Evolution of Diesel Exhaust Particulate Matter in a Ventilated Mine Tunnel

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Objectives

- To investigate the evolution of aerosols in the exhaust plume of a non-road diesel engine operating in an underground mine under typical ventilation and mixing conditions.

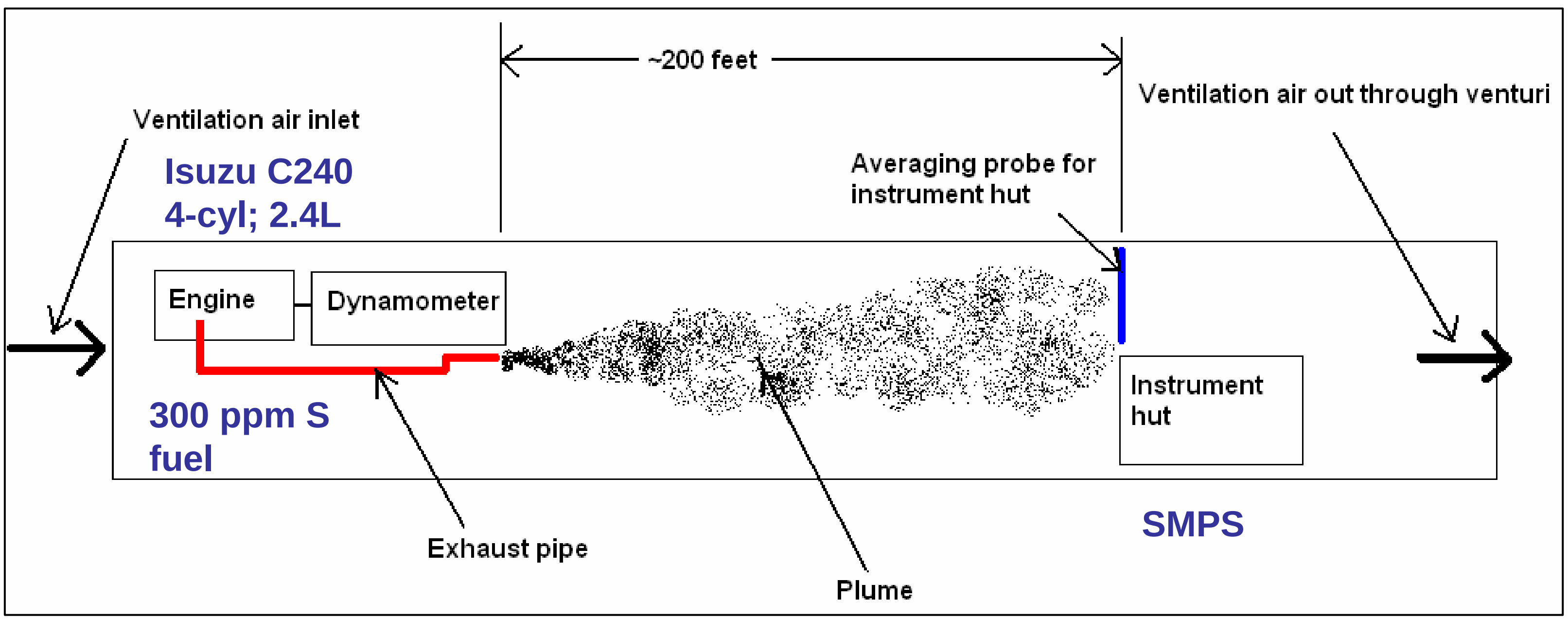
- To develop an efficient method of generating comprehensive spatial maps of the exhaust plume inside the mine tunnel.

Introduction

- The formation and evolution of diesel exhaust aerosols depends on a number of variables (for example, dilution ratio (DR), temperature, and residence time).
- Within a naturally occurring exhaust plume, these variables can collectively assume many different states throughout space and in time.
- Laboratory dilution tunnel studies of uniformly mixed exhaust streams fail to account for those states.
- Furthermore, an exhaust plume carries developing aerosols through a multitude of differing states, which are not typically observed in laboratory dilution tunnels.
- As such, emissions maps are necessary for better understanding and characterizing aerosol formation and evolution.

