure 4). To incorporate filtration removal in AIRC, the user can calculate the equivalent AER in hr^{-1} as follows:

$$AER_{filtration}\ (hr^{-1}) = \frac{Q_{recirculated} \bullet \eta_{filter}}{\mathrm{V}}$$

where $Q_{recirculated}$ is the airflow rate recirculated from the space through the filter, η_{filter} is the infectious droplet removal efficiency of the filter, and V is the volume of the room.

	The recirculated airflow plus the fresh outdoor airflow will equal the total airflow rate of the air handler. Remember that the air exchange rate is calculated using only the fresh outdoor airflow rate, and if air is recirculated the AER will be reduced. Example Application 3 presents how this calculation is performed for an air handler serving an office space.

Parameter	Particle Deposition Rate (k) (SARS-CoV-2)
Units	hr^{-1}
Recommended Value	0.24
Notes/Estimation Methods	The recommended value is from Buonanno et al. (2020a), which calculated the deposition rate as the ratio between the settling velocity of super-micrometric particles (roughly 1.0×10^{-4} m s^{-1} as measured by Chatoutsidou and Lazaridis [2019]) and the height of the emission source (1.5 m). A site-specific computational fluid dynamics (CFD) model may be needed to quantify this parameter more accurately.

Parameter	Viral Inactivation Rate (λ) (SARS-CoV-2)
Units	hr^{-1}
Recommended Value	0.63
Notes/Estimation Methods	The recommended viral inactivation rate is calculated from the SARS-CoV-2 half-life (1.1 hr) detected by van Doremalen et al. (2020) as follows: $$\lambda\ (hr^{-1}) = \frac{0.693}{t_{1/2}}$$ Users should follow the evolving literature on SARS-CoV-2 with a view towards refinement of this parameter. Fears et al. (2020) reports retained infectivity and virion integrity of SARS-CoV-2 for up to 16 hours in respirable-sized aerosols. For a resource to help incorporate UV treatment or relative humidity into this parameter, the user is referred to: https://www.dhs.gov/science-and-technology/sars-airborne-calculator (Schuit et al., 2020).

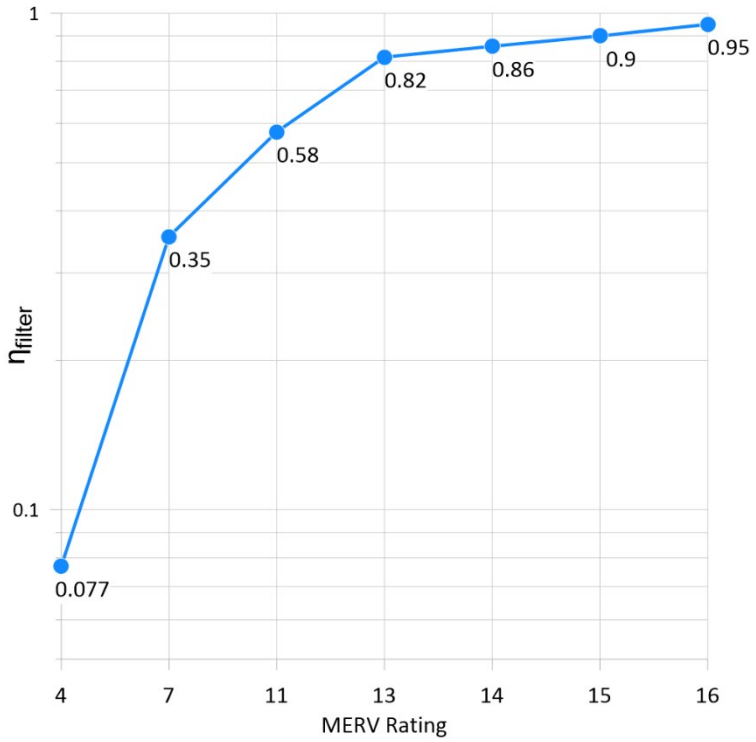


Figure 4: Infectious droplet nuclei filtration efficiency (η_{filter}) as a function of HVAC filter MERV rating, using the minimum reported values from Azimi and Stephens (2013).

3. Initial Quanta Concentration

The initial quanta concentration term, in quanta/m^3, has been provided in the event the user wants to model a scenario where residual viral emissions are present in indoor air at time zero. This is a useful function where the user wants to begin a new simulation using the final quanta concentration of a previous simulation. Example Application 4 (Night Office Cleaning) presents how the initial quanta concentration parameter can be used. If the indoor air environment is expected to be free of airborne virus at the start of the simulation, the user should enter zero for this parameter.

4. Total Time of Occupancy

The total time of occupancy, in minutes, represents the maximum duration of continuous occupancy of the modeled room by any person. The maximum simulation length supported by AIRC is 480 minutes (8 hours), therefore, the maximum value for this parameter is 480. This parameter must be entered as an integer value. AIRC calculates the continuous occupancy risk and maximum room occupancy based on the total time of occupancy entered by the user. The total time of occupancy value entered by the user should be greater than the time of exit values for Infectious Occupant #1, Infectious Occupant #2, and Susceptible Occupant A.

5. Exposure Scenario

In the Exposure Scenario data entry section, the user enters the time of entry and time of exit for two infectious occupants and one susceptible occupant. All times are to be entered in minutes and represent minutes after the start of the simulation. Infectious Occupant #2 can be omitted from the model by selecting “No” from the drop-down list next to the “Include in Model?” field. The values for

quanta emission rate (ER_q) for each infectious occupant, and the value for inhalation rate (IR) for the susceptible occupant are pulled from the “ERq IR Selector” Tab, described below.

ER_q IR Selector Tab

This tab is used to select ER_q and IR rates for the model in quanta/hr and m^3/hr, respectively. Two reference value tables are provided, one for infectious occupant quanta emission rates, and one for susceptible occupant inhalation rates. As with the “Include in Model?” field on the “Input and Results” tab, the user must select the representative activity for each occupant using a drop-down list beneath the “Select Activity Below” fields. If Infectious Occupant #2 is not included in the model as indicated on the "Input and Results" tab, its drop-down list will be greyed out and no entry is required. If the user would like to use a custom value for Er_q, the user should select “Custom Emission Rate” for the activity and then enter the value in the SARS-CoV-2 ER_q table, and a value for the associated probability of occurrence of that emission rate. If a custom emission rate is selected for Infectious Occupant #1, this rate will also apply to Infectious Occupant #2 if included in the model.

All provided values of ER_q in the lookup tables are specific to the SARS-CoV-2 virus and represent the 85^{th} percentile value of a lognormally distributed data set (base 10), as reported in Buonanno et al. (2020a). The 85^{th} percentile value is provided because the total individual exposure risk is expected to be at its maximum value at this approximate percentile, with a probability of occurrence of 15% (Buonanno et al., 2020b). All values of IR for the susceptible occupant are also provided from Buonanno et al. (2020a). As with ER_q, a custom entry option is provided for IR for advanced users, and different IR values can be specified for Susceptible Occupant A and a continuous occupant of the space.

For reference, AIRC also calculates the exposure scenario infection risks and maximum room occupancies for the following pathogens other than SARS-CoV-2: measles, influenza, tuberculosis and rhinovirus. These calculations assume the exact same input parameters except for the quanta emission rates (ER_q) and associated probabilities of occurrence, which can be specified by the user on the Ref Disease Tables tab. For the non-SARS pathogens, the same emission rate is used for Infectious Occupant #1 and Infectious Occupant #2. A range of literature values for ER_q for different pathogens is presented in Figure 5, alongside the range of SARS-CoV-2 values reported in Buonanno et al. (2020b). Quanta emission rates used in similar risk modeling analyses are presented in Table 1 and Table 2, the latter for tuberculosis only.

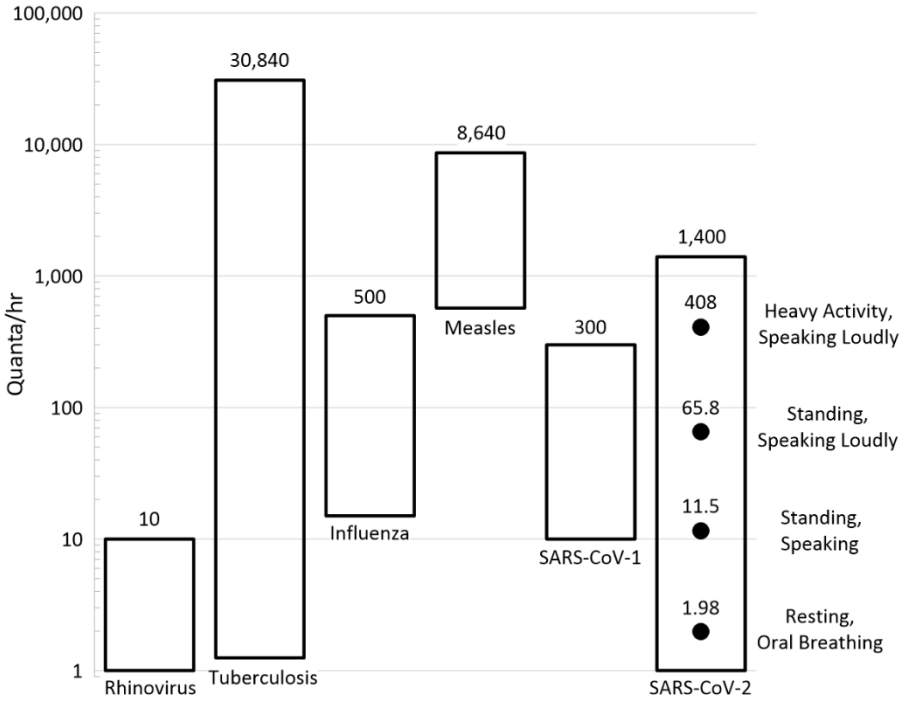


Figure 5: Range of published quanta emission rates for six pathogens. Ranges for rhinovirus, influenza, and SARS-CoV-1 from Azimi and Stephens (2013). Range for tuberculosis from Riley et al. (1962) and Gammaitoni and Nucci (1997), and range for measles from Riley et al. (1978) and Remington et al. (1985). For SARS-CoV-2, the 85th percentile values for different activities are presented for comparison from Buonanno et al. (2020b).

