Title: Mass depopulation of swine facilities via on-site generation of carbon monoxide – **NPB#21-072**

Investigator: Brett C. Ramirez, PhD

Institution: Iowa State University

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Industry Summary

In the event of an infectious animal disease outbreak, rapid depopulation of the infected livestock herds can help prevent the spread of the disease and potentially reduce suffering of the impacted animals. There are several options for rapid depopulation; however, many methods require substantial labor inputs or specialized equipment, both of which may be difficult and expensive to procure. Delays in depopulation prolong the infection, spread of the disease, and suffering of the affected animal. Inhaled gases for depopulation are advantageous because moderate to low skill is required, can be aesthetically preferable, with only some excitatory movement or vocalization, and can be used on any size pig. Carbon dioxide (CO_2) is the most common gas used, but carbon monoxide (CO) could become a viable alternative to CO_2. This project aimed to explore the feasibility of using CO as inhalant at full-scale. The first step was to create computational fluid dynamics (CFD) simulation to investigate the transport of CO in a 28 ft wide, 120 ft long, and 7.5 ft tall with a 3 ft deep-pit nursery. Initial modeling with only one CO inlet into the barn showed the desired CO concentration of 4,000 ppm was quite unachievable, especially if any building envelope leakage or strong wind was present. Then, the simulation was adapted for three CO inlets and results showed more uniform distribution of CO within the pig occupied space; however, concentration of CO failed to achieve the desired 4,000 ppm within 30 minutes. Implementation of CO at full-scale unachievable with the following conclusions: compressed, pure CO procured from an industrial gas

supplier, as compared to on-site CO generation, is a more viable option for depopulation when considering cost, safety, availability of application equipment and system reliability. Currently sales of inert gases, such as CO, "where the planned use is as an asphyxiant or toxin to be applied to animals is prohibited, without formal product risk review" by Linde Gas and Equipment, which is the primary supplier of compressed CO in the US. Linde will not move forward with their formal product risk review without justification of the market potential of CO for depopulation. For more information, please contact Dr. Brett Ramirez in the Department of Agricultural and Biosystems Engineering at Iowa State University; email: bramirez@iastate.edu

Key Findings

- A computer simulation using computational fluid dynamics was performed to explore the transport of CO throughout a small nursery building with one and three CO inlets. A simulation of this scale, in three dimensions, has never been created before and could be easily adjusted for different gases, injection locations, buildings, etc.
- One CO inlet showed the target CO concentration of 4,000 ppm was quite unachievable. Three CO inlets results showed more uniform distribution of CO within the pig occupied space; however, concentration of CO failed to achieve the desired 4,000 ppm within 30 minutes.
- Building envelope leakage (infiltration) due to poor/degraded construction or materials and/or wind have a substantial effect on the transport of CO within the room and should be strongly considered for any future discussion on full-scale usage of inhalants.
- Compressed, pure CO procured from an industrial gas supplier, as compared to on-site CO generation, is a more viable option for depopulation when considering cost, safety, availability of application equipment and system reliability.
- Currently sales of inert gases, such as CO, "where the planned use is as an asphyxiant or toxin to be applied to animals is prohibited, without formal product risk review" by Linde Gas and Equipment, which is the primary supplier of compressed CO in the US. Linde will not move forward with their formal product risk review without justification of the market potential of CO for depopulation.

Keywords: foreign animal disease, gas, inhalant, pig, housing.

Introduction

A foreign animal disease (FAD) outbreak would be truly devastating to all aspects of the US swine industry. African Swine Fever (ASF) is a highly contagious virus of paramount relevance that causes high morbidity and mortality (USDA APHIS, 2019). By February 2019, an estimated 45M pigs had been culled in China due to ASF with an economic loss of nearly \$8.5B (estimated at 100 kg hd^{-1} at 13.5 RMB kg^{-1}; Zhang et al., 2019). Comparatively, a FAD outbreak in the US could cost upwards of \$50B over 10 years (Carriquiry et al., 2020). While extreme prevention measures can be deployed and enforced, a confirmed ASF outbreak would force instant response to limit the viral spread. This will require mass pig depopulation, which must be performed humanely, timely and reliably, while simultaneously upholding personnel safety and limiting psychological impacts (AVMA, 2019). Depopulation needs to be done rapidly to limit the potential for disease spread as well as low cost, enabling a faster return to production, ultimately boosting the competitive advantage of US producers. Thoroughly considered, evidence-based strategies are needed for successful depopulation.

Approved methods to achieve mass depopulation goals are detailed in FAD PReP/NAHEMS (2015). The recent 2014-2015 Highly Pathogenic Avian Influenza (HPAI) outbreak demonstrated the need for alternative methods of rapid depopulation and the critical need for evidence-based, best management practices (Gingerich, 2015). If a FAD outbreak occurs, the depopulation approach must be rapidly implemented with the goal to decrease the amount of virus in the environment. Other depopulation methods can create delays, as was found during the HPAI outbreak, due to a lack of material, device availability (CO_2, foam, euthanasia devices, etc.) and high labor input needed to perform the depopulation. Delays in depopulation would increase the amount of virus shed over time, which would amplify total virus shed in the environment, and increase the probability of transmission to other herds. Gerritzen et al. (2006) describe the use of compressed CO for depopulation poultry in the Netherlands and targeted 1.5% to 2% (15,000 to 20,000 ppm) CO concentration inside a 35,000 bird barn. There was limited information presented on the gas source and flow, but results indicate 100% mortality and challenges associated with execution and mixing.