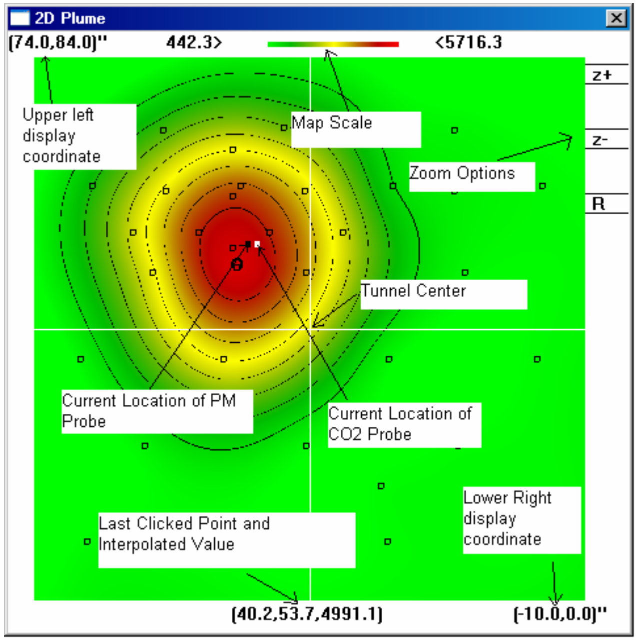
Approach

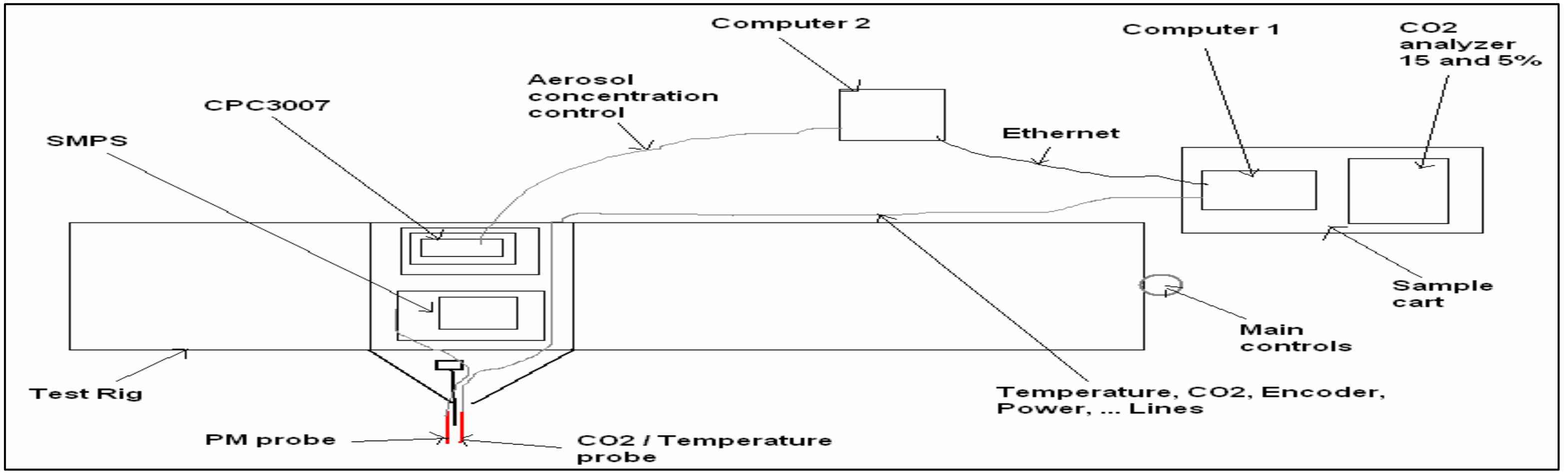
- **The study is conducted in the experimental mine tunnel at the Lake Lynn Laboratory established by the National Institute for Occupational Safety and Health (NIOSH).**
- **Aerosol evolutionary trends are measured within the 200- foot test section of 20 by 7 foot drift between the engine / dynamometer system and instrument hut.**
- **The measurements allowed for obtaining an sequence of cross-sectional aerosol size distribution maps**.

