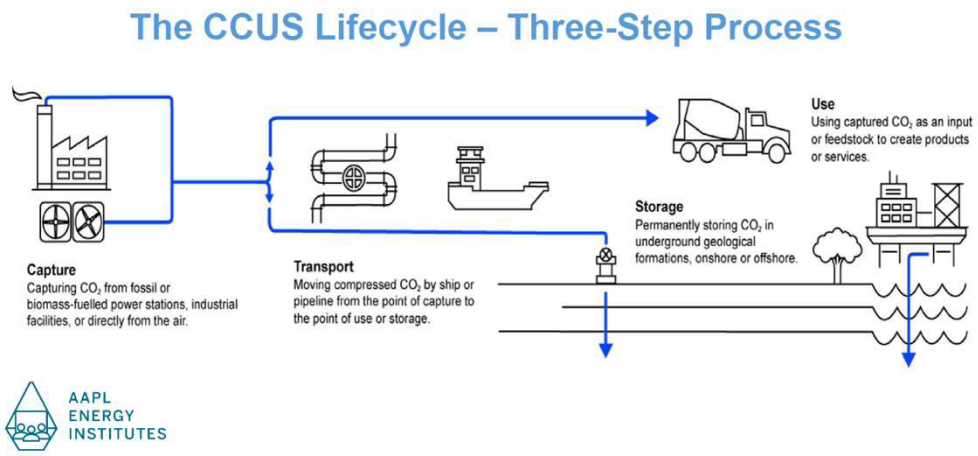
Indoor Carbon Dioxide Loading Following a Simulated Carbon Dioxide Pipeline Release

CTEH®

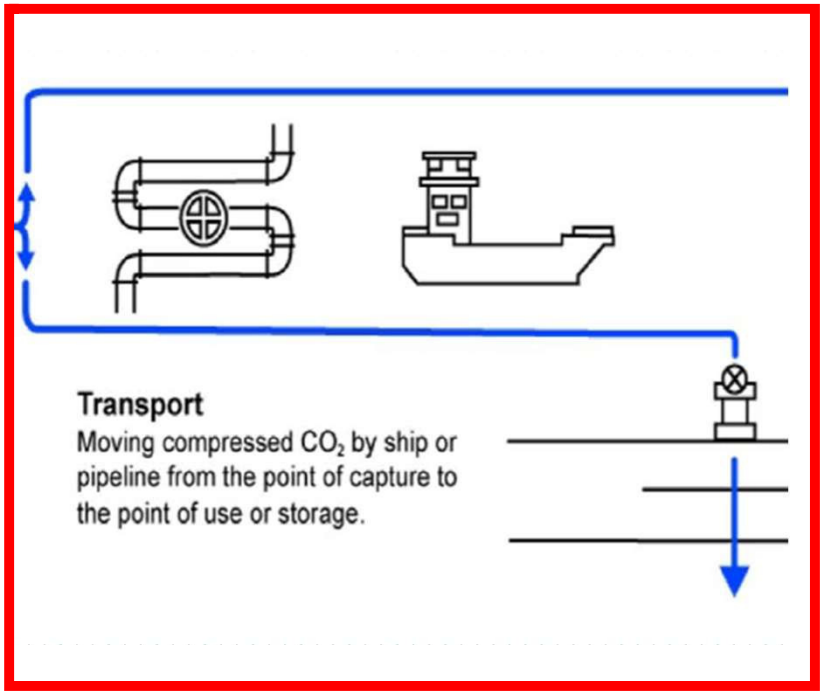
CTEH has significant experience with carbon capture



- CTEH has responded too and performed industrial hygiene assessment for more than 25 separate sites and incidences across the life cycle
  - Capture
  - Transport
  - Storage
  - Use

Carbon Capture is Growing

- US currently has 5,000 miles of CO_2 transport pipeline
  - 3,000,000 miles of pipeline that transports natural gas
  - 84,000 miles of pipeline carrying crude oil
  - 75,000 miles of pipeline that transport hazardous liquids (ammonia/propane)



"Annual Report Mileage for Hazardous Liquid or Carbon Dioxide Systems."
U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, July 2024.