Carbon monoxide is a colorless, odorless gas that is primarily produced from the incomplete combustion of hydro-carbonaceous fuels, such as propane and gasoline. It is slightly less dense than air (air = 1.29; CO = 1.25; CO_2 = 1.98 kg m^{-3}) and is toxic to animals when exposed to concentrations greater than 35 ppm. It is highly toxic because CO binds to the site in hemoglobin, that would normally carry oxygen, to produce carboxyhemoglobin, thereby rendering hemoglobin ineffective for delivering oxygen to bodily tissues. For humans, symptoms are characterized by dizziness, nausea, fatigue, shortness of breath, loss of consciousness and death (Mayo Clinic, 2021). Each year, approximately 50,000 people in the US seek emergency medical care due to accidental CO poisoning from exposure to fumes from home furnaces, gas appliances, gas heaters, etc. (CDC, 2021). Accidental

CO poisoning results in 350 to 500 deaths on an annual basis (CDC, 2021). The (2010) reports lethal concentration-time exposure levels for CO of 40,000 ppm for 2 min, 16,000 ppm for 5 min, 8,000 ppm for 10 min, 3,000 ppm for 30 min, and 1,500 ppm for 60 min. The desired CO concentration reported by Gerritzen et al. (2006) is ***five times greater*** than the lethal dose for humans after 30 mins of exposure. This strongly indicates poor distribution and mixing; thus, warranting further investigation. Also, with respect to pigs, literature is scarce on lethal concentrations and no such concentration-time relationship exists.

Carbon monoxide is produced industrially in US by a limited number of firms via partial oxidation of hydro-carbonaceous gases. Most industrially derived CO is used immediately downstream of manufacture for chemical synthesis (Wilbur et al., 2013). Carbon monoxide is considered a "chemical of concern" by the EPA and requires approval of any use application prior to purchase. Due to the liability associated with its use on-farm, it is unlikely that the sale of CO for depopulation would be approved without significant use restrictions and a lengthy approval timeline for individual end user. Onsite production of CO, in concert with strict safety protocols and necessary safety equipment (i.e., CO monitors) minimizes the liability associated with the use of CO for depopulation. Carbon monoxide can be produced by means other than the partial oxidation of hydrocarbons; however, these methods require specialized reactants and specific reaction conditions (i.e., temperature, etc.). In this proposal, we will use partial oxidation, that is, combustion under oxygen-limiting conditions of natural gas and liquid propane gas to produce CO with additional CO-enrichment by conversion of CO_2 in the combustion stream to CO with heated activated charcoal.

Specific objectives are:

1. Develop a CFD model to quantify dispersion of CO in a typical deep pit building that has been sealed to the extent practical under real-world conditions to determine time to reach lethal CO levels at animal-level throughout the building under differing environmental conditions.
2. Design, construct, and commission a turnkey, mobile platform for onsite production and dispersion of CO using liquid propane as fuel.

Materials and Methods

Configuration of Simulated Barn

The geometry of the barn used to perform the numerical simulations is illustrated in Figure 1.

The barn, including the headspace, is 28 ft wide, 120 ft long, and 11.33 ft tall (8.534 m x 36.576 m x 3.454 m). The floor is made of 4 in thick slatted concrete, with each slat having dimensions of 4 x 8 ft, with 1 in openings placed as illustrated in Figure 2. The red arrows in Figure 1 represent the sides of the barn where building envelope exfiltration takes place.

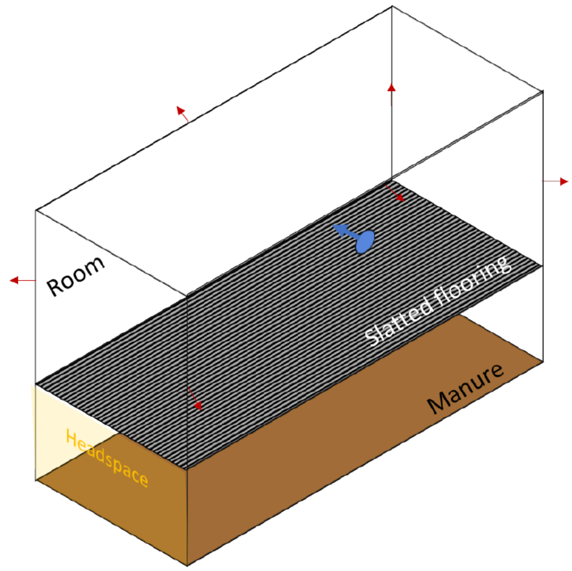

Figure 1: Schematic representation of the barn.

Before CO injection is started, the indoor air conditions are assumed to be $T = 75°\text{F} = 297.04$ K at 60% relative humidity, while below the floor, in the headspace, the initial temperature is assumed equal to $68°\text{F} = 293.15$ K, while the manure has a temperature of $55\ °\text{F} = 285$ K .

Two inlet configurations have been considered in the simulations. The first one, with a single inlet, is shown in Figure 3, where the arrow indicates the location of the CO injection.