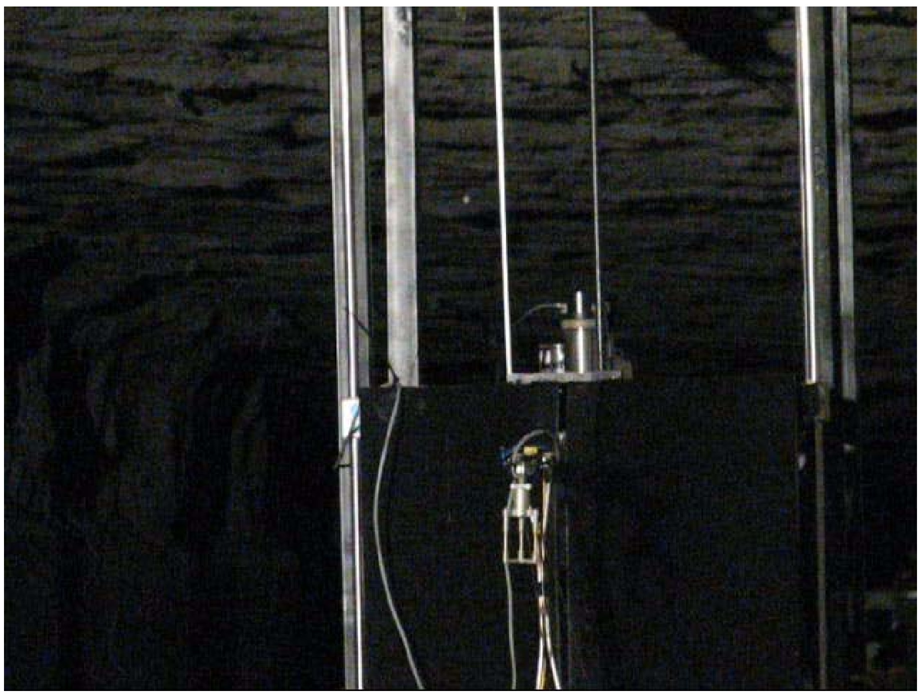


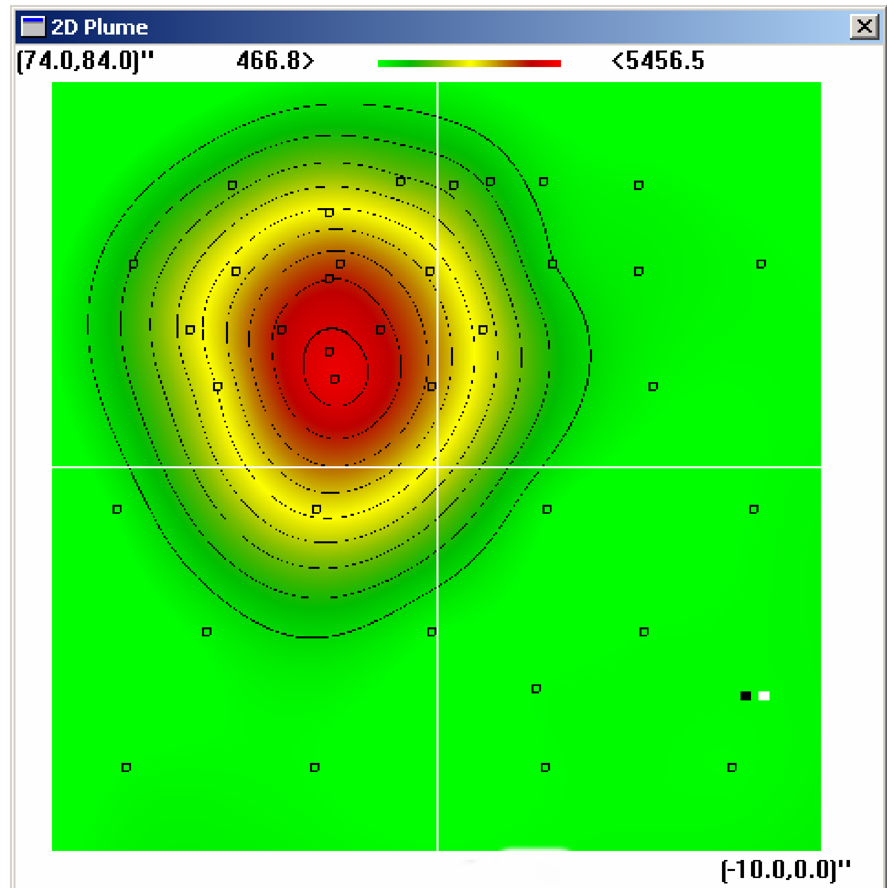
Approach

- A custom built digital 2-axis traversing probe allowed ~84 inches of continuous horizontal and vertical travel, geared to an encoder resolution of ~0.1 inch.
- Mapping software was also created and interfaced with the device to improve sample efficiency.
- This software allowed the operator to continuously view the sampling probes as they appeared projected on top of interpolated predictions of CO_2, temperature, and aerosol concentration (based on past samples).