People are concerned

- Failures rates are similar to those for oil and gas pipelines
- US recorded 3 rupture accidents related to onshore CO_2 pipelines between 1986 and 2021
  - Satartia, MS incident was precipitated by a landslide
- Between 1994 and 2021
  - 48%= leaks
  - 3%= ruptures
  - 49%= sinkholes, extraction process, etc.

Vitali, Matteo et. al, "Statistical analysis of incidents on onshore CO_2 pipelines based on PHMSA database." *Journal of Loss Prevention in the Process Industries*, Volume 77, July 2022, doi:10.1016/j.jlp.2022.104799

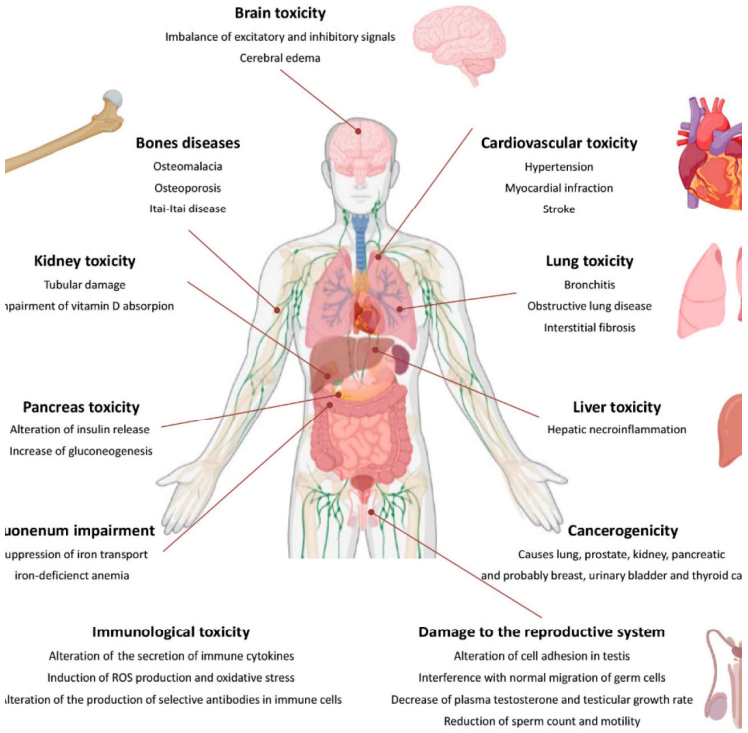
Is this concern toxicolgically warranted?

- CO_2 is a colorless odorless gas
  - 0.0423% (423 ppm) of the atmosphere
  - 800-1,000 ppm indoor building
  - 5,000 ppm: max occupational exposure for 8 hours
- During transport, CO_2 is transported at high pressure, as a supercritical liquid which can cause freezing
  - The main concern is related to people breathing in levels of CO_2 that cause intoxication, unconsciousness and asphyxiation

https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

What are the main levels of concern during a rupture?

- Toxicity reference values are based on preventing asphyxiation and acute intoxication
  - Immediately dangerous to health or life (NIOSH): 40,000 ppm
  - Provisional Acute Exposure Guideline Levels (AEGL): 30,000-50,00 ppm
    - Headaches, dizziness, nausea
  - ACGIH STEL: 30,000 ppm for 15 minutes
  - 70,000-100,000 ppm
    - dimmed sight, trembling, sweating, and unconsciousness



https://www.cdc.gov/niosh/idlh/124389.html

What is the best advice to give people in the case of ruptures?

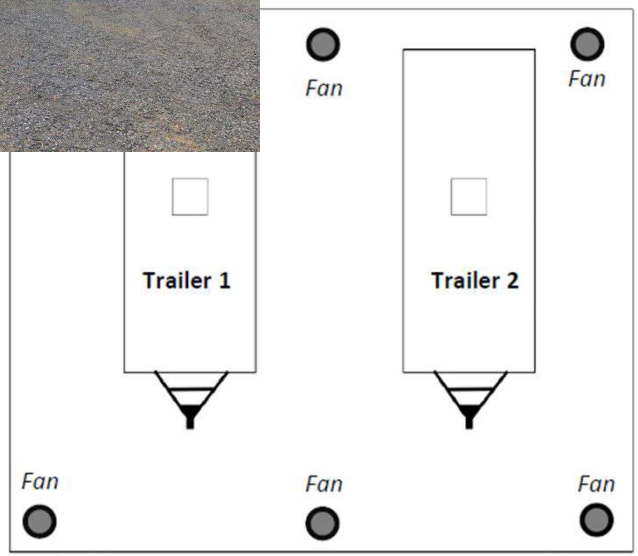
- **If such an incident was to occur in the future, what should the recommendations be to impacted residents': shelter in place or evacuate?**
- In the case of Satartia:
  - The highest measured concentration was 28,000 ppm
  - The highest modeled concentration was 33,316 ppm