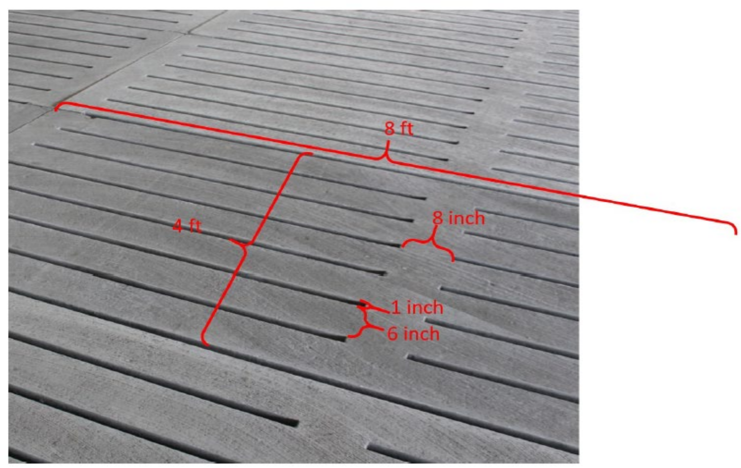

Figure 2: Photographic view of a portion of the barn floor.

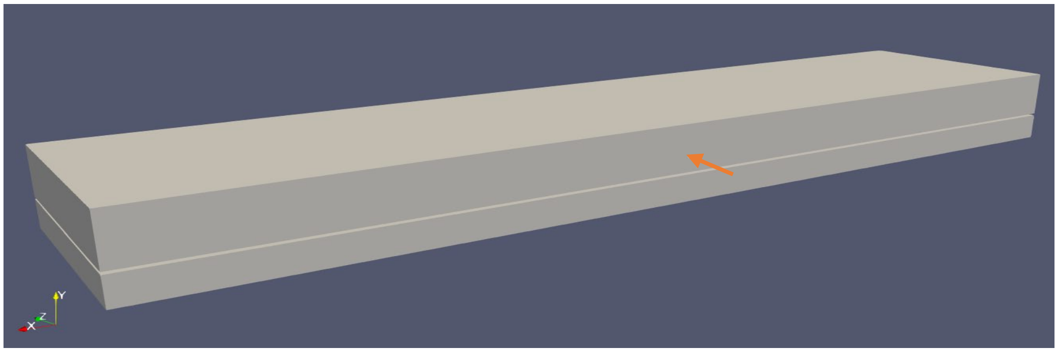

Figure 3: Schematic representation of the barn in the CFD simulations and single-inlet location.

To better distribute the CO in the barn and reduce the time needed to obtain the desired CO concentration, a second inlet configuration with three equidistant inlets was considered, as shown in Figure 4.

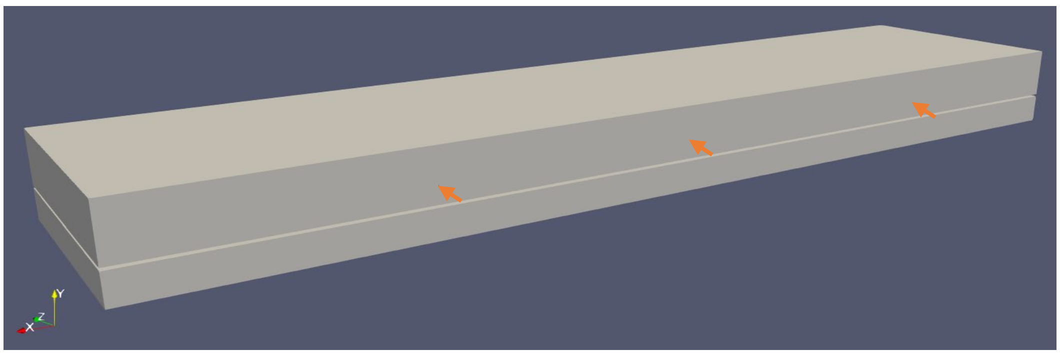

Figure 4: Schematic of the barn in the CFD simulations and location of the three inlets.

Flow Conditions

Air was assumed to be a mixture of water vapor, oxygen, carbon dioxide, and nitrogen, with mass fractions reported in

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Table 1: Air composition before CO injection.

Component	Mass fraction (Y)
H_2O	0.01113
O_2	0.22744
CO_2	0.00064
N_2	0.7608

The flow rate of CO at each inlet was set to $300\ \mathrm{ft^3/min} = 0.14158\ \mathrm{m^3/s}$. The concentration of CO at the inlet was assumed to be 20,000 ppm at a temperature of 200 °F = 366.48 K. Since the inlet diameter was $d = 0.3281\ \mathrm{ft} = 0.1\ \mathrm{m}$, this leads to a flow velocity at each inlet of $3548.6417\ \mathrm{ft/min} = 18.0271\ \mathrm{m/s}$.

Computational Approach

The numerical simulations were performed with the open-source code OpenFOAM® [1], which relies on the finite-volume approach [2]. The simplified geometry of the barn shown in Figure 3 was discretized using the automatic hex-dominant mesh tool snappyHexMesh included in OpenFOAM. This process led to a computational mesh consisting of 11,586,415 control volumes in the case of single-inlet simulations and 11,481,205 control volumes in the case with three inlets.

The rhoReactingBuoyantFoam solver in OpenFOAM was used to perform the simulation. This solver considers a weakly compressible flow and solves the energy equation to account for heat transfer and the species equations to describe species transport and mass transfer. Buoyancy effects, as well as turbulence, are considered. Specifically, the fluid is treated as an ideal gas mixture with local variable composition. Turbulence effects are modeled using the $k - \omega$ SST turbulence model [3–6]. Unsteady simulations were performed using an adaptive time step to ensure the numerical stability of the simulation. The iterative PIMPLE algorithm was used for pressure-velocity coupling.