- These maps were then used to strategically position the probe for more time exhaustive sampling and determining aerosol size distributions and concentrations.

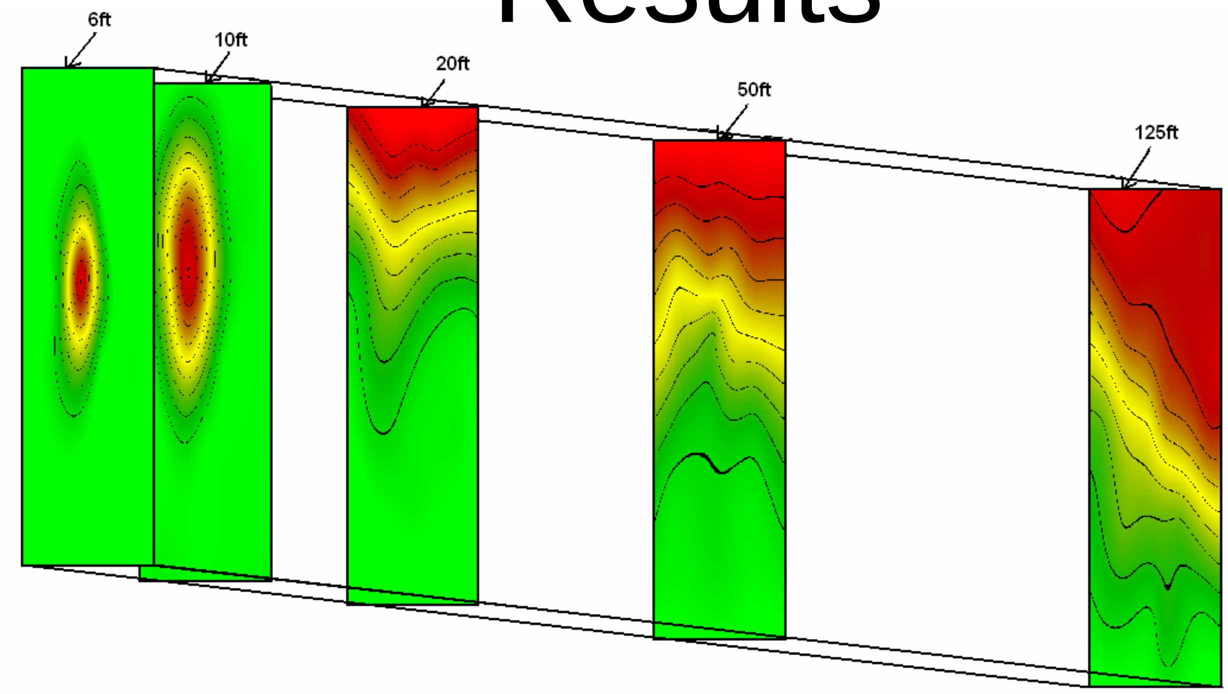



Computer 2
Computer 1
CO2 analyzer 15 and 5%
Aerosol concentration control
CPC3007
SMPS
Ethernet
Sample cart
Main controls
Test Rig
Temperature, CO2, Encoder, Power, ... Lines
PM probe
CO2 / Temperature probe