Table 1: Quanta Emission Rates from Published Risk Modeling Studies

Pathogen	Assumed or Estimated Er_q (Quanta/hr)	Modeling Application	Reference
Rhinovirus	5.0	Household Spread of Respiratory Viruses	Myatt et al. (2008), after Rudnick and Milton (2003)
Influenza	67	Derived Emission Rate from School Influenza Surveillance Reports	Liao et al. (2005)
	100	Assessing Filtration in a Hypothetical Office Building	Azimi and Stephens (2013)
	50-128	Assessment of Airborne Influenza Transmission on an Airplane	Wagner et al. (2009), after Rudnick and Milton (2003)
Measles	5,600 (Index Case) 570 (Average Case)	Measles Epidemic in an Elementary School	Riley et al. (1978)
	8,640	Airborne Transmission in a Physician's Office	Remington et al. (1985)
SARS-CoV-1	29	Airborne SARS-CoV-1 Infection in a School and Hospital	Liao et al. (2005)
SARS-CoV-2	61	Guangzhou Restaurant Superspreading Event	Buonanno et al. (2020b)
	970	Skagit Valley Chorale Superspreading Event	Miller et al. (2020)

Table 2: Tuberculosis Quanta Emission Rates from Published Risk Modeling Studies

Calculated ER_q (Quanta/hr)	Modeling Application	Controlled Experiment with Guinea Pigs as Susceptibles	Reference
1.25	TB patient on treatment	x	Riley et al. (1962)
1.8 – 226 (average of 37)	Drug susceptible and MDR-TB, HIV co-infected patient	x	Escombe et al. (2008)
12.7	Untreated TB case causing outbreak in an office		Nardell et al. (1991)
34	MDR-TB, mixed HIV status, masks worn	x	Dharmadhikari et al. (2012)
60	Laryngeal case of TB	x	Riley et al. (1962)
138	MDR-TB, mixed HIV status, no mask use	x	Dharmadhikari et al. (2012)
250	Bronchoscopy-related outbreak		Nardell et al. (1991)
360	Bronchoscopy-related outbreak		Gammaitoni & Nucci (1997)
2,280	Outbreak related to jet-irrigation of an abscess		Gammaitoni & Nucci (1997)
5,400	Autopsy outbreak		Gammaitoni & Nucci (1997)
30,840	Intubation-related outbreak		Gammaitoni & Nucci (1997)

Notes:

1) Modeling application descriptions and overall table concept based on Internal Clinical Guidelines Team (UK) (2016)
2) TB: Tuberculosis; MDR-TB: Multidrug-Resistant Tuberculosis; HIV: Human Immunodeficiency Virus

As shown in Figure 5, the quanta emission rate for SARS-CoV-2 is highly variable depending on the emitting activity of the infectious individual. The emissions rate for oral breathing at rest is comparable to the reported range for Rhinovirus, whereas the emissions rate for speaking loudly during heavy activity (for example, singing), falls within the range of the highly infectious measles virus. This may explain why SARS-CoV-2 superspreading events have been reported at nightclubs, choir practices and other settings where people are speaking loudly or singing at high activity levels in enclosed spaces. For a common asymptomatic person activity (standing and speaking loudly), infectiousness appears comparable to influenza. On a population level, Dai and Zhao (2020) estimated the quantum generation rate of SARS-CoV-2 at 14-48 per hour using a reproductive number-based curve fitting approach. This approximately corresponds to an activity level of standing and speaking. Dai and Zhao (2020) also report an ER_q range of 6-140 quanta/hr for Middle East Respiratory Syndrome (MERS) virus, but the original source of this estimate could not be verified. To derive an independent estimate of ER_q for MERS and other viruses, AIRC can be used as an inverse model to back-calculate the quantum generation rate for a known airborne transmission scenario with a measured attack rate. Example

Application #6 illustrates this process for an experiment involving a simulated live-poultry market slaughter.

With respect to mask wearing, Wood et al. (2018) found that at 2 meters from the source, both surgical and N95 masks reduced aerosols containing viable *Pseudomonas aeruginosa* in the droplet nuclei size range by over 90% during voluntary coughing in people with Cystic Fibrosis. The findings were consistent with Driessche et al. (2015), which found an 86% reduction in environmental detection of airborne *Pseudomonas aeruginosa* concentration during mask wearing compared with the reference group (coughing without a surgical mask) in a controlled laboratory model. While mask wearing therefore has the potential to be a highly effective measure reducing the quanta emission rate of an infectious subject, masks may be worn improperly or intermittently in indoor environments. Therefore, the user is advised against using custom quanta emission rates where the provided 85th percentile values are significantly reduced to account for mask wearing.

The Institute for Health Metrics and Evaluation (IHME) at the University of Washington performed a meta-analysis of peer-reviewed scientific studies and medRxiv pre-prints to assess mask efficacy, the results of which suggest a reduction in infection for mask wearers by at least one-third (33%) compared to control groups (IHME, 2020). Therefore, reducing the calculated risk value by a factor of 33% or less to account for effective mask wearing of both infectious and susceptible occupants may be a reasonably defensible approach.

6. Results

The results section reports calculated risk values of interest for Susceptible Occupant A and for susceptible persons who occupy the space for the entirety of the simulation (i.e. the total time of occupancy parameter). The following values are reported:

- Modeled Exposure Time: For Susceptible Occupant A this will be the time of exit minus the time of entry in minutes. For continuous occupants this will be equal to the total time of occupancy parameter.
- Individual Infection Risk: The individual infection risk, R (%), represents an estimate of the percent chance of individual infection for exposure to the quanta concentration profile integrated across the modeled exposure time.
- Exposure Time for 0.1% Risk: This value is the exposure time in minutes associated with a 0.1% chance of infection, or a risk threshold of 10^{-3}. If the exposure time is less than this value, risk is estimated to be less than 0.1%, and vice versa. The quanta concentration profile for Susceptible Occupant A will be different from that of the continuous occupants; hence, calculated exposure times may be different. If Susceptible Occupant A or the continuous occupants do not exceed the 0.1% risk threshold during the simulation, AIRC presents a result of greater than (“>”) the modeled exposure time. If a user enters extreme value parameters such as a very high ER_q combined with a very small room volume, a #N/A value may result, meaning that the risk threshold is already exceeded at the first time step of 1 minute.
- Exposure Time for 1% Risk: This value has the same characteristics as the above parameter but uses a higher risk threshold of 1% (or 10^{-2}). The calculated exposure time for 1% risk will be higher than that of 0.1% risk. The decision of what threshold to use for risk management purposes is up to the user and should depend on the type of occupancy and characteristics of

the inhabitants and should appreciate the screening-level intent of the tool. Calculated exposure times associated with other risk thresholds can be evaluated on the Model Graph.

- Maximum Room Occupancy for $R_0 < 1$: This parameter represents the maximum number of occupants allowable in the room for the exposure time and quanta concentration profile of the designated scenario (e.g. Susceptible Person A or continuous occupancy) in order to keep the basic reproduction number (R_0) below 1 for that exposure. In other words, more than one person may be expected to become infected if the occupancy increases beyond this number. Conceptually this is easier to understand for the continuous occupancy calculation as it represents the allowable number of occupants who will be present for the entire simulation. For Susceptible Occupant A, the maximum room occupancy calculation applies to a cohort of persons sharing the same exact exposure profile as Susceptible Occupant A (i.e. entering and leaving at the same time). Example Application 3 (Open Office) illustrates this concept. If a user is interested in the calculated R_0 value for a pre-determined number of occupants, it can be obtained by dividing the pre-determined occupancy by the maximum room occupancy calculated by AIRC (see Example Application 1 for this process). It is reiterated that the maximum room occupancy is for a specific exposure scenario up to a maximum of 8 hours (480 minutes). If this exposure scenario is expected to occur repeatedly, such as daily, the user may want to reduce the calculated occupancy further as R_0 would be expected to exceed 1 over time. As the reproduction number scales linearly with occupancy, reducing the AIRC calculated occupancy by one-half corresponds to an estimated R_0 of 0.5.

7. Model Graph

To help the user visualize how model calculations change in time based on the entered parameters, a graph of model results is presented including the following data series:

- The calculated quanta concentration in the room in quanta/m^3;
- The individual infection risk for Susceptible Occupant A;
- The individual infection risk for a person continuously occupying the space; and
- The calculated maximum occupancy to maintain $R_0 < 1$ for continuous occupants of the space (e.g. the number of occupants allowable for a cohort entering at time zero).

As the user may create scenarios of varying time scales, two graphs are provided: one limited to 120 minutes and the second displaying results for the maximum 480 minutes. The graphs are the same and two versions are only provided to facilitate data visualization for times of interest.

8. Ref Disease Tables & Graph

The “Ref Disease Tables” and “Ref Disease Graph” tabs in AIRC summarize the results of the exposure scenario modeling using quanta emission rates for the four other common infectious airborne diseases (measles, influenza, tuberculosis and rhinovirus) instead of SARS-CoV-2. On the “Ref Disease Tables” tab, the user can input any quanta emission rate with an associated probability of occurrence for each disease. Individual exposure risks, exposure time thresholds, and maximum cohort occupancies for Susceptible Occupant A and a continuous occupant are also presented on the “Ref Disease Tables” tab. Infection risk graphs for continuous occupancy are presented on the “Ref Disease Graph” tabs. These graphics are provided to establish a frame of reference for the model results and facilitate use of AIRC

for other established airborne contagions. The user can also adjust the ER_q values for the reference diseases to create a deterministic sensitivity analysis for his or her original simulation, as all other parameters remain the same. As the non-SARS simulations use the same emission rate for Infectious Occupants #1 and #2, the slope of the graphs may be different from that of SARS-CoV-2.

9. Calculations

With a goal of transparency, the Calculations tab of AIRC allows users to see the Excel formulas used to implement the infection risk model described in Section III. Users can click on individual cells to see formulas and cell references and can adjust formatting if a time step is of interest. The implementation approach is straightforward, and the formulas can be copied and pasted into a different spreadsheet program as needed.

SECTION V: EXAMPLE APPLICATIONS

Seven example applications are described and illustrated below to assist the user in the process of creating a conceptual exposure model, entering input data, and visualizing and interpreting results.

1. Classroom

Scenario Description: This application represents a typical classroom that relies on natural ventilation (AER = 0.5 hr^{-1}). It is a cold winter day so windows cannot be readily opened. The classroom size is modeled at 46.5 m^2 (500 square feet) with a ceiling height of 3 m. The school day is modeled to be a shortened day from 9:00 AM until 3:00 PM, with a two-hour break in the middle of the day (11:00 AM to 1:00 PM). One student is assumed to be infected with SARS-CoV-2, but this same student is modeled as both Infectious Occupant #1 and Infectious Occupant #2 to account for the break. Susceptible Occupant A represents a teacher's assistant who only works between 1:00 PM and 3:00 PM. The selected activity for the quanta emission rate is resting for the morning session and loudly speaking for the afternoon, and susceptible occupants are assumed to be resting for the inhalation rate.