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf
https://www.sciencedirect.com/science/article/pii/S0950423026000185

How much would people be exposed to under a shelter in place order?

1. How much CO_2 is generated during a shelter in place event?
2. What happens to CO_2 and O_2 during inside a structure during a release event?

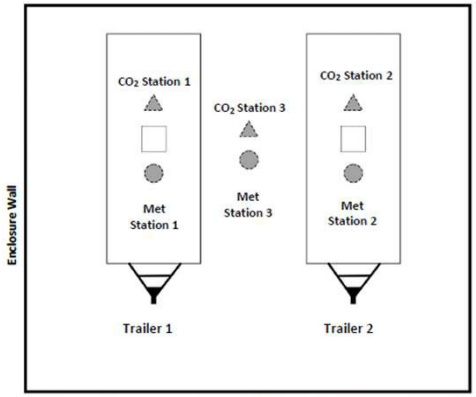
Experimental set-up



- Placed 2 camper trailers into a tented enclosure
- Weighted Sandbags were used to hold the bottom of the tent close to the ground surface and tape was used to seal pinpoint holes
- Fans were placed to ensure rapid mixing of CO2

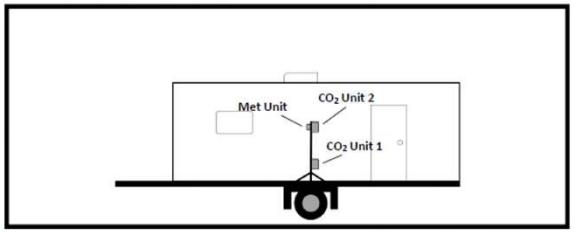
Monitoring Equipment

- Remote monitoring equipment was placed into each trailer to transmit readings either every 1 second or every 20 seconds depending on the compound
  - Adult breathing zone= 63-69 inches above ground
  - Floor(Toddler) breathing zone= 24 inches
- Additional remote unit placed within the tent to monitor “ambient” air concentrations



Met stations consist of instruments capable of measuring temperature, relative humidity, and ambient pressure.

Figure 2.6 Trailer Interior Remote Data/Logging Monitoring Locations (Side View)



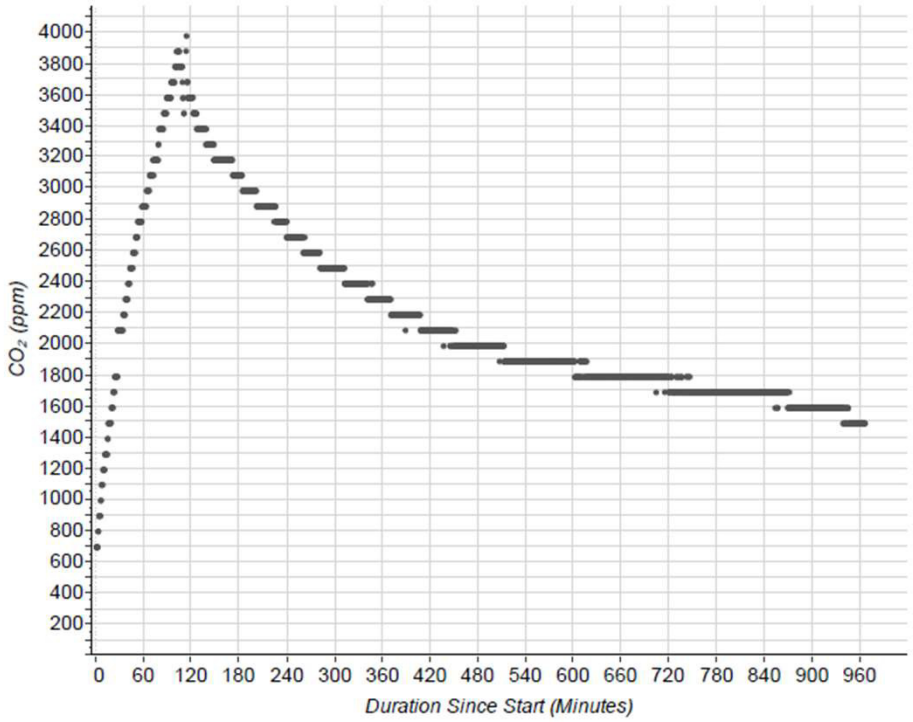
How much CO_2 is generated during a shelter in place event?