Under-relaxation was applied to all the flow variables, using the under-relaxation factors reported in Table 2. Convergence criteria for the residuals of all flow variables were set to 0.001 to establish the convergence of the numerical solution at each time step. Up to twenty outer iterations were allowed for each time step to ensure proper coupling among the flow variables and achieve convergence at each time step.

The objective of the simulations was to establish if the flow conditions under consideration allow reaching the desired average concentration of CO approximately equal to 4,000 ppm in the barn within a timeframe of 30 minutes (1,800 s).

The average CO concentration and the temperature in the upper part of the barn, excluding the headspace, were monitored during the simulation.

Table 2: Values of the under-relaxation factors used in the simulations.

Flow variable	Under-relaxation factor
Flow velocity U	0.4
Pressure p	0.6
Enthalpy h	0.5
Turbulence quantities k, ω	0.2
Species mass fraction Y_i	0.2

Simulations were performed using the cloud computing service Microsoft Azure Batch, with HBv2 virtual machines. These virtual machines were equipped with two 64-core AMD EPYC 7742 CPUs operating at ~3.2 GHz and 480 GB of RAM.

Investigation of On-Farm CO Generation Technologies

In the initial project plan, a system for on-farm CO generation would be developed using a combination of controlled incomplete combustion of propane to generate of stream of $CO/CO_2/H_2O$ with further enrichment of CO by passing the gas stream through a heated carbon bed. While this method is possible, during the initial system design stages it became clear that this approach has number of safety issues when operating a full-size system on-farm. As such, a more complete investigation of methods to generate CO on-farm was completed. Procurement of pure, compressed CO from an industrial gas supplier was also investigated.

Results and Discussion

Simulations with One Inlet

Two simulations, one assuming a building envelope exfiltration of 1.5 ACH, corresponding to favorable weather conditions, and one with 5 ACH, corresponding to very unfavorable weather conditions, were initially considered for the one-inlet configuration of the barn. Figure 5 shows the time evolution for the case with ACH of 1.5 up to 1,247 s (20.78 minutes). The simulation was terminated early because the flow configuration clearly cannot provide the desired CO concentration of 4,000 ppm within the desired time window of 30 minutes.

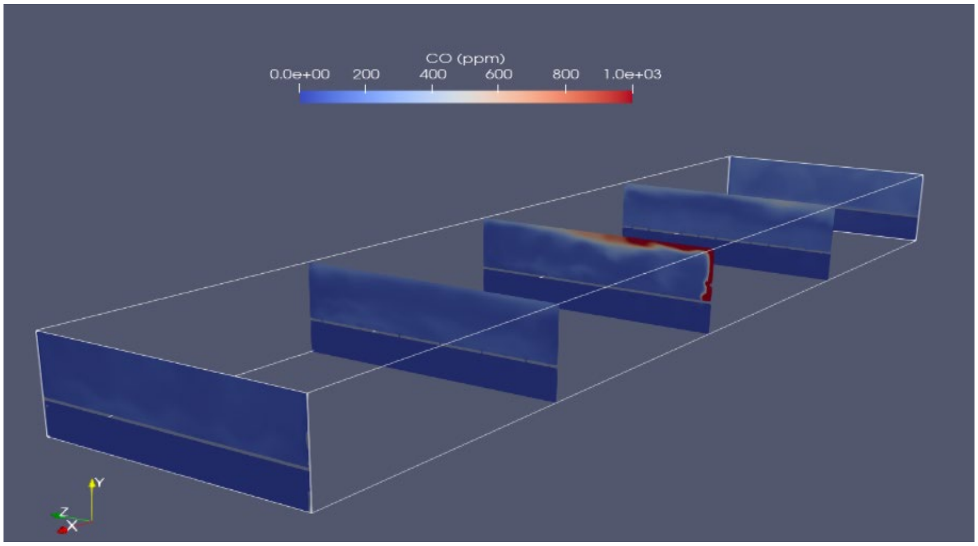

Figure 6: Contour plot of CO after seven minutes of flow time. Configuration with one inlet, 1.5 ACH.

Similarly, the simulation with the same geometric configuration but ACH of 5 was terminated at 330 seconds and is reported only to confirm that, as expected, if weather conditions are adverse, the configuration under examination cannot provide the desired CO concentration.

An example of CO distribution after seven minutes with a single inlet during a calm day is shown in Figure 6, which also highlights the tendency of CO to accumulate below the ceiling of the barn.