2D Plume
(74.0,84.0)"
466.8>
<5456.5
(-10.0,0.0)"

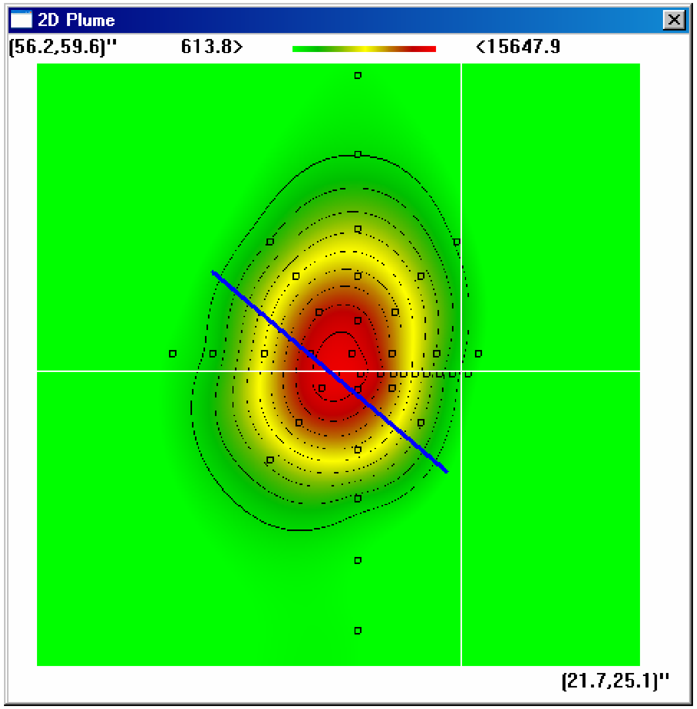
Results

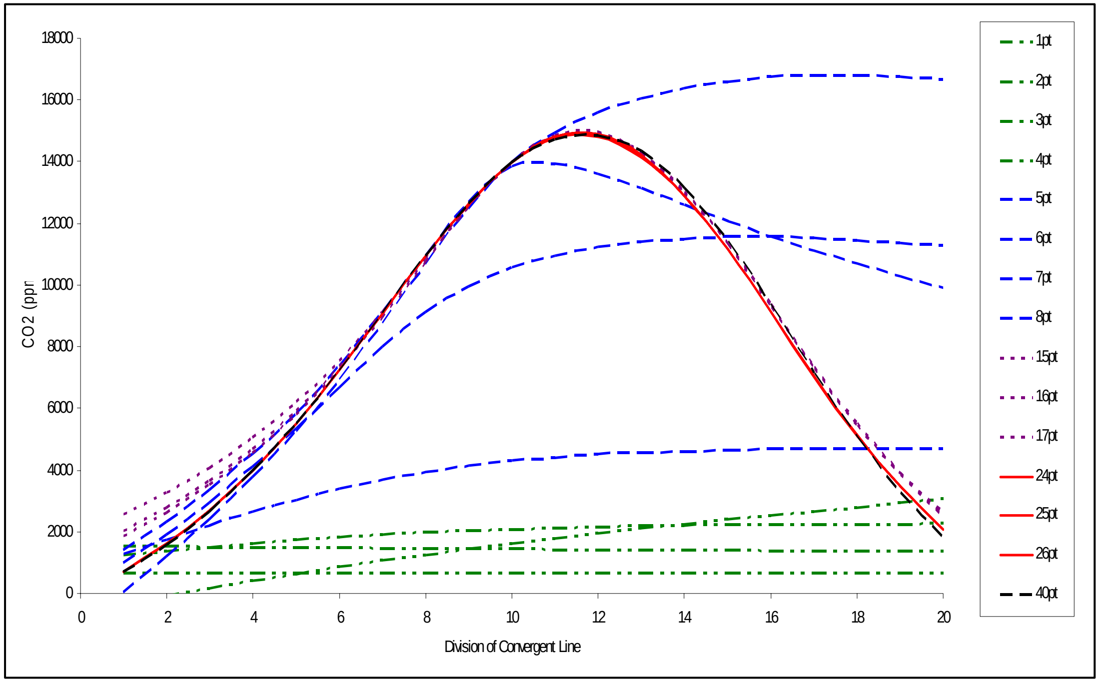


- Each map provided details concerning localized gradients and contours of the plume.
- These demonstrate the overall tendency of the plume to rise and form stratified layers (due to buoyancy and tunnel slope) .