AIRC Screenshots:

Airborne Infection Risk Calculator — *Version 1.0* — **AIRC**

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	A	46.5	(m^2)
Ceiling Height	h	3	(m)
Room Volume	V	140	(m^3)

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	AER	0.5	(hr^{-1})
Particle Deposition Rate	k	0.24	(hr^{-1})
Viral Inactivation Rate	λ	0.63	(hr^{-1})
Total Viral Removal Rate	IVRR	1.4	(hr^{-1})

3. INITIAL QUANTA CONCENTRATION

n_0 0.0E+0 ($quanta/m^3$)

4. TOTAL TIME OF OCCUPANCY

Time t 360 (minutes)

5. EXPOSURE SCENARIO

Infectious Occupant #1		
Time of Entry	0	(minutes)
Time of Exit	120	(minutes)
ER_q from Selector Tab	9.49	(quanta/hr)
Infectious Occupant #2		
Include in Model?	Yes	← Select
Time of Entry	240	(minutes)
Time of Exit	360	(minutes)
ER_q from Selector Tab	61.1	(quanta/hr)
Susceptible Occupant A		
Time of Entry	240	(minutes)
Time of Exit	360	(minutes)
IR from Selector Tab	0.49	(m^3/hr)

6. RESULTS

Susceptible Occupant A

Modeled Exposure Time (minutes) =	120
Individual Infection Risk (%) =	2.82%
Exposure Time for 0.1% Risk (minutes) =	14
Exposure Time for 1% Risk (minutes) =	57
Maximum Room Occupancy for $R_0 < 1$ =	5

Continuous Occupancy

Modeled Exposure Time (minutes) =	360
Individual Infection Risk (%) =	3.39%
Exposure Time for 0.1% Risk (minutes) =	43
Exposure Time for 1% Risk (minutes) =	268
Maximum Room Occupancy for $R_0 < 1$ =	4

Quanta Emission Rate (ER_q) and Inhalation Rate (IR) Selector

SARS-CoV-2 ER_q (85^{th} Percentile Values)

Activity	ER_q (Quanta/hr)
Resting, Oral Breathing	1.98
Resting, Speaking	9.49
Resting, Loudly Speaking	61.1
Standing, Oral Breathing	2.32
Standing, Speaking	11.5
Standing, Loudly Speaking	65.8
Light Exercise, Oral Breathing	5.7
Light Exercise, Speaking	26.5
Light Exercise, Loudly Speaking	170
Heavy Exercise, Oral Breathing	13.3
Heavy Exercise, Speaking	63.7
Heavy Exercise, Loudly Speaking	408
Custom Emission Rate	970
Custom Probability of Emission	100%

(enter as percentage: 50 for 50%)

Inhalation Rate

Activity	IR (m^3/hr)
Resting	0.49
Standing	0.54
Light Exercise	1.38
Heavy Exercise	3.3
Custom Inhalation Rate	2.00

Quanta Emission Rate (ER_q) Selection

Infectious Person	Select Activity Below	ER_q (Quanta/hr)
Infectious Occupant #1	Resting, Speaking	9.49
Infectious Occupant #2	Resting, Loudly Speaking	61.1

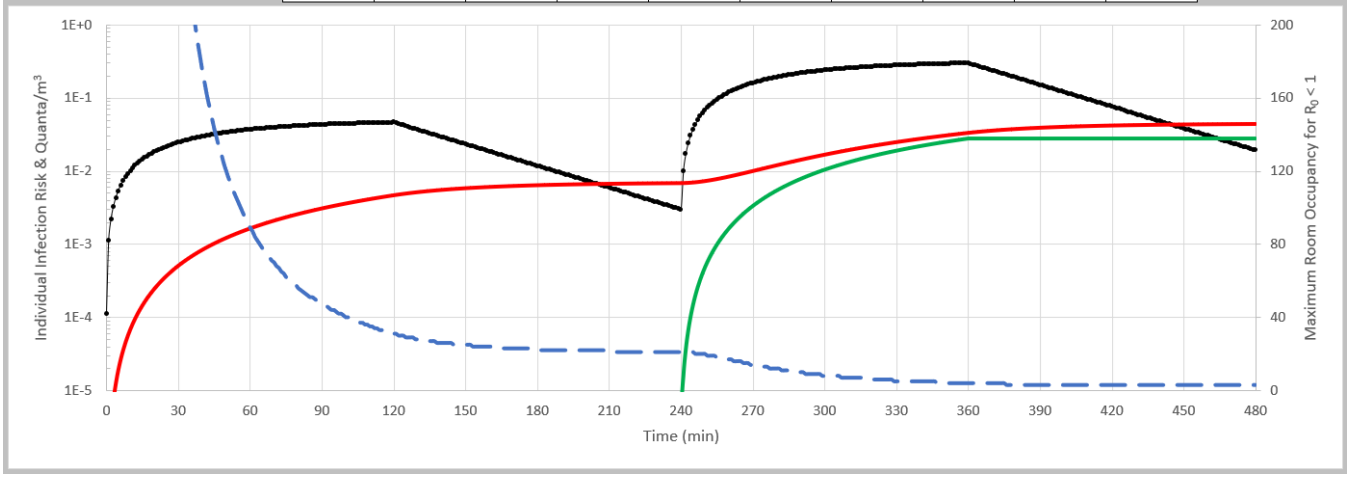
Inhalation Rate (IR) Selection

Susceptible Person	Select Activity Below	IR (m^3/hr)
Susceptible Occupant A	Resting	0.49
Continuous Occupant	Resting	0.49

Instructions:
1) Select the representative activity for Infectious Occupant #1, Infectious Occupant #2, Susceptible Occupant A, and Continuous Occupant for use in the model by clicking in the activity drop-down list cells highlighted in yellow.
2) If you would like to input your own value for ER_q, enter Custom Emission Rate and Custom Probability of Emission values in the SARS-CoV-2 Erq table and select Custom Emission Rate from the drop-down list for Infectious Occupant #1. This custom emission rate will apply to Infectious Occupant #2 if included in the model.
3) If you would like to input your own value for IR, enter the Custom Inhalation Rate value in the Inhalation Rate table, and select Custom Inhalation Rate from the drop-down list.

Model Results: Quanta Concentration, Individual Infection Risk, and Maximum Room Occupancy for $R_0 < 1$

Time (min)	120	160	200	240	280	320	360	400	440	480
Quanta Concentration	4.6E-02	1.9E-02	7.5E-03	3.0E-03	1.9E-01	2.7E-01	3.0E-01	1.2E-01	4.8E-02	1.9E-02
Occupant A Risk (%)	0.00%	0.00%	0.00%	0.00%	0.55%	1.63%	2.82%	2.82%	2.82%	2.82%
Continuous Risk (%)	0.48%	0.62%	0.67%	0.70%	1.22%	2.25%	3.39%	4.10%	4.38%	4.48%
Occupancy for $R_0 < 1$	31	24	22	21	12	6	4	3	3	3



Discussion: The model results indicate a poorly ventilated classroom presents a relatively high risk of infection, at over 3% for students and a full-day teacher, and slightly below 3% for the afternoon assistant. The design occupancy to keep R_0 below 1 for the full day is only 4 (or 3 students plus 1 teacher). For a densely packed classroom with a typical occupancy of 25 students and 1 teacher, the calculated R_0 for the full-day exposure is 6.5 (calculated as the typical occupancy [26] divided by the calculated $R_0 = 1$ occupancy of 4). The model graph shows the impact of the break with the declining quanta concentration between 120 and 240 minutes; however, the quanta concentration quickly rebounds in the afternoon.

The beneficial impact of substantially improved ventilation can be assessed by increasing the AER an order of magnitude to 5 hr^{-1}. This reduces the full-day individual risk of infection to approximately 1.1% and increases the $R_0 = 1$ occupancy to 13, or approximately half of the typical occupancy. It is noted that this occupancy is for a single day of exposure and further reductions in occupancy, or additional engineering controls, may be warranted if similar daily exposures are expected.

The user can perform multiple model runs varying one or more parameters to create powerful graphs with results normalized per occupant. This enables comparison of ventilation rates and occupancies across different rooms or buildings by quickly scaling the normalized model results. For example, for the classroom scenario, the AER was varied between 0.5 and 10 hr^{-1}, and the resulting ventilation rate per student and required classroom area to maintain $R_0 < 1$ were plotted against the AER to generate the graph presented in Figure 6. The results of this analysis indicate that a ventilation rate above approximately 15 L/s (32 CFM) per student is needed to reduce individual infection risk below 1% for this one-day exposure, and that the required classroom area at this ventilation rate is approximately 3 m^2 (32 square feet)/student to maintain $R_0 < 1$. For reference, this ventilation rate is approximately twice the ASHRAE recommendation of 6.7 to 7.4 L/s per person, depending on the student's age, but is between the European EN 13779 standards of 12.5 L/s per person and 20 L/s per person corresponding to medium and high air quality, respectively (Stabile et al., 2015). The value of 32 CFM is also similar to a conceptual threshold value of 35 CFM per occupant reported by Nardell et al. (1991) in a retrospective

study of a tuberculosis outbreak, above which there are diminished risk reduction returns to additional ventilation. These values may be refined for different exposure scenarios most representative of the classroom in question, and different acceptable risk thresholds.

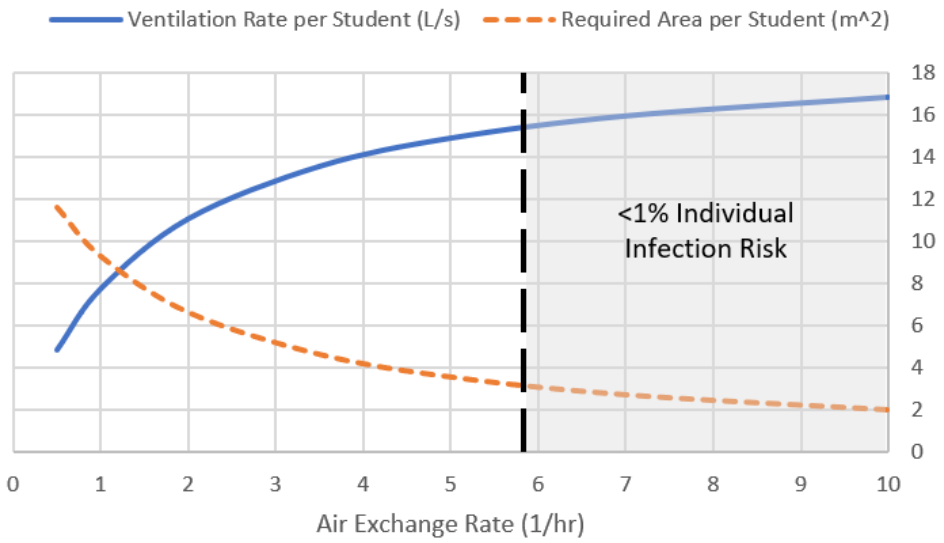


Figure 6: Classroom Ventilation Rates and Required Area per Student

2. Subway

Scenario Description: This application represents a typical subway commute in a modern subway car with an advanced ventilation system. The subway car is assumed to be 18.4 meters long by 2.9 meters wide (53.5 m^2 (575 square feet)) with a ceiling height of 2.4 m. The maximum fresh air delivery rate for each car is approximately 1,055 CFM (1,792 m^3/hr), which provides a maximum AER of 14. The entire one-way route of the subway line lasts approximately one hour, so a 60-minute total time of occupancy is specified. Infectious Occupant #1 is assumed to board the subway at the beginning of the route and leave after 30 minutes, with an activity level of standing and talking. Infectious Occupant #2 is assumed to board the subway after 30 minutes and stay for 15 minutes while talking loudly. Susceptible Occupant A enters and leaves with Infectious Occupant #2 and is standing.