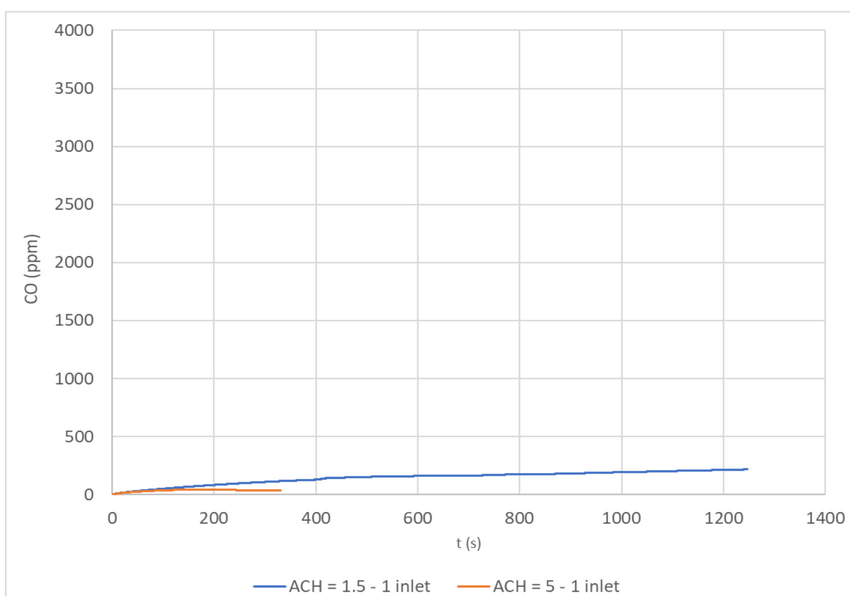

Figure 5: Time evolution of average CO concentration in the barn - Single-inlet cases.

Simulation with Three Inlets

A more detailed simulation was performed considering the three-inlet setup for the injection of CO in the barn. In this simulation, the heat generation from the animals was also accounted for in one of the examined cases by assuming that a temperature-dependent heat flux was released from the top of the floor. The heat flux was approximated with a simple polynomial function:

$$\dot{Q} = -0.4675\,T^2 + 40.051T - 499.31, \tag{0.1}$$

where T is measured in Kelvin and $\dot{Q}$ is measured in W/m^2. This expression is used for temperatures below 315.15 K (107.6°F), above which $\dot{Q}$ is set to zero.

The time evolution of the CO concentration in the barn is shown in Figure 7 for both the case without heat source due to the presence of the animals and with it. The figure indicates a concentration of 3,000 ppm is reached, on average, inside the barn after 1,800 seconds (30 minutes), when the heat generated by the animals is considered in the simulation. The CO concentration observed at $t = 1800\ s$ is slightly higher in the case when such heat source is not considered, possibly because of the impact of animal's heat on buoyancy at lower elevations in the barn.

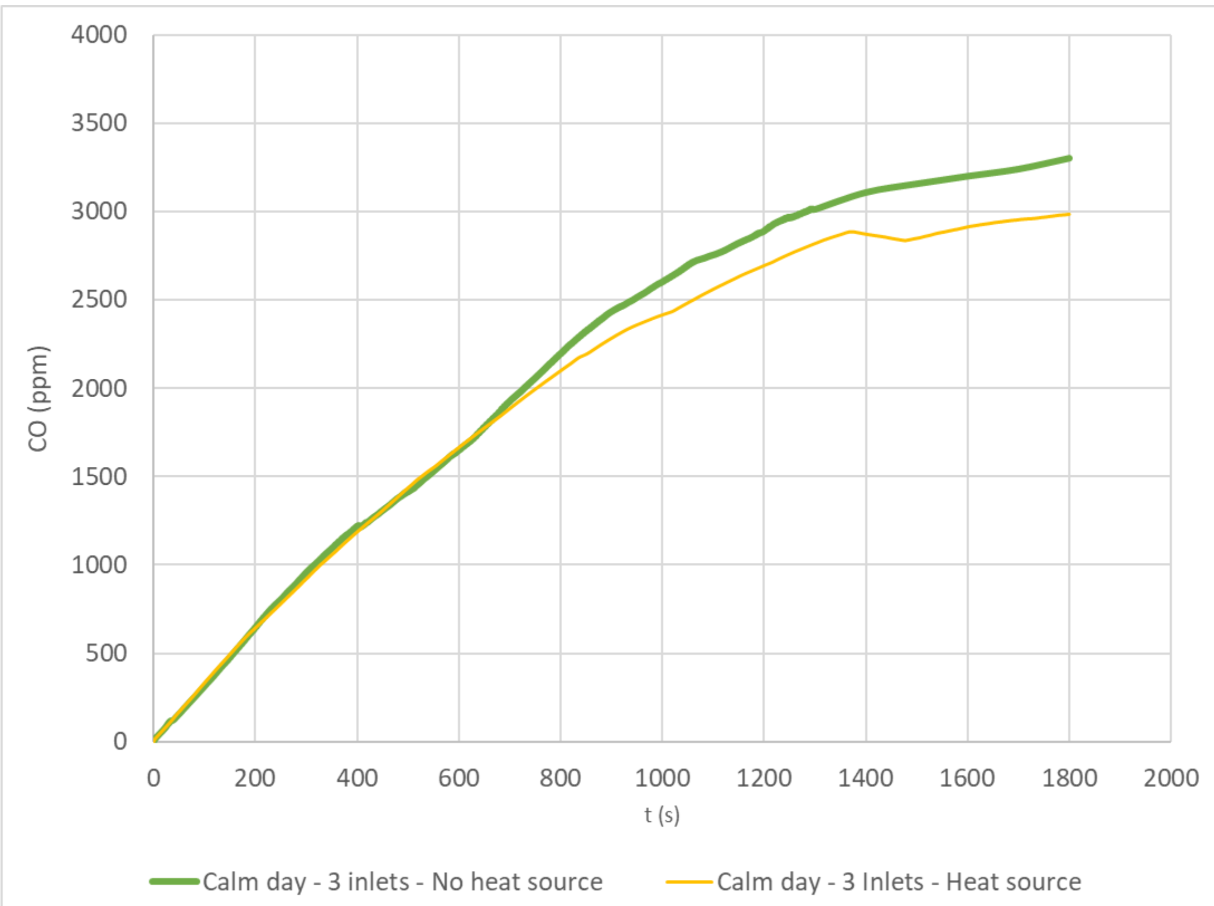

Figure 7: Time evolution of CO concentration in the upper part of the barn with three inlets. A calm day was assumed to correspond to 1.5 ACH.