Results

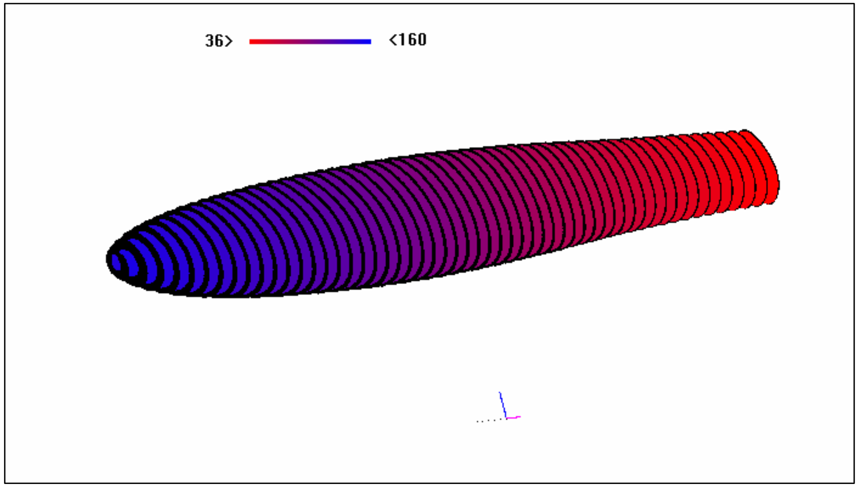
- Each map was converged to, upon acquiring a number of single point exhaust averages.
- Each emerging map was resolved by driving the probes into regions which appeared irregular and extracting further samples.
- This process would be repeated until no further improvement of the map could be detected.
- To aid in the visualization of convergence, an arbitrary line was drawn through the mapped region, whose exhaust distribution was monitored with advancing sample number.

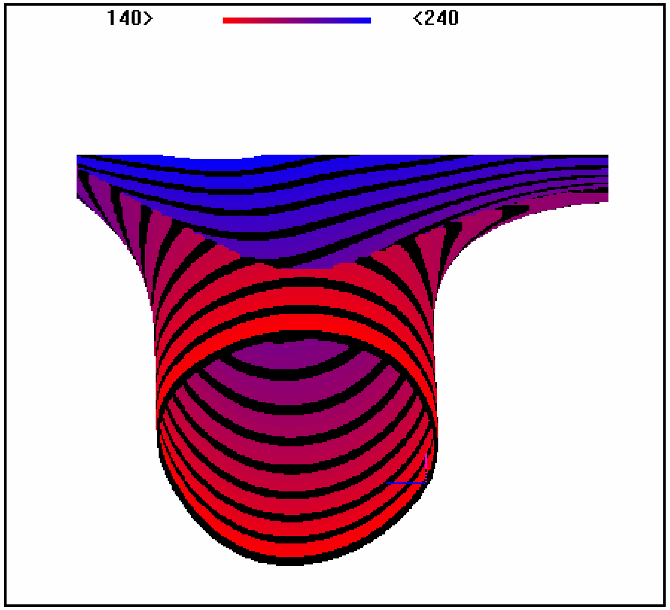




Results

- It became apparent that natural dilution contours occurred as 3-dimensional surfaces.
- These surfaces were found to have two basic forms within the tunnel.
- Lower dilution levels were defined by conical geometries that closed at given axial locations.
- Larger dilution levels started out conical and split into stratified layers upon contact with the ceiling.
- These surfaces should ultimately collapse into a single dilution solid representing fully mixed flow.
- However, this solid was not observed for the entire 200-foot test region.