AIRC Screenshots (on following page):

Airborne Infection Risk Calculator — AIRC

Version 1.0

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	A	53.5	(m^2)
Ceiling Height	h	2.4	(m)
Room Volume	V	128	(m^3)

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	AER	14.0	(hr^{-1})
Particle Deposition Rate	k	0.24	(hr^{-1})
Viral Inactivation Rate	λ	0.63	(hr^{-1})
Total Viral Removal Rate	$IVRR$	14.9	(hr^{-1})

3. INITIAL QUANTA CONCENTRATION

n_0 0.0E+0 $(quanta/m^3)$

4. TOTAL TIME OF OCCUPANCY

Time t 60 *(minutes)*

5. EXPOSURE SCENARIO

Infectious Occupant #1		
Time of Entry	0	*(minutes)*
Time of Exit	30	*(minutes)*
ER_q from Selector Tab	11.5	*(quanta/hr)*
Infectious Occupant #2		
Include in Model?	Yes	← *Select*
Time of Entry	30	*(minutes)*
Time of Exit	45	*(minutes)*
ER_q from Selector Tab	65.8	*(quanta/hr)*
Susceptible Occupant A		
Time of Entry	30	*(minutes)*
Time of Exit	45	*(minutes)*
IR from Selector Tab	0.54	(m^3/hr)

6. RESULTS

Susceptible Occupant A		
Modeled Exposure Time (minutes)	=	15
Individual Infection Risk (%)	=	0.06%
Exposure Time for 0.1% Risk (minutes)	=	>15
Exposure Time for 1% Risk (minutes)	=	>15
Maximum Room Occupancy for $R_0 < 1$	=	262
Continuous Occupancy		
Modeled Exposure Time (minutes)	=	60
Individual Infection Risk (%)	=	0.09%
Exposure Time for 0.1% Risk (minutes)	=	>60
Exposure Time for 1% Risk (minutes)	=	>60
Maximum Room Occupancy for $R_0 < 1$	=	160

Quanta Emission Rate (ER_q) and Inhalation Rate (IR) Selector

SARS-CoV-2 ER_q (85^{th} Percentile Values)

Activity	ER_q (Quanta/hr)
Resting, Oral Breathing	1.98
Resting, Speaking	9.49
Resting, Loudly Speaking	61.1
Standing, Oral Breathing	2.32
Standing, Speaking	11.5
Standing, Loudly Speaking	65.8
Light Exercise, Oral Breathing	5.7
Light Exercise, Speaking	26.5
Light Exercise, Loudly Speaking	170
Heavy Exercise, Oral Breathing	13.3
Heavy Exercise, Speaking	63.7
Heavy Exercise, Loudly Speaking	408
Custom Emission Rate	970
Custom Probability of Emission	100%

(enter as percentage: 50 for 50%)

Inhalation Rate

Activity	IR (m^3/hr)
Resting	0.49
Standing	0.54
Light Exercise	1.38
Heavy Exercise	3.3
Custom Inhalation Rate	2.00

Quanta Emission Rate (ER_q) Selection

Infectious Person	Select Activity Below	ER_q (Quanta/hr)
Infectious Occupant #1	Standing, Speaking	11.5
Infectious Occupant #2	Standing, Loudly Speaking	65.8

Inhalation Rate (IR) Selection

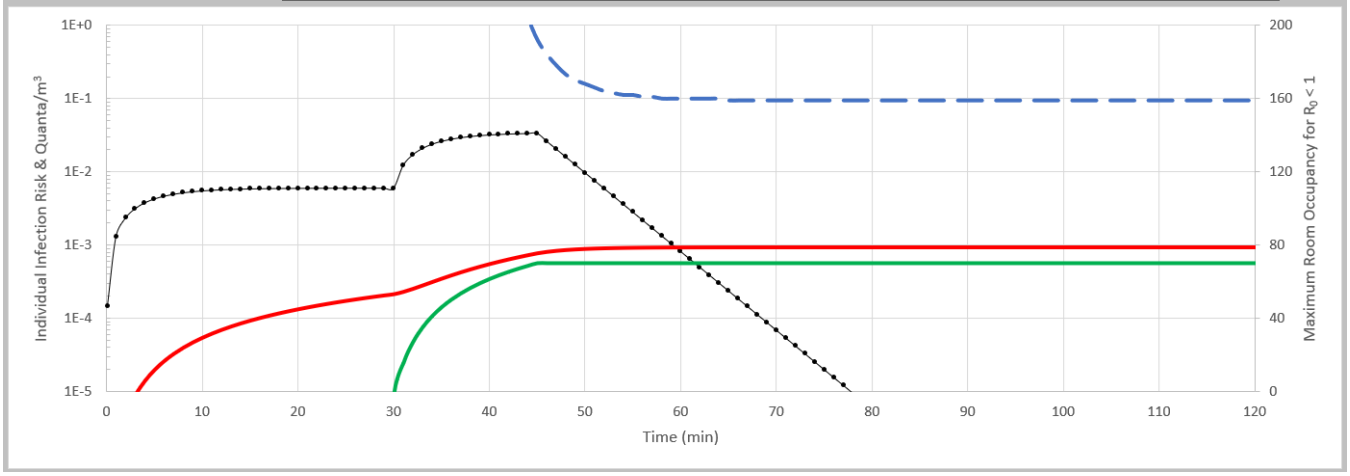
Susceptible Person	Select Activity Below	IR (m^3/hr)
Susceptible Occupant A	Standing	0.54
Continuous Occupant	Standing	0.54

Instructions:

1) Select the representative activity for Infectious Occupant #1, Infectious Occupant #2, Susceptible Occupant A, and Continuous Occupant for use in the model by clicking in the activity drop-down list cells highlighted in yellow.
2) If you would like to input your own value for ER_q, enter Custom Emission Rate and Custom Probability of Emission values in the SARS-CoV-2 Erq table and select Custom Emission Rate from the drop-down list for Infectious Occupant #1. This custom emission rate will apply to Infectious Occupant #2 if included in the model.
3) If you would like to input your own value for IR, enter the Custom Inhalation Rate value in the Inhalation Rate table, and select Custom Inhalation Rate from the drop-down list.

Model Results: Quanta Concentration, Individual Infection Risk, and Maximum Room Occupancy for $R_0 < 1$

Time (min)	20	30	40	50	60	70	80	90	100	110	120
Quanta Concentration	6.0E-03	6.0E-03	3.2E-02	9.8E-03	8.2E-04	6.9E-05	5.8E-06	4.8E-07	4.1E-08	3.4E-09	2.9E-10
Occupant A Risk (%)	0.00%	0.00%	0.03%	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%
Continuous Risk (%)	0.01%	0.02%	0.06%	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%	0.09%
Occupancy for $R_0 < 1$	1122	698	270	168	160	159	159	159	159	159	159



Discussion: The model results indicate the risks of subway travel with a modern ventilation system may present a comparatively lower risk to individuals for airborne infection than a full day in a poorly-ventilated classroom for the two scenarios evaluated herein. A susceptible passenger who rides the entire subway line (60 minutes) experiences an individual infection risk of 0.09%, and the continuous subway car occupancy to keep R_0 below 1 is calculated to be 162, which is comparable to the design passenger occupancy of 190. However, the user must consider how many such 60-minute scenarios may occur over the course of a week, and how that would increase reproductive effects. If the AER were to drop an order of magnitude due to mechanical failure or maintenance issues, this individual 60-minute trip risk would increase to 0.39% and the risk for the 15-minute susceptible rider would also increase over the 0.1% threshold. This example illustrates the potential of ventilation to reduce the risk of SARS-CoV-2 infection to manageable levels. This risk of subway travel calculated by AIRC may not be as high as what one would expect; however, the finding is consistent with a modeling study by Cooley et al. (2011), which estimated that only 4% of community transmissions would occur on the New York City subway amidst an influenza outbreak with the characteristics of the 1957–1958 pandemic. As a reminder, AIRC only considers airborne transmission, and the direct contact pathway should also be considered when evaluating high occupant density situations.

The AER can be varied as part of a sensitivity analysis to create risk and maximum occupancy curves versus ventilation rate. In this case the goal may be to optimize ventilation and evaluate when the point of diminished returns has been reached. Figure 7 presents the results of the analysis for the peak occupancy period of the ride between 30 and 45 minutes and shows that there is diminished incremental benefit of increasing the AER above 9 hr^{-1}. At this AER, the subway car can be filled to its capacity of 190 passengers without exceeding an R_0 of 1, and the individual risk has already been reduced below 0.1% with a slower rate of decrease with further increases in AER. As with the classroom example, the calculated AER threshold can be applied to other subway cars of similar geometry but older vintage to see where ventilation improvements may be necessary.

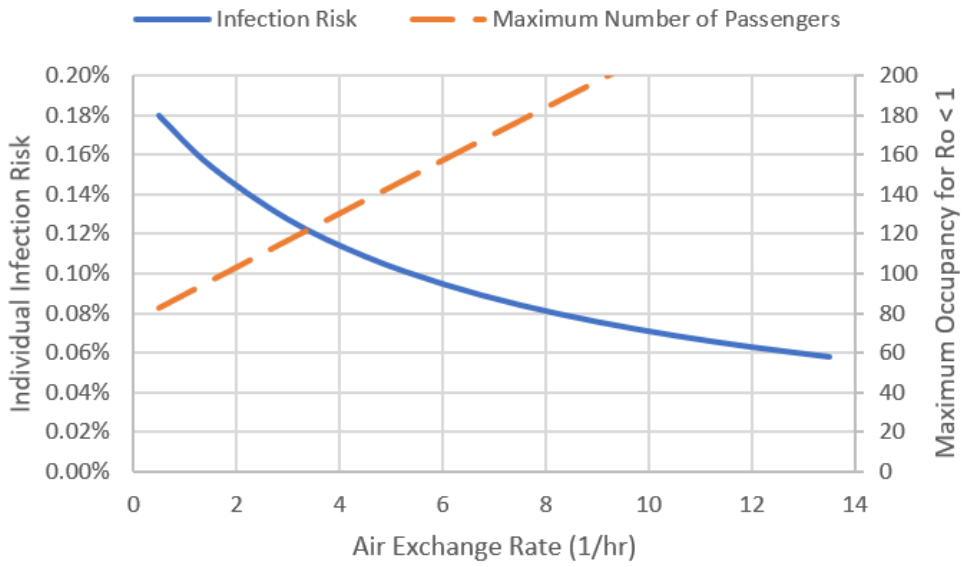


Figure 7: Individual Infection Risk and Maximum Number of Passengers for 15-Minute Subway Ride

3. Open Office

Scenario Description: This application represents a typical office space with cubicles placed in a large, common open area. The office is assumed to be 664 square meters in size (7,145 square feet) with a ceiling height of 2.6 m. The measured fresh air delivery rate from the air handler serving the space is approximately 1,700 m^3/hr (1,000 CFM), which provides an AER of 1. The outdoor air damper is open 100%, meaning that ventilation is maximized, and an additional 1,700 m^3/hr is recirculated though the air handler from the space. While the AER seems to be low for a fully open outdoor air damper, the occupancy of the space is only 68 persons, meaning the ventilation rate is a reasonable 7 L/s per person (~15 CFM/person). Together with opening the outdoor air damper to 100%, the office has been reconfigured for "social distancing," with cubicles separated by at least 2 meters (6 feet) in all directions.