Figure 9 shows the time evolution of temperature inside the barn, which accounts for the contributions of the heat generated by the animals and the heat provided by the CO injection.

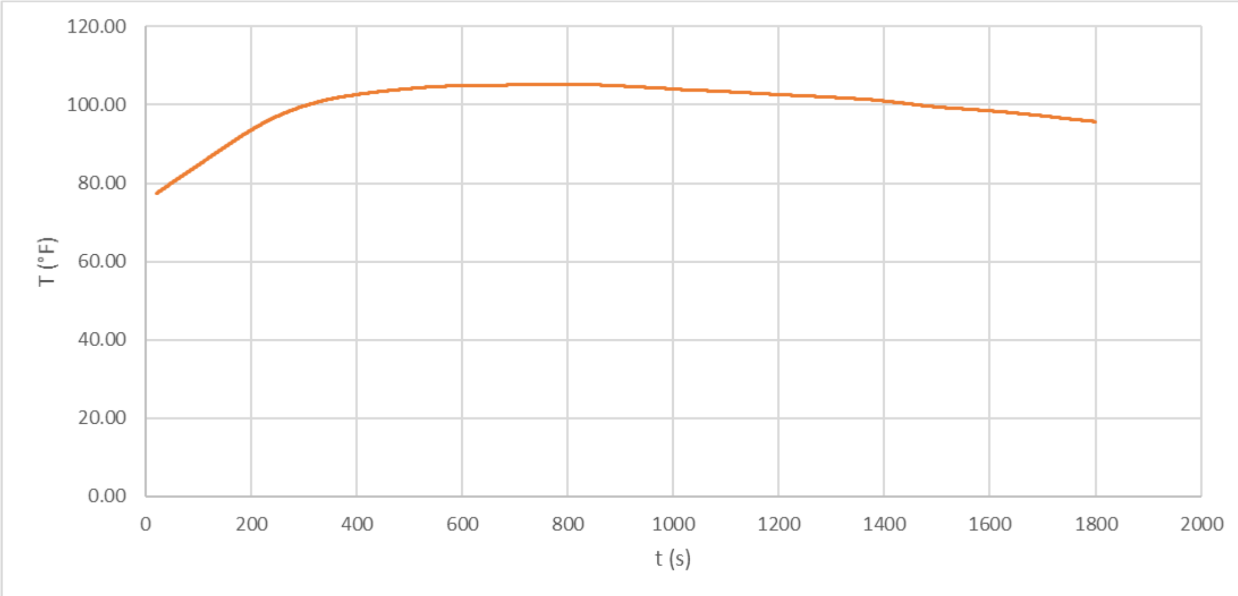

Figure 9: Average temperature inside the barn with three CO injections and heat source.

The contour plot in Figure 8 show the CO concentration at 1800 s from the start of the CO injection inside the barn. The view is from the exterior and highlights the inlets used to feed CO in the environment. The interior of the barn is shown in Figure 10, where the injection points of CO are visible along three of the vertical planes.

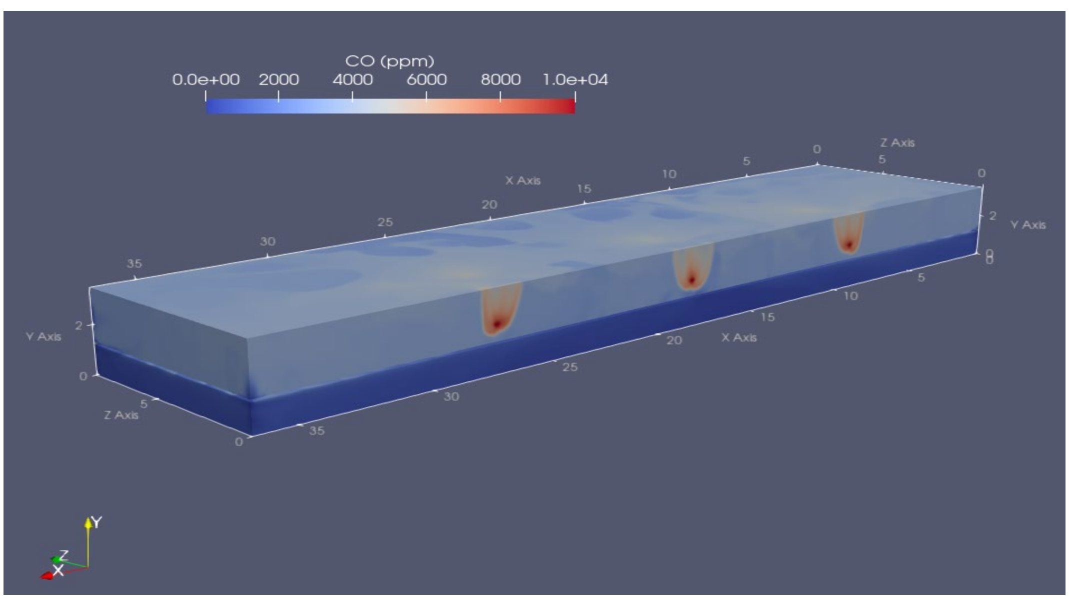

Figure 8: Time snapshot at t = 1800 s of the CO concentration in the barn (exterior view), with inlet visible. Coordinates are in meters (1 m = 3.2808 ft). Simulation with 1.5 ACH and heat source due to the animals.