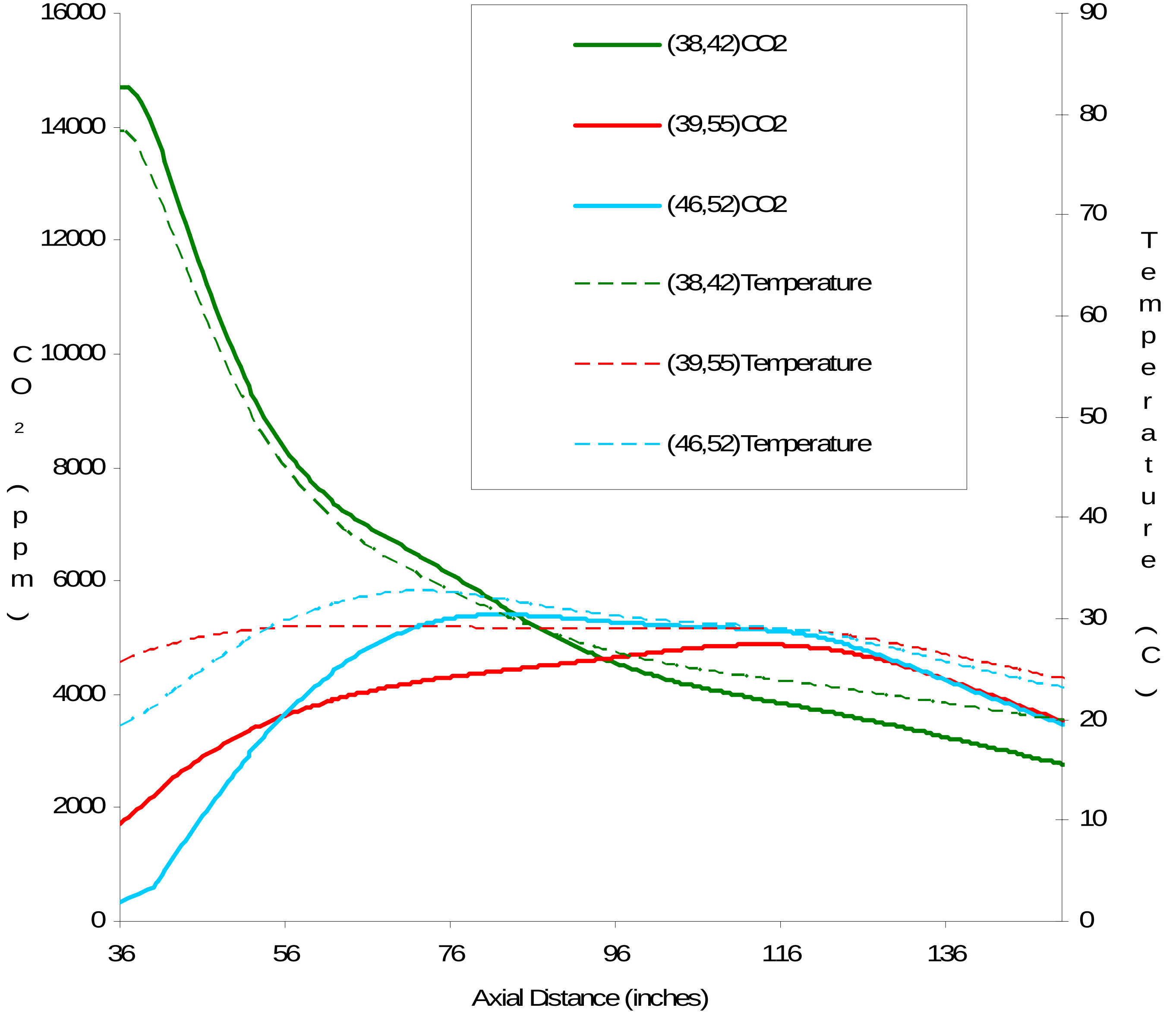


Results

- In addition, contours of dilution were not found to be spatially consistent with other recorded exhaust scalars.