Infectious Occupant #1 is assumed to enter the office at 8:00 AM, and stay the full day until 4:00 PM, leading to a total time of occupancy of 480 minutes, with an activity level of resting and speaking in his cubicle. Infectious Occupant #2 is assumed come to the office for a lunchtime gathering, entering at 240 minutes and leaving two hours later, and is loudly speaking while standing. Susceptible Occupant A enters and leaves with Infectious Occupant #2 and is resting during the gathering.

AIRC Screenshots:

Airborne Infection Risk Calculator — *Version 1.0* — **AIRC**

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	A	664	(m^2)
Ceiling Height	h	2.6	(m)
Room Volume	V	1,726	(m^3)

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	AER	1.0	(hr^{-1})
Particle Deposition Rate	k	0.24	(hr^{-1})
Viral Inactivation Rate	λ	0.63	(hr^{-1})
Total Viral Removal Rate	$IVRR$	1.9	(hr^{-1})

3. INITIAL QUANTA CONCENTRATION

n_0 0.0E+0 ($quanta/m^3$)

4. TOTAL TIME OF OCCUPANCY

Time t 480 *(minutes)*

5. EXPOSURE SCENARIO

Infectious Occupant #1		
Time of Entry	0	(minutes)
Time of Exit	480	(minutes)
ER_q from Selector Tab	9.49	(quanta/hr)
Infectious Occupant #2		
Include in Model?	Yes	← Select
Time of Entry	240	(minutes)
Time of Exit	360	(minutes)
ER_q from Selector Tab	65.8	(quanta/hr)
Susceptible Occupant A		
Time of Entry	240	(minutes)
Time of Exit	360	(minutes)
IR from Selector Tab	0.49	(m^3/hr)

6. RESULTS

Susceptible Occupant A

Modeled Exposure Time (minutes)	=	120
Individual Infection Risk (%)	=	0.26%
Exposure Time for 0.1% Risk (minutes)	=	58
Exposure Time for 1% Risk (minutes)	=	>120
Maximum Room Occupancy for $R_0 < 1$	=	56

Continuous Occupancy

Modeled Exposure Time (minutes)	=	480
Individual Infection Risk (%)	=	0.45%
Exposure Time for 0.1% Risk (minutes)	=	262
Exposure Time for 1% Risk (minutes)	=	>480
Maximum Room Occupancy for $R_0 < 1$	=	33

Quanta Emission Rate (ER_q) and Inhalation Rate (IR) Selector

SARS-CoV-2 ER_q (85^{th} Percentile Values)

Activity	ER_q (Quanta/hr)
Resting, Oral Breathing	1.98
Resting, Speaking	9.49
Resting, Loudly Speaking	61.1
Standing, Oral Breathing	2.32
Standing, Speaking	11.5
Standing, Loudly Speaking	65.8
Light Exercise, Oral Breathing	5.7
Light Exercise, Speaking	26.5
Light Exercise, Loudly Speaking	170
Heavy Exercise, Oral Breathing	13.3
Heavy Exercise, Speaking	63.7
Heavy Exercise, Loudly Speaking	408
Custom Emission Rate	970
Custom Probability of Emission	100%
(enter as percentage: 50 for 50%)	

Inhalation Rate

Activity	IR (m^3/hr)
Resting	0.49
Standing	0.54
Light Exercise	1.38
Heavy Exercise	3.3
Custom Inhalation Rate	2.00

Quanta Emission Rate (ER_q) Selection

Infectious Person	Select Activity Below	ER_q (Quanta/hr)
Infectious Occupant #1	Resting, Speaking	9.49
Infectious Occupant #2	Standing, Loudly Speaking	65.8

Inhalation Rate (IR) Selection

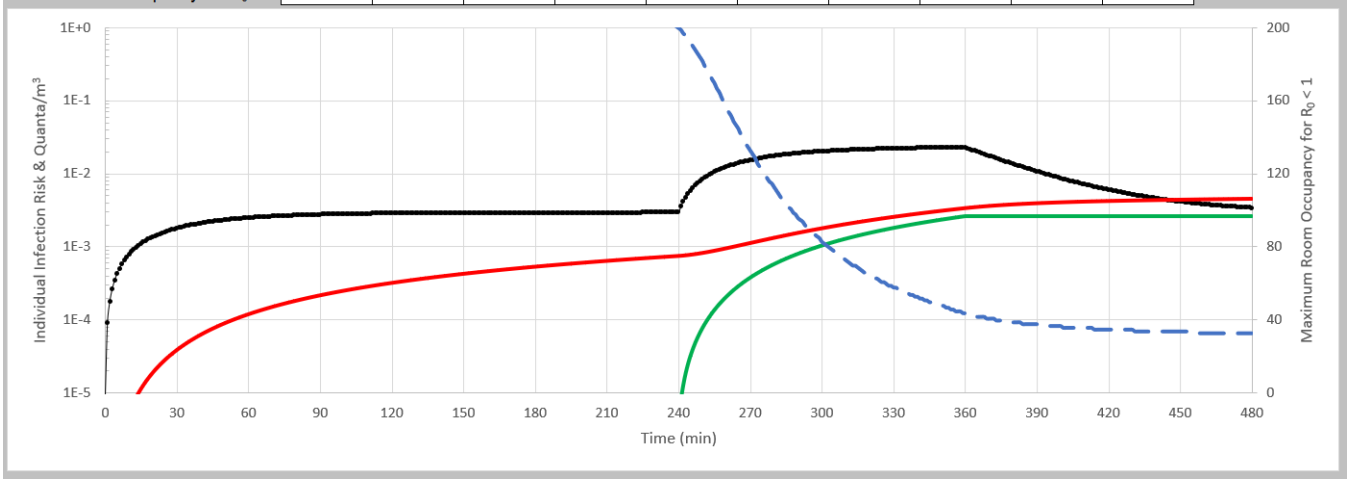
Susceptible Person	Select Activity Below	IR (m^3/hr)
Susceptible Occupant A	Resting	0.49
Continuous Occupant	Resting	0.49

Instructions:

1) Select the representative activity for Infectious Occupant #1, Infectious Occupant #2, Susceptible Occupant A, and Continuous Occupant for use in the model by clicking in the activity drop-down list cells highlighted in yellow.
2) If you would like to input your own value for ER_q, enter Custom Emission Rate and Custom Probability of Emission values in the SARS-CoV-2 Erq table and select Custom Emission Rate from the drop-down list for Infectious Occupant #1. This custom emission rate will apply to Infectious Occupant #2 if included in the model.
3) If you would like to input your own value for IR, enter the Custom Inhalation Rate value in the Inhalation Rate table, and select Custom Inhalation Rate from the drop-down list.

Model Results: Quanta Concentration, Individual Infection Risk, and Maximum Room Occupancy for $R_0 < 1$

Time (min)	120	160	200	240	280	320	360	400	440	480
Quanta Concentration	2.9E-03	2.9E-03	2.9E-03	2.9E-03	1.7E-02	2.2E-02	2.3E-02	8.7E-03	4.6E-03	3.4E-03
Occupant A Risk (%)	0.00%	0.00%	0.00%	0.00%	0.06%	0.16%	0.26%	0.26%	0.26%	0.26%
Continuous Risk (%)	0.03%	0.05%	0.06%	0.07%	0.13%	0.23%	0.34%	0.40%	0.43%	0.45%
Occupancy for $R_0 < 1$	467	324	247	200	113	65	44	37	34	33



Discussion: The model results indicate individual infections risks above the 0.1% threshold for both Susceptible Occupant A (who attended the 2-hour lunch gathering), and continuous 8-hour occupants of the office. The maximum number of 8-hour occupants to maintain a R_0 less than 1 is calculated at 33, or approximately half of the standard 68-person occupancy. With only 33 people, the maximum ventilation rate is increased to approximately 14 L/s per person (~30 CFM/person), similar to the enhanced ventilation scenario for the classroom. Once again the user should consider further reductions in occupancy considering this potential exposure could occur on a daily basis; however, a universal masking requirement in the office and elimination of lunchtime gatherings would offset some incremental risk from repeat exposures. The occupancy calculation for the Susceptible Occupant A cohort is 56 people, meaning that the R_0 would increase past 1 if more than 56 people attended the lunchtime gathering. With 33 people already in the office, 23 additional people could attend the gathering without compromising the reproductive number threshold of 1.

Since the outdoor air damper is already 100% opened, to further reduce risk, the building manager decides to increase the MERV filter rating on the air handler from 7 to 13 based on ASHRAE (2020) guidance. To incorporate this upgrade in AIRC, $AER_{filtration}$ is calculated to be 0.8 hr^{-1} ($Q_{recirculated}$ (1,700 m^3/hr) multiplied by the η_{filter} for MERV 13 (0.82 per Figure 4), divided by the room volume (1,726 m^3)). However, due to concerns regarding filter bypass and flow loss, $AER_{filtration}$ was reduced 25% to 0.6 hr^{-1} as a conservative measure. The adjusted AER parameter, including the filtration term, is thus calculated to be 1.6 hr^{-1}, leading to a revised IVRR of 2.5 hr^{-1}. The effect of the filtration is to reduce the individual infection risk for 8-hour occupancy from 0.45% to 0.35%, which does not appear that significant. However, the maximum number of allowable occupants for the reproduction number increases by 10 to 43, illustrating a more obvious benefit on a population level when an exposure may be recurring.

4. Night Office Cleaning

Scenario Description: This application represents a simulation of the time period after the open office in Example Application 3 is vacated by the office workers. For exposure purposes, a security guard is assumed to stay in the office for a period of six hours (360 minutes, continuous occupancy), and a custodian is assumed to clean the office from 120 minutes to 240 minutes after the office closes (Susceptible Occupant A). The security guard and the custodian are both susceptible to SARS-CoV-2, and therefore there is no active emission of SARS-CoV-2. However, residual virus is present in the air, and this is represented through the initial quanta concentration term. The input for this parameter is specified at 0.003 quanta/m^3, which is equal to the final concentration at the end of the previous 8-hour occupancy. The objective of this scenario is to calculate the risk experienced by the security guard and custodian while residual virus is flushed out of the air. The HVAC system is assumed to run continuously overnight as per ASHRAE (2020) guidance. To implement a no-source model, a custom ER_q of zero is entered on the "ERq IR Selector" tab with a 100% probability of occurrence, and Infectious Occupant #2 is turned off (see screenshots). Activity levels of light exercise and heavy exercise are selected for the security guard and custodian, respectively.