The concentration of CO appears relatively uniform in the top part of the barn, but it is necessary to investigate further its values in the volume occupied by the animals. To such a purpose, we consider three vertical lines extending along the barn's entire height and are located at z = 14.009 ft = 4.27 m (mid-point along the z-axis), and, respectively, at x = 6.562 ft = 2 m, x = 60 ft = 18.288 m, and x = 111.549 ft = 34 m. The values of CO concentration along these lines are reported in Figure 11. The concentration of CO reaches approximately 2,000 ppm below the floor and rapidly decreases towards the bottom of the headspace, where the actual barn manure is collected.

The CO concentration remains relatively uniform with respect to elevation in the region of space occupied by the animals but varies significantly depending on the position of the vertical line where it was sampled.

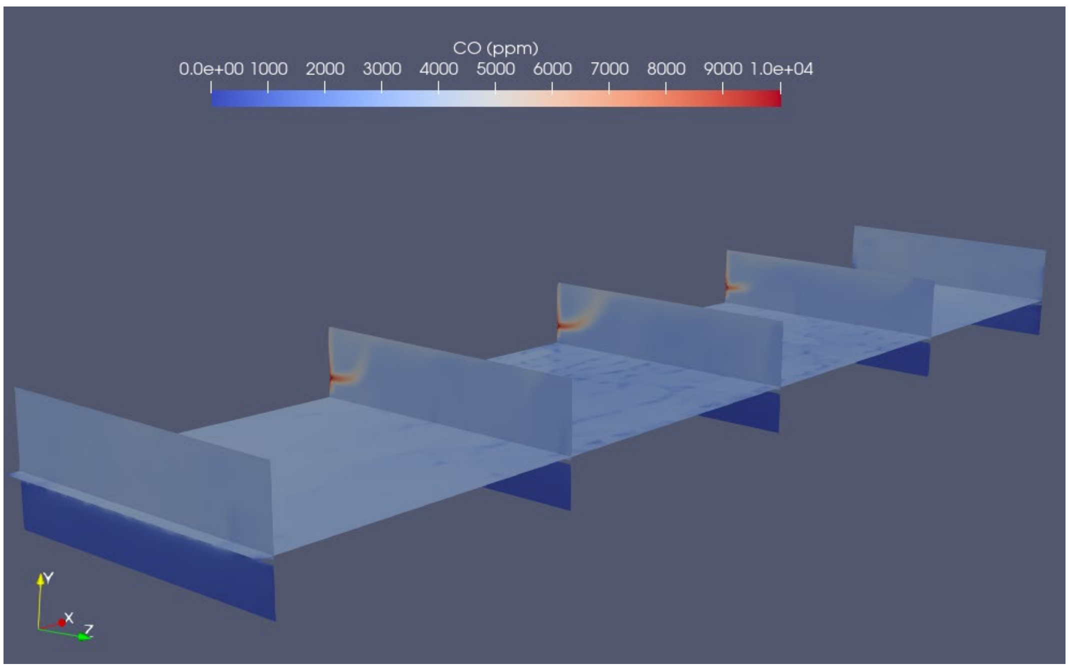

Figure 10: Contour of CO concentration in the barn at t = 1800 s over several vertical planes. The horizontal plane is at floor level. Simulation with 1.5 ACH and heat source due to the animals.