- People expire CO_2, so a SIP will result in CO_2 building up inside a house
- GOAL: measure the proportion of CO_2 contributed by trailer occupants
- 4 adults occupied trailer 1 for approximately 1.5 hours
  - Sitting, standing, walking, talking

CO_2 Loading by Occupants

- CO_2 concentrations peak around 4,000 ppm
- Used this to estimate that 4 adults within a 1,700 ft3 structure will preload the structure by Shelter-in-place

Figure 3.1 CO_2 Loading and Clearance Profile Following Trailer 1 Occupancy



How much external CO_2 ends up inside the structure during a release event?

Figure 2.3 CO_2 Manifold and Pipe Inlet to Tent Enclosure.

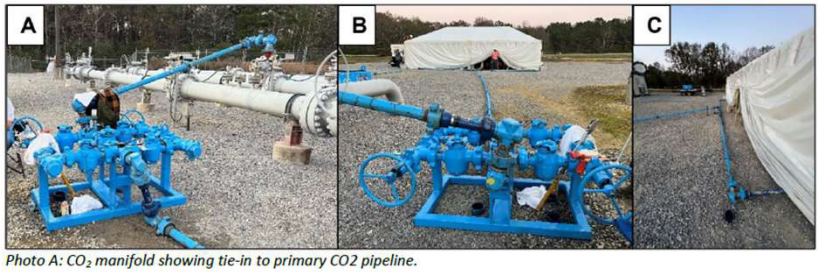


Photo A: CO_2 manifold showing tie-in to primary CO2 pipeline.
Photo B: CO_2 manifold showing leading pipeline to tent enclosure.
Photo C: Pipeline inlet to the front and back of the trailers inside of the tent enclosure.

Table 2.2 Supplied Gas Mixture

Carbon Dioxide (CO_2)	≥ 99.3%	≥ 993,000 ppm
Hydrogen Sulfide (H_2S)	< 0.001 %	< 10 ppm
Methane (CH_4)	0.30%	3,000 ppm
Nitrogen (N_2)	0.30%	3,000 ppm

- Mixture supplied to the tent came from a manually actuated manifold
- Certificate of analysis was supplied to ensure supplied gas was correctly characterized
  - Using the supplied gas will better help characterize what an actual release will look like rather than an purified gas

How much external CO_2 ends up inside the structure during a release event?

Figure 2.7 CO_2 Study Tests

	CO_2 Concentration (ppm)
Test 1	10,000
Test 2	20,000
Test 3	30,000
Test 4	40,000

- Tested each concentration in response to a 4-hour outdoor environment
- During the tested doors, vents and windows are fully closed
  - No active ventilation during the 4-hour period
- Used active ventilation to clear residual CO_2 between each of the different studies