AIRC Screenshots:

Airborne Infection Risk Calculator — *Version 1.0*

AIRC

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	*A*	664	*(m^2)*
Ceiling Height	*h*	2.6	*(m)*
Room Volume	*V*	1,726	*(m^3)*

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	*AER*	1.0	*(hr^{-1})*
Particle Deposition Rate	*k*	0.24	*(hr^{-1})*
Viral Inactivation Rate	*λ*	0.63	*(hr^{-1})*
Total Viral Removal Rate	*IVRR*	1.9	*(hr^{-1})*

3. INITIAL QUANTA CONCENTRATION

n_0 3.0E-3 *(quanta/m^3)*

4. TOTAL TIME OF OCCUPANCY

Time t 360 *(minutes)*

5. EXPOSURE SCENARIO

Infectious Occupant #1

Time of Entry	0	*(minutes)*
Time of Exit	360	*(minutes)*
ER_q from Selector Tab	0	*(quanta/hr)*

Infectious Occupant #2

Include in Model?	No ← *Select*	
Time of Entry		*(minutes)*
Time of Exit		*(minutes)*
ER_q from Selector Tab		*(quanta/hr)*

Susceptible Occupant A

Time of Entry	120	*(minutes)*
Time of Exit	240	*(minutes)*
IR from Selector Tab	3.30	*(m^3/hr)*

6. RESULTS

Susceptible Occupant A

Modeled Exposure Time (minutes) =	120
Individual Infection Risk (%) =	0.01%
Exposure Time for 0.1% Risk (minutes) =	>120
Exposure Time for 1% Risk (minutes) =	>120
Maximum Room Occupancy for R_0 < 1 =	8014

Continuous Occupancy

Modeled Exposure Time (minutes) =	360
Individual Infection Risk (%) =	0.22%
Exposure Time for 0.1% Risk (minutes) =	19
Exposure Time for 1% Risk (minutes) =	>360
Maximum Room Occupancy for R_0 < 1 =	460

Quanta Emission Rate (ER_q) and Inhalation Rate (IR) Selector

SARS-CoV-2 ER_q (85^{th} Percentile Values)

Activity	ER_q (Quanta/hr)
Resting, Oral Breathing	1.98
Resting, Speaking	9.49
Resting, Loudly Speaking	61.1
Standing, Oral Breathing	2.32
Standing, Speaking	11.5
Standing, Loudly Speaking	65.8
Light Exercise, Oral Breathing	5.7
Light Exercise, Speaking	26.5
Light Exercise, Loudly Speaking	170
Heavy Exercise, Oral Breathing	13.3
Heavy Exercise, Speaking	63.7
Heavy Exercise, Loudly Speaking	408
Custom Emission Rate	0
Custom Probability of Emission *(enter as percentage: 50 for 50%)*	100%

Inhalation Rate

Activity	IR (m^3/hr)
Resting	0.49
Standing	0.54
Light Exercise	1.38
Heavy Exercise	3.3
Custom Inhalation Rate	2.00

Quanta Emission Rate (ER_q) Selection

Infectious Person	Select Activity Below	ER_q (Quanta/hr)
Infectious Occupant #1	Custom Emission Rate	0
Infectious Occupant #2		

Inhalation Rate (IR) Selection

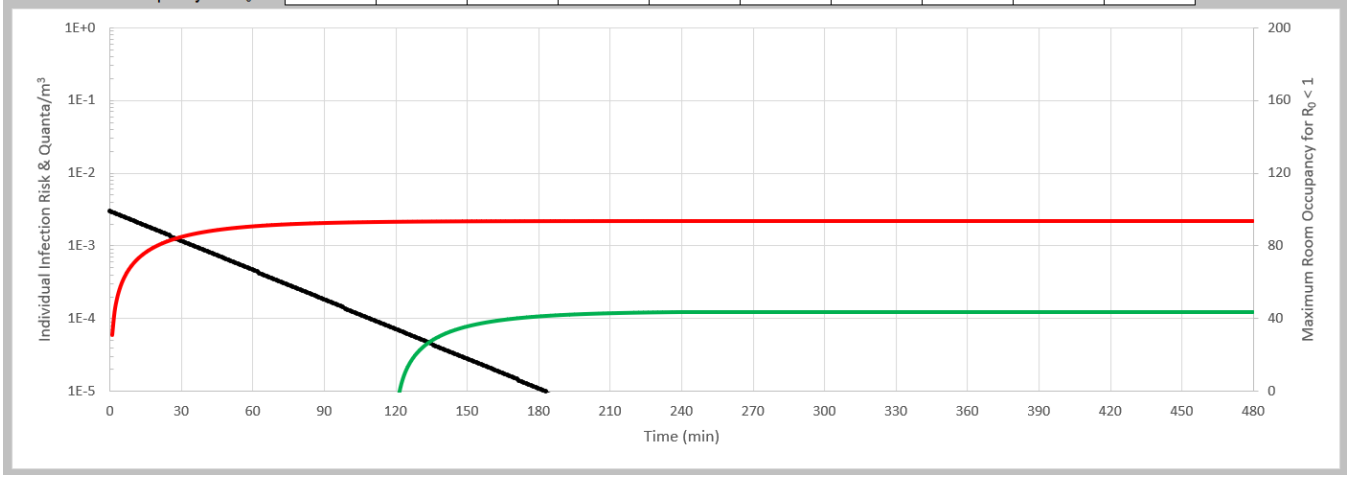
Susceptible Person	Select Activity Below	IR (m^3/hr)
Susceptible Occupant A	Heavy Exercise	3.30
Continuous Occupant	Light Exercise	1.38

Instructions:

1) Select the representative activity for Infectious Occupant #1, Infectious Occupant #2, Susceptible Occupant A, and Continuous Occupant for use in the model by clicking in the activity drop-down list cells highlighted in yellow.
2) If you would like to input your own value for ER_q, enter Custom Emission Rate and Custom Probability of Emission values in the SARS-CoV-2 Erq table and select Custom Emission Rate from the drop-down list for Infectious Occupant #1. This custom emission rate will apply to Infectious Occupant #2 if included in the model.
3) If you would like to input your own value for IR, enter the Custom Inhalation Rate value in the Inhalation Rate table, and select Custom Inhalation Rate from the drop-down list.

Model Results: Quanta Concentration, Individual Infection Risk, and Maximum Room Occupancy for $R_0 < 1$

Time (min)	120	160	200	240	280	320	360	400	440	480
Quanta Concentration	7.1E-05	2.0E-05	5.9E-06	1.7E-06	4.9E-07	1.4E-07	4.0E-08	1.2E-08	3.3E-09	9.6E-10
Occupant A Risk (%)	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Continuous Risk (%)	0.21%	0.22%	0.22%	0.22%	0.22%	0.22%	0.22%	0.22%	0.22%	0.22%
Occupancy for $R_0 < 1$	471	463	461	460	460	460	460	460	460	460



Discussion: The model results indicate individual infections risk below the 0.1% threshold for the custodian (Susceptible Occupant A), but above 0.1% for the continuous occupant (security guard). The majority of the security guard's dose exposure occurs within the first hour of the simulation. This simulation indicates that a two-hour post-occupancy flushing is sufficient to reduce exposure risks to acceptable levels for the modeled scenario, and 24/7 operation is not justified for risk management purposes for this space. A recommendation to flush spaces post-occupancy for 2 hours, and again for 2 hours prior to occupancy appears prudent for this space, the latter conceptually to address resuspension of settled particles. However, facility managers should be mindful that residual infectious aerosols may be present after infectious occupant(s) leave an indoor space, as illustrated by the risk calculated for the security guard.

5. Abattoir

Scenario Description: As of June 25, 2020, the Midwest Center for Investigative Reporting's database tracking SARS-CoV-2 infections in meatpacking plants in the United States reports at least 25,700 positive cases tied to at least 243 plants in 33 states, with at least 95 reported worker deaths (Chadde, 2020). The situation in the USA is not unique, as SARS-CoV-2 outbreaks in slaughterhouses have been reported in Australia, Brazil, Germany, the Netherlands, Ireland, France and the UK (Terazono and Schipani, 2020). The prevalence of the virus in abattoirs is often attributed to high worker density, long shifts, and difficulty in maintaining social distance. The airborne transmission pathway should also be considered as quanta emission and inhalation rates would be high for the physically demanding job, and workers share the same airspace for extended periods of time with potentially insufficient ventilation.

This application evaluates a hypothetical abattoir using parameters representing a modern, mechanically ventilated facility studied using CFD modeling and aerosol sampling in Beck et al. (2019). The facility consists of one large rectangular room with no walls separating clean and unclean areas, with a total volume of 2,126 m^3 and a reported air exchange rate of 9.3 hr^{-1}. CFD modeling indicates that aerosols emitted from workers entering from the main hallway into the slaughter room would spread throughout the space. Significant airborne concentrations of Shiga-toxin producing Escherichia coli (STEC) and Salmonella were reported, reflecting poor removal of aerosols during processing (Beck et al., 2019).

For the AIRC simulation, Infectious Occupant #1 and Infectious Occupant #2 are assumed to be frontline employees working a full eight-hour shift, with activity levels of heavy exercise-loudly speaking and heavy exercise-speaking. Susceptible Occupant A represents a meat inspector conducting an hour-long site visit in the middle of the day with an inhalation rate also corresponding to heavy exercise.

AIRC Screenshots:

Airborne Infection Risk Calculator — *Version 1.0*

AIRC

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	A	531.5	(m^2)
Ceiling Height	h	4	(m)
Room Volume	V	2,126	(m^3)

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	AER	9.3	(hr^{-1})
Particle Deposition Rate	k	0.24	(hr^{-1})
Viral Inactivation Rate	λ	0.63	(hr^{-1})
Total Viral Removal Rate	$IVRR$	10.2	(hr^{-1})

3. INITIAL QUANTA CONCENTRATION

n_0 0.0E+0 $(quanta/m^3)$

4. TOTAL TIME OF OCCUPANCY

Time t 480 *(minutes)*

5. EXPOSURE SCENARIO

Infectious Occupant #1		
Time of Entry	0	*(minutes)*
Time of Exit	480	*(minutes)*
ER_q from Selector Tab	63.7	*(quanta/hr)*
Infectious Occupant #2		
Include in Model?	Yes	← *Select*
Time of Entry	0	*(minutes)*
Time of Exit	480	*(minutes)*
ER_q from Selector Tab	408	*(quanta/hr)*
Susceptible Occupant A		
Time of Entry	240	*(minutes)*
Time of Exit	300	*(minutes)*
IR from Selector Tab	3.30	(m^3/hr)