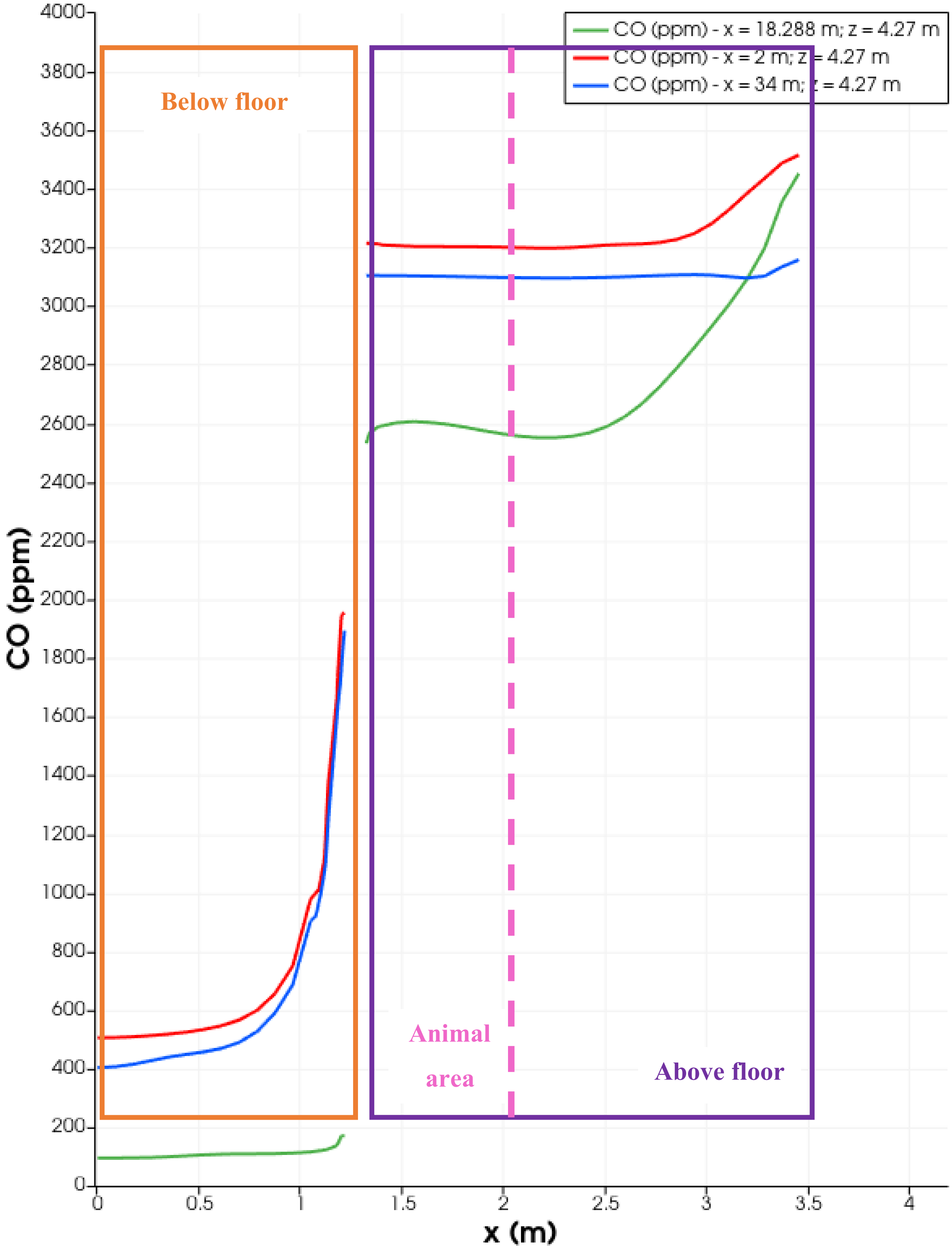

Figure 11: CO concentration at t = 1,800 s along three vertical lines spanning the entire height of the barn. Simulation with 1.5 ACH and heat source due to the animals.

Specifically, it tends to be higher for lines close to an inlet. Since CO is lighter than air, all the lines show a higher CO concentration outside of the area occupied by the animals, with increasing values when moving towards the barn ceiling. However, it is worth observing that for none of the considered lines, the concentration of CO reaches the desired value of 4,000 ppm within 30 minutes.

Finally, while not explicitly quantified during the simulations, it is expected that the accumulation of CO in areas responsible for the building envelope exfiltration, such as the ceiling, may lead to CO leaks in the environment.

On-Farm Generation and Use of CO

Table 3 summarizes the technologies investigated for on-farm generation and procurement of CO. Based on this research it is our opinion that pure, compressed CO from a gas supplier is the most viable option for use of CO in depopulation when considering safety (i.e., for operator and animals), capital and operating costs, availability of off-shelf components and materials and overall system reliability.

Linde Gas and Equipment is the primary supplier of CO for industrial use in the US. At the start project, the regional sales team at Linde was in engaged to understand the potential to purchase CO for depopulation. It was determined that use of CO for depopulation was not a restricted use; however, CO would need to be regionally approved for this application. Further discussion with Linde yielded the following statement from their corporate research team:

"Sales of inert gas (pure or mixture) where the planned use is as an asphyxiant or toxin to be applied to animal is prohibited, without a formal company product risk review (e.g., turkey stunning)".

At present, the only barrier to Linde completing their risk review is proper justification of the market potential. Estimation of CO usage for emergency depopulation, as well as daily animal euthanasia was provided to Linde; however, engagement of the National Pork Board in this discussion would likely be needed for Linde to commit to a risk review for sales of CO for depopulation.

Table 3. Summary of technologies for on-farm generation of carbon monoxide.

Methods	Description	Pros/Cons
Planned Approach: Incompletion combustion of propane + oxygen stripping	Control oxygen available to propane gas burner to shift CO_2 to CO in flue gases; concentrating CO by passing gases through high-temp carbon bed	- Incomplete combustion uses off-the-shelf components - Precise control of O_2 is necessary during startup - CO is generated at the front end of the system - Significant time for carbon bed to reach steady-state operating conditions - High temperature of gas stream entering building
Incompletion combustion of propane	Control oxygen available to propane gas burner to shift CO_2 to CO in flue gases	- Uses off-the-shelf components - Precise control of O_2 is necessary during startup
Complete combustion of propane + electrolysis	CO_2 in flue gases from propane combustion converted to CO by electrolysis	- H_2O in flue gas converted to H_2 which is highly combustible - Requires drying of flue gases, but flue gas temp is constraint for low-cost air-drying systems
Electrolysis using proton-exchange membranes cells with compressed CO_2 feed gas	Converting CO_2 to CO with low-cost fuel cell units operated in reverse	- Uses off-the-shelf components - Operated at ambient conditions - CO_2 can be toxic to PEM cells and life of cells is unknown
Electrolysis using solid oxide electrolysis cell with compressed CO_2 feed gas	Converting CO_2 to CO with solid fuel electrolysis systems n	- 60% conversion of CO_2 to CO - High temperature - High potential but early in technology development - $500K to 1M for turnkey system

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