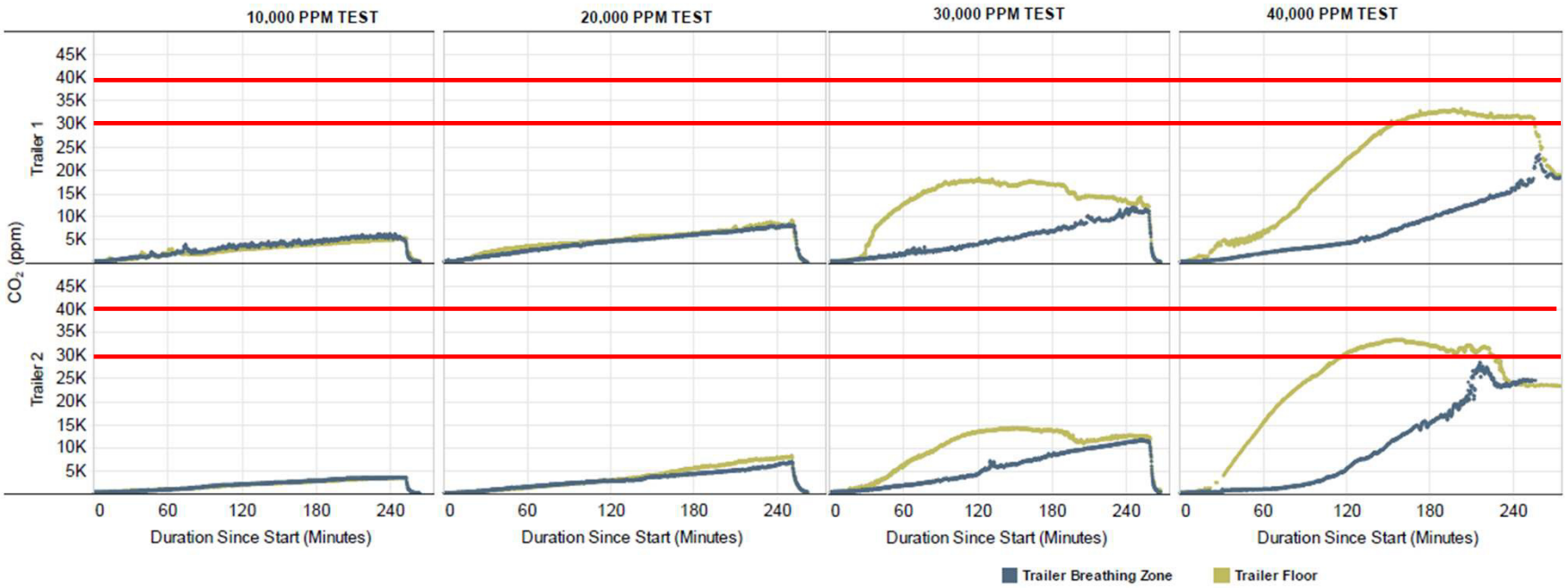
If you are outside during a CO_2 release, what concentrations are you exposed too?

Table 2. Target and Actual Measured CO_2 Level in Tent Breathing Zone

Target CO2 Concentrations (ppm)	Measured Average Ground CO_2 Concentrations (ppm)	Measured Average Breathing Zone CO_2 Concentrations (ppm)	Measured Average Rooftop CO_2 Concentrations (ppm)	Measured Overall Average CO_2 Concentrations (ppm)
10,000	10,891	10,613	10,576	10,664
20,000	20,861	20,724	19,531	20,168
30,000	29,991	30,484	28,272	29,266
40,000	41,250	40,426	38,242	39,543