6. RESULTS

Susceptible Occupant A

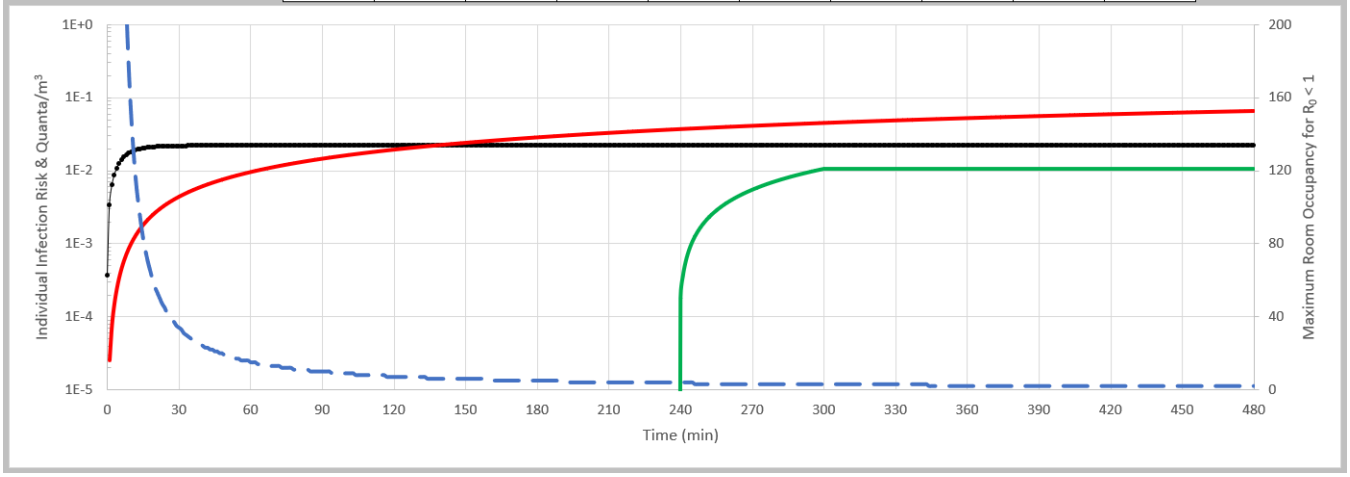
Modeled Exposure Time (minutes)	=	60
Individual Infection Risk (%)	=	1.06%
Exposure Time for 0.1% Risk (minutes)	=	4
Exposure Time for 1% Risk (minutes)	=	56
Maximum Room Occupancy for $R_0 < 1$	=	14

Continuous Occupancy

Modeled Exposure Time (minutes)	=	480
Individual Infection Risk (%)	=	6.51%
Exposure Time for 0.1% Risk (minutes)	=	10
Exposure Time for 1% Risk (minutes)	=	62
Maximum Room Occupancy for $R_0 < 1$	=	2

Model Results: Quanta Concentration, Individual Infection Risk, and Maximum Room Occupancy for $R_0 < 1$

Time (min)	120	160	200	240	280	320	360	400	440	480
Quanta Concentration	2.2E-02	2.2E-02	2.2E-02	2.2E-02	2.2E-02	2.2E-02	2.2E-02	2.2E-02	2.2E-02	2.2E-02
Occupant A Risk (%)	0.00%	0.00%	0.00%	0.02%	0.72%	1.06%	1.06%	1.06%	1.06%	1.06%
Continuous Risk (%)	1.93%	2.54%	3.12%	3.68%	4.21%	4.72%	5.20%	5.66%	6.10%	6.51%
Occupancy for $R_0 < 1$	7	5	4	4	3	3	2	2	2	2



Discussion: The model results indicate individual infection risks above 1% for both a susceptible worker on an 8-hour shift, and the meat inspector. Reproductive numbers for this abattoir could exceed 10 with a high density of workers, illustrating the potential need for additional engineering controls to help minimize airborne transmission, combined with effective personal protective equipment for workers.

6. Live-Poultry Market

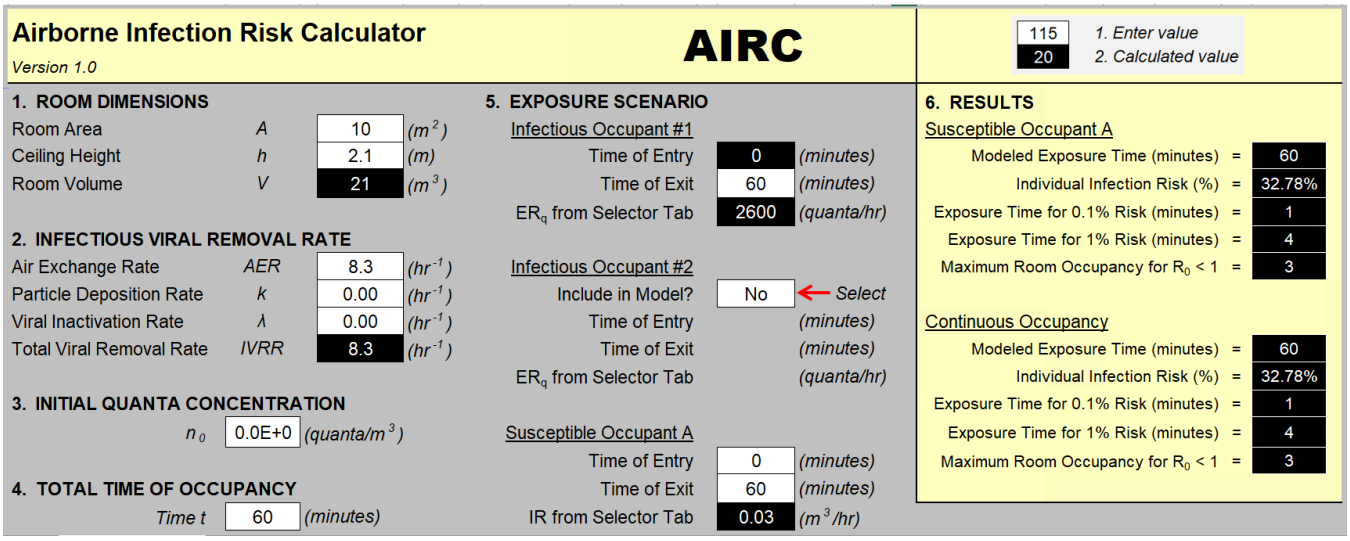
Scenario Description & Discussion: This application is an AIRC representation of a controlled experiment in which researchers quantified aerosolization of avian influenza resulting from slaughter and processing methods used in a typical live-poultry market (LPM) (Bertran et al., 2017 and Bertran et al., 2018). The example is provided for three reasons:

1) To demonstrate how AIRC can be used as an inverse model to back-calculate a quanta emission rate from a defined exposure scenario with a known rate of infection (attack rate);
2) To show a scenario where airborne viral emissions result from a non-respiratory source, with another example of concern being toilet flushing; and
3) To highlight the likely importance of the airborne pathway for zoonotic disease transmission and show how AIRC may be useful for animal models of airborne contagion. For example, Dharmadhikari et al. (2012) used the Wells-Riley mathematical model to estimate quanta emission rates for multidrug-resistant tuberculosis patients with and without masks using guinea pigs as exposed susceptibles in a controlled research facility (see Table 2). These estimates may be translatable to humans on some level, as Buhnerkempe et al. (2015) found a significant correlation between ferrets and humans for the secondary attack rate (SAR) via respiratory droplet transmission of influenza.

The LPM processing area was a 10 m^2 enclosure with an air exchange rate of 8.3 hr^{-1}. Over the course of the one-hour experiment, H5N1 highly pathogenic avian influenza (HPAI) virus-infected chickens were processed using a five-step method taking 6 minutes per bird. Three susceptible ferrets were placed in the enclosure downwind of the processing area and exposed to aerosols resulting from the processing.

When non-vaccinated poultry was slaughtered using the conventional five-step method, all three ferrets were infected with HPAI virus. When non-vaccinated poultry was contained in a plastic bag during the kill step, one of three ferrets was infected with HPAI virus (Bertran et al., 2018). AIRC was used to estimate the quanta emission rate for the bag scenario with the 33% attack rate. A custom inhalation rate of 0.03 m^3/hr was used for the ferrets based on Bide et al. (1997). Using an iterative approach, the custom quanta emission rate was adjusted in AIRC until the infection risk was calculated to be 33%. The custom probability of emission was fixed at 100% for this process since the goal was to match a known attack rate (the individual risk of infection becomes the same as the probability of infection for reproduction). Particle deposition and viral inactivation were assumed to be insignificant relative to the AER. As shown on the subsequent screenshots, the quanta emission rate for the LPM processing was calculated at 2,600 quanta/hr. This estimate is presented solely for illustrative and conceptual purposes and not meaningful analysis of the calculated emission rate.

AIRC Screenshots:



Airborne Infection Risk Calculator — *Version 1.0*

AIRC

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	A	10	(m^2)
Ceiling Height	h	2.1	(m)
Room Volume	V	21	(m^3)

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	AER	8.3	(hr^{-1})
Particle Deposition Rate	k	0.00	(hr^{-1})
Viral Inactivation Rate	λ	0.00	(hr^{-1})
Total Viral Removal Rate	$IVRR$	8.3	(hr^{-1})

3. INITIAL QUANTA CONCENTRATION

n_0 0.0E+0 ($quanta/m^3$)

4. TOTAL TIME OF OCCUPANCY

Time t 60 (minutes)

5. EXPOSURE SCENARIO

Infectious Occupant #1		
Time of Entry	0	(minutes)
Time of Exit	60	(minutes)
ER_q from Selector Tab	2600	(quanta/hr)
Infectious Occupant #2		
Include in Model?	No ← *Select*	
Time of Entry		(minutes)
Time of Exit		(minutes)
ER_q from Selector Tab		(quanta/hr)
Susceptible Occupant A		
Time of Entry	0	(minutes)
Time of Exit	60	(minutes)
IR from Selector Tab	0.03	(m^3/hr)

6. RESULTS

Susceptible Occupant A

Modeled Exposure Time (minutes)	=	60
Individual Infection Risk (%)	=	32.78%
Exposure Time for 0.1% Risk (minutes)	=	1
Exposure Time for 1% Risk (minutes)	=	4
Maximum Room Occupancy for $R_0 < 1$	=	3

Continuous Occupancy

Modeled Exposure Time (minutes)	=	60
Individual Infection Risk (%)	=	32.78%
Exposure Time for 0.1% Risk (minutes)	=	1
Exposure Time for 1% Risk (minutes)	=	4
Maximum Room Occupancy for $R_0 < 1$	=	3

Quanta Emission Rate (ER_q) and Inhalation Rate (IR) Selector

SARS-CoV-2 ER_q (85th Percentile Values)

Activity	ER_q (Quanta/hr)
Resting, Oral Breathing	1.98
Resting, Speaking	9.49
Resting, Loudly Speaking	61.1
Standing, Oral Breathing	2.32
Standing, Speaking	11.5
Standing, Loudly Speaking	65.8
Light Exercise, Oral Breathing	5.7
Light Exercise, Speaking	26.5
Light Exercise, Loudly Speaking	170
Heavy Exercise, Oral Breathing	13.3
Heavy Exercise, Speaking	63.7
Heavy Exercise, Loudly Speaking	408
Custom Emission Rate	2,600
Custom Probability of Emission	100%

(enter as percentage: 50 for 50%)

Inhalation Rate

Activity	IR (m^3/hr)
Resting	0.49
Standing	0.54
Light Exercise	1.38
Heavy Exercise	3.3
Custom Inhalation Rate	0.03

Quanta Emission Rate (ER_q) Selection

Infectious Person	Select Activity Below	ER_q (Quanta/hr)
Infectious Occupant #1	Custom Emission Rate	2600
Infectious Occupant #2		

Inhalation Rate (IR) Selection

Susceptible Person	Select Activity Below	IR (m^3/hr)
Susceptible Occupant A	Custom Inhalation Rate	0.03
Continuous Occupant	Custom Inhalation Rate	0.03

Instructions:
1) Select the representative activity for Infectious Occupant #1, Infectious Occupant #2, Susceptible Occupant A, and Continuous Occupant for use in the model by clicking in the activity drop-down list cells highlighted in yellow.
2) If you would like to input your own value for ER_q, enter Custom Emission Rate and Custom Probability of Emission values in the SARS-CoV-2 Erq table and select Custom Emission Rate from the drop-down list for Infectious Occupant #1. This custom emission rate will apply to Infectious Occupant #2 if included in the model.
3) If you would like to input your own value for IR, enter the Custom Inhalation Rate value in the Inhalation Rate table, and select Custom Inhalation Rate from the drop-down list.