- This increases the perceived difficulty in addressing issues such as residence time and furthers arguments for studying aerosol evolution based on natural exhaust paths.

Results



16000
14000
12000
10000
8000
6000
4000
2000
0
CO2 (ppm)
90
80
70
60
50
40
30
20
10
0
Temperature (C)
36
56
76
96
116
136
Axial Distance (inches)
(38,42)CO2
(39,55)CO2
(46,52)CO2
(38,42)Temperature
(39,55)Temperature
(46,52)Temperature

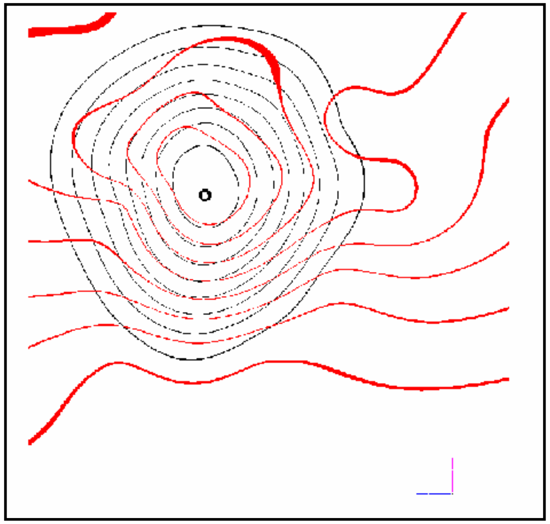
Results

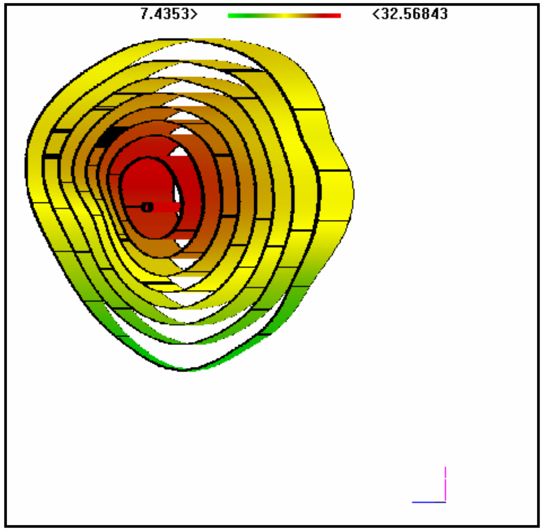
- Contact with the tunnel ceiling lead to increased dissimilarities in the expansion patterns of CO_2 concentration and temperature.

- Ceiling contact was in part responsible for a premature stratification of the temperature contours.

- As such, waviness in the temperature maps can be expected from this non-steady state event.

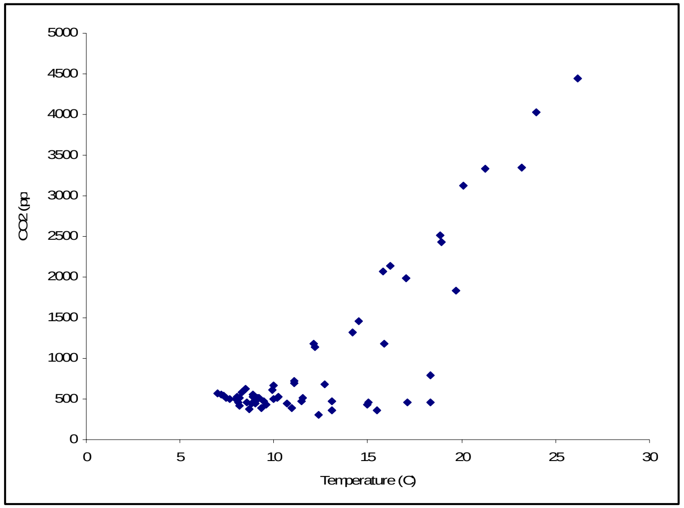
- Since contours of CO_2 concentration and temperature were not found in agreement, the scalars had to be compared to establish which if any provide a better indication of aerosol evolution.