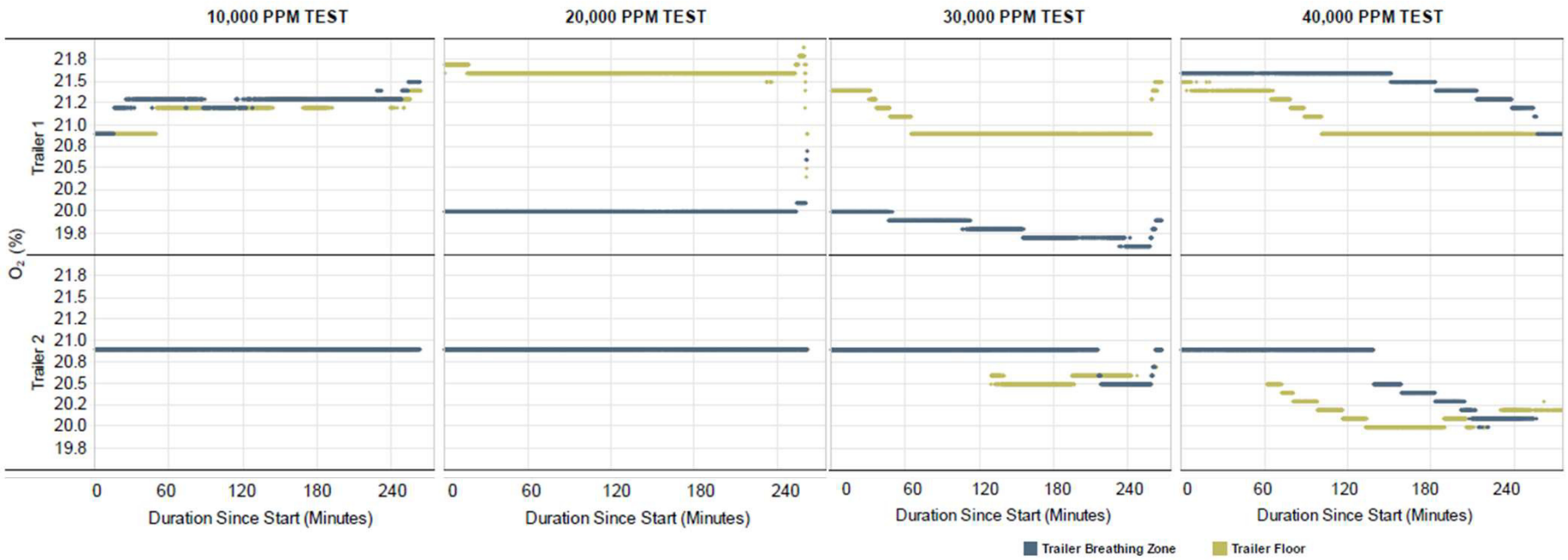
- Well mixed

Inside what kinds of CO_2 concentrations are you exposed too?



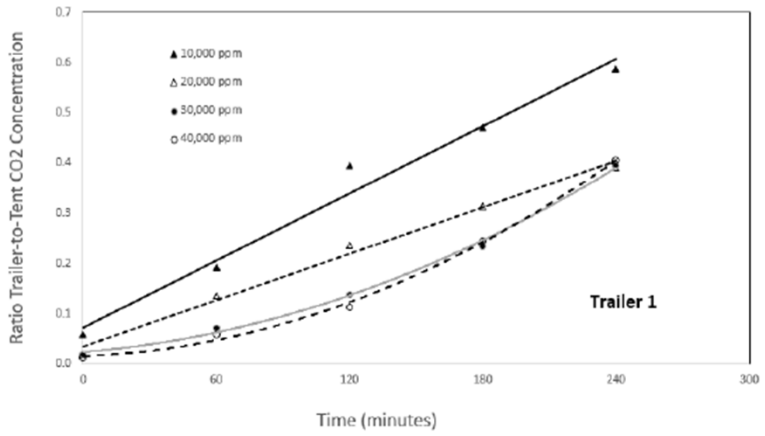
- With the exception of 40,000 ppm, everything is below the AEGL-1 level (30,000 ppm)
- No exposure exceeds the IDLH (40,000 ppm)
- Differences between trailers suggests construction matters

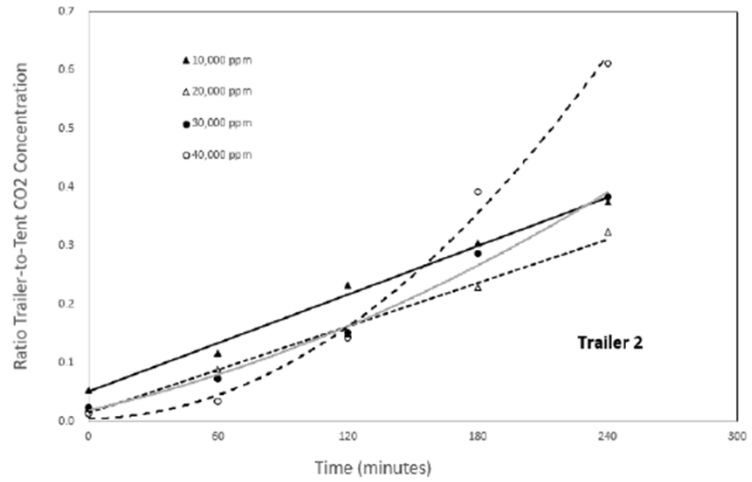
Inside what kinds of O_2 concentrations are you exposed too?