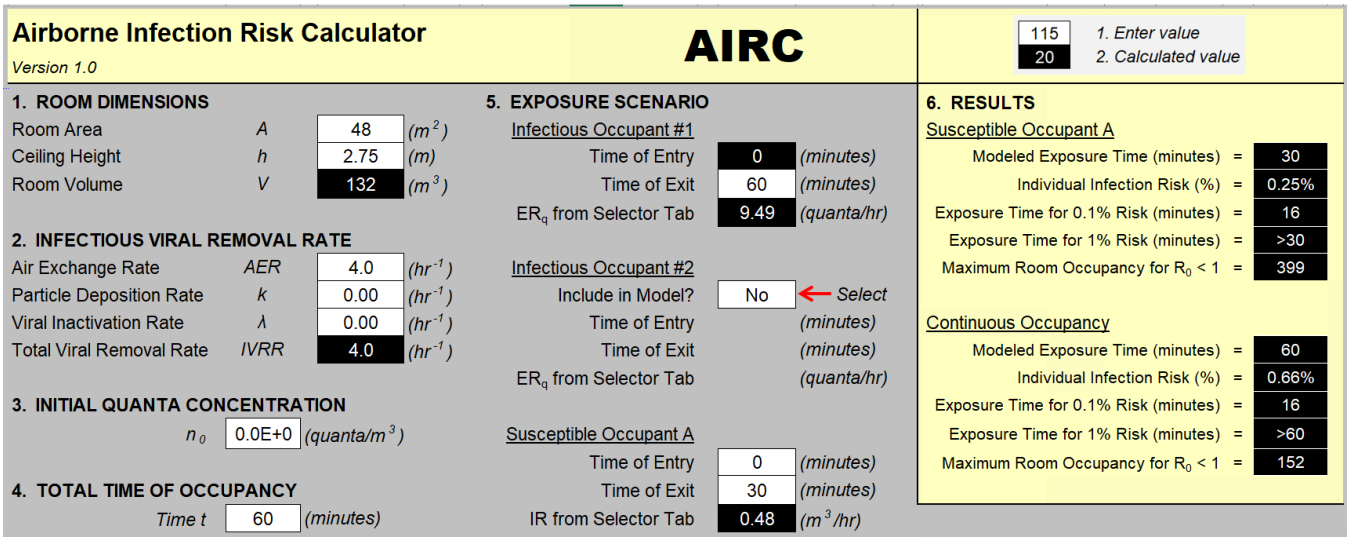
7. Hospital Waiting Area

Scenario Description & Discussion: This example is an AIRC reproduction of a modeling scenario presented in Beggs et al. (2010) to evaluate the risk of airborne infection in a hypothetical 132 m^3 hospital waiting area in the presence of one infectious occupant. This example demonstrates the utility of the Reference Disease feature of AIRC and compares AIRC output to a similar Gammaitoni-Nucci equation application in literature. As Beggs et al. (2010) conducted a Monte Carlo simulation to evaluate the probability of infection for tuberculosis, measles, and influenza, the AIRC results are compared to the mean probability values calculated in the study for 30 minutes and 60 minutes of exposure. A comparison of AIRC output and Beggs et al. (2010) results is presented in Table 3, below, and shows strong agreement. Minor differences are potentially due to the integration approach, time step differences, and/or rounding, and are largest for measles. Input parameters are shown in the screenshots that follow. Since the metric of interest for comparison is the probability of infection, the ER_q emission probabilities are set to 100% in AIRC, making individual infection risk equal to the probability of infection for reproduction number evaluation.

Table 3: Comparison of Calculated Probability of Infection, AIRC vs. Beggs et al. (2010)

Disease	30-Minute Waiting Room Exposure		60-Minute Waiting Room Exposure	
	AIRC Probability of Infection	Beggs et al. (2010) Mean Probability of Infection	AIRC Probability of Infection	Beggs et al. (2010) Mean Probability of Infection
Tuberculosis	0.34 %	0.34 %	0.88 %	0.87 %
Influenza	2.61 %	2.62 %	6.70 %	6.62 %
Measles	14.0 %	13.5 %	32.6 %	30.9 %

AIRC Screenshots:



Airborne Infection Risk Calculator — *Version 1.0*

AIRC

115 *1. Enter value*
20 *2. Calculated value*

1. ROOM DIMENSIONS

Room Area	*A*	48	*(m^2)*
Ceiling Height	*h*	2.75	*(m)*
Room Volume	*V*	132	*(m^3)*

2. INFECTIOUS VIRAL REMOVAL RATE

Air Exchange Rate	*AER*	4.0	*(hr^{-1})*
Particle Deposition Rate	*k*	0.00	*(hr^{-1})*
Viral Inactivation Rate	*λ*	0.00	*(hr^{-1})*
Total Viral Removal Rate	*IVRR*	4.0	*(hr^{-1})*

3. INITIAL QUANTA CONCENTRATION

n_0 0.0E+0 *(quanta/m^3)*

4. TOTAL TIME OF OCCUPANCY

Time t 60 *(minutes)*

5. EXPOSURE SCENARIO

Infectious Occupant #1

Time of Entry	0	*(minutes)*
Time of Exit	60	*(minutes)*
ER_q from Selector Tab	9.49	*(quanta/hr)*

Infectious Occupant #2

Include in Model?	No	← *Select*
Time of Entry		*(minutes)*
Time of Exit		*(minutes)*
ER_q from Selector Tab		*(quanta/hr)*

Susceptible Occupant A

Time of Entry	0	*(minutes)*
Time of Exit	30	*(minutes)*
IR from Selector Tab	0.48	*(m^3/hr)*

6. RESULTS

Susceptible Occupant A

Modeled Exposure Time (minutes)	=	30
Individual Infection Risk (%)	=	0.25%
Exposure Time for 0.1% Risk (minutes)	=	16
Exposure Time for 1% Risk (minutes)	=	>30
Maximum Room Occupancy for $R_0 < 1$	=	399

Continuous Occupancy

Modeled Exposure Time (minutes)	=	60
Individual Infection Risk (%)	=	0.66%
Exposure Time for 0.1% Risk (minutes)	=	16
Exposure Time for 1% Risk (minutes)	=	>60
Maximum Room Occupancy for $R_0 < 1$	=	152

Simulation of Reference Airborne Infectious Disease ER_q

	SARS-CoV-2 or Custom	Measles	Influenza	Tuberculosis	Rhinovirus
ER_q (Quanta/hr)	9.49	570	100	12.7	5
Probability of Emission (enter as %)	100%	100%	100%	100%	100%

Susceptible Occupant A

Modeled Exposure Time (minutes) = 30

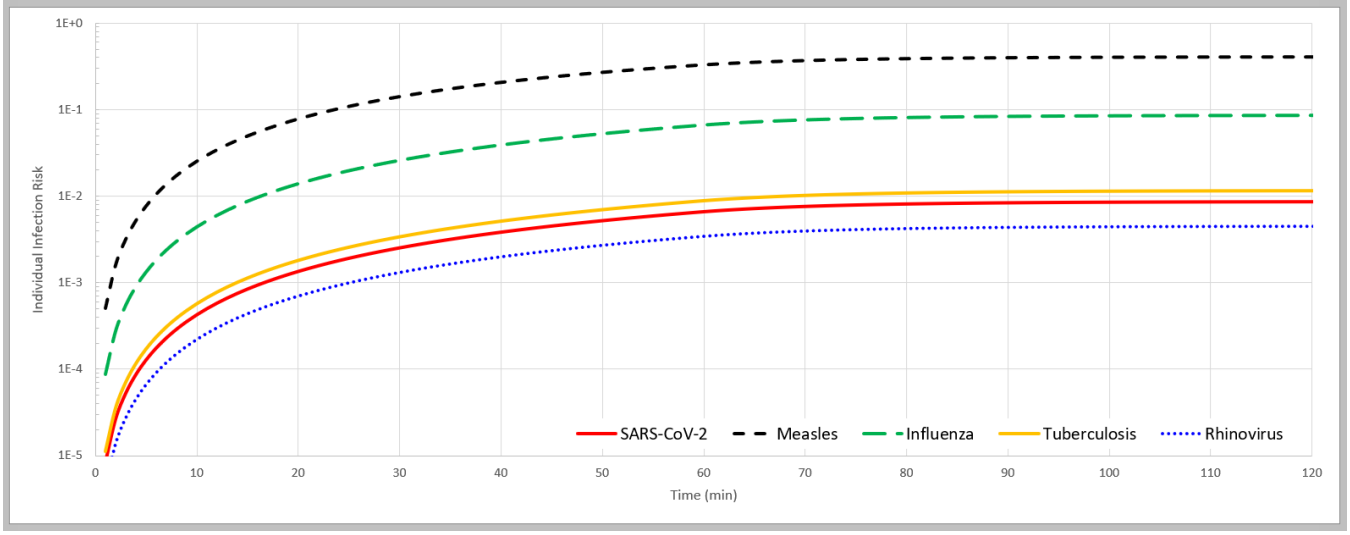
	SARS-CoV-2 or Custom	Measles	Influenza	Tuberculosis	Rhinovirus
Individual Infection Risk (%)	0.25%	14.0%	2.61%	0.34%	0.13%
Exposure Time for 0.1% Risk (minutes)	16	1	4	14	24
Exposure Time for 1% Risk (minutes)	>30	5	16	>30	>30
Maximum Room Occupancy for $R_0 < 1$	399	7	38	298	756

Continuous Occupancy

Modeled Exposure Time (minutes) = 60

	SARS-CoV-2 or Custom	Measles	Influenza	Tuberculosis	Rhinovirus
Individual Infection Risk (%)	0.66%	32.6%	6.70%	0.88%	0.35%
Exposure Time for 0.1% Risk (minutes)	16	1	4	14	24
Exposure Time for 1% Risk (minutes)	>60	5	16	69	>60
Maximum Room Occupancy for $R_0 < 1$	152	3	14	114	289

Individual Risk Curves for Continuous Exposure Scenario: Reference Infectious Diseases



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