- Oxygen deficient; danger of asphyxiation, dizziness, and death=19.5%
- Lowest observed level was 19.8%

How does the ratio of internal to external CO_2 change over time?

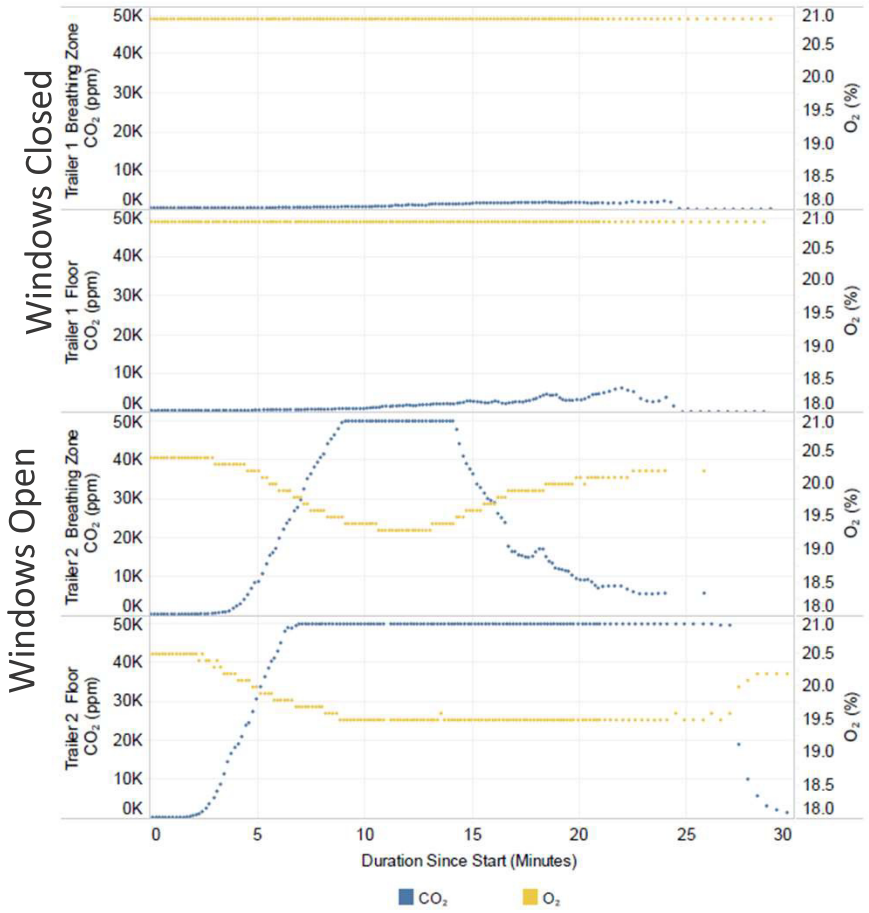




- Question: how do concentrations inside a space change over time given a constant level outside of the space?
- The ratio of inside to outside rise linearly over time
  - i.e. The longer the external concentration is high, the more CO_2 will accumulate internally

Does sealing the structure matter?

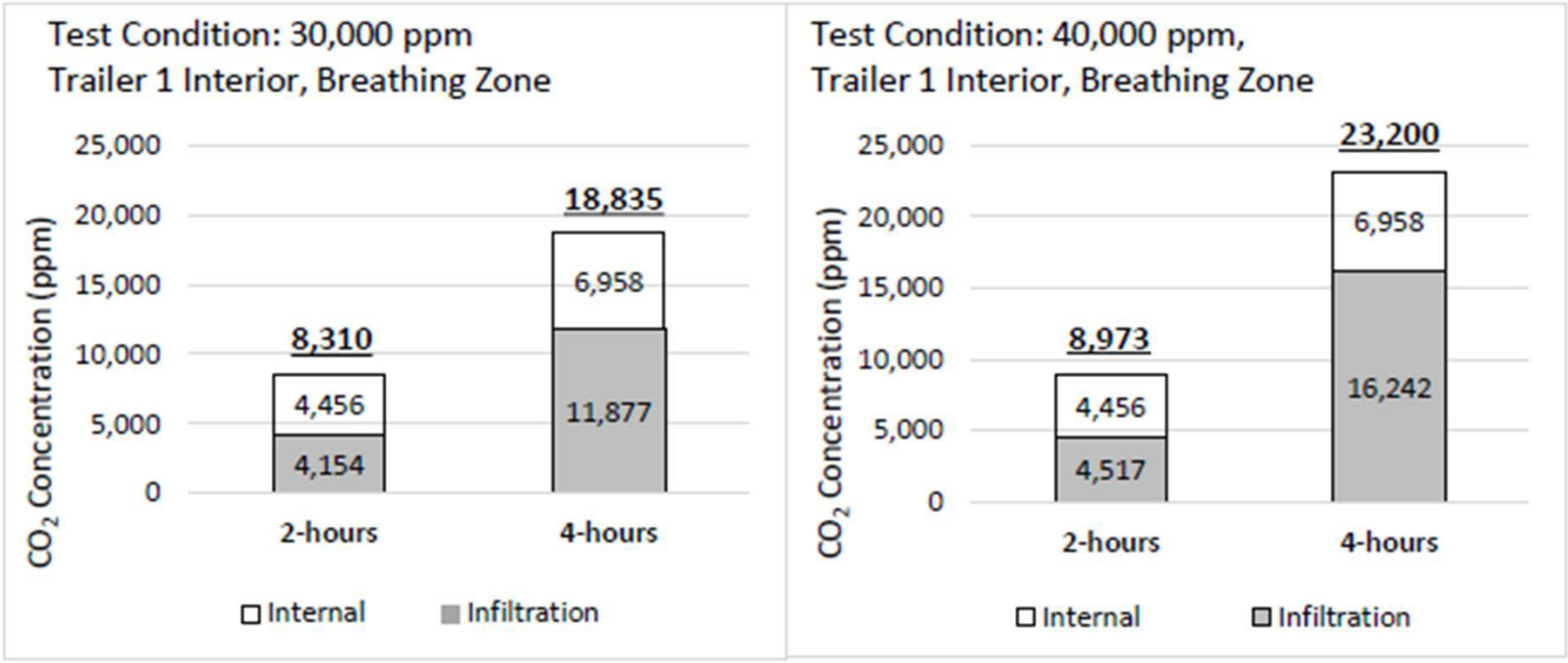
Figure 3.9 CO_2 and O2 Inside the Trailer 1 (windows closed) and Trailer 2 (windows open) During CO_2 Maximum Loading Test



- Compared the levels with the windows open vs. windows closed
  - With windows open, there is no difference from the external atmosphere for the most part
  - With windows closed, CO_2 and O_2 readjust towards a safe environment more rapidly

How much CO_2 is associated with internal CO_2 vs. external CO_2 if everything is closed?

Figure 4.2. Estimated Cumulative Infiltrated and Internally Generated CO_2 Concentrations in Trailer 1.



Findings

- Sheltering in Place with all windows and doors closed as well as shutting off outdoor air intakes is a reasonable strategy in the event of a CO_2 pipeline rupture with respect to CO_2 concentrations and O_2 during simulated events
  - Distance from site: closer=higher exposure for longer time periods
  - Location and meteorology= winds can shift and cause exposures at higher levels
  - Building type= Is it a commercial buildings without access to shut off ventilation buildings
  - Duration= if the pipeline has a emergency shut off valve, how much residual is left in the pipeline: if less than 2 hours SIP is a better option
- Differences in construction appear to impact the amount of CO_2 and O_2 exposure

Limitations

- Used camper trailers in place of actual homes
  - More or less sealed depending on construction
- Only used two trailers
  - Could be more variability in structures
- Did not assess for other potential gas contribution
  - There are contributions from H_2S and CH_4
  - <10 ppm H_2S in this line but it could be different depending on source

Bottom Line

- There is a need for well-defined emergency response plan for these pipelines
  - Who is communicating?
  - How is communication being disseminated?
  - Are appropriate instructions being relayed appropriately (shut windows, doors, shut off AC, etc.)?

Questions?

Thank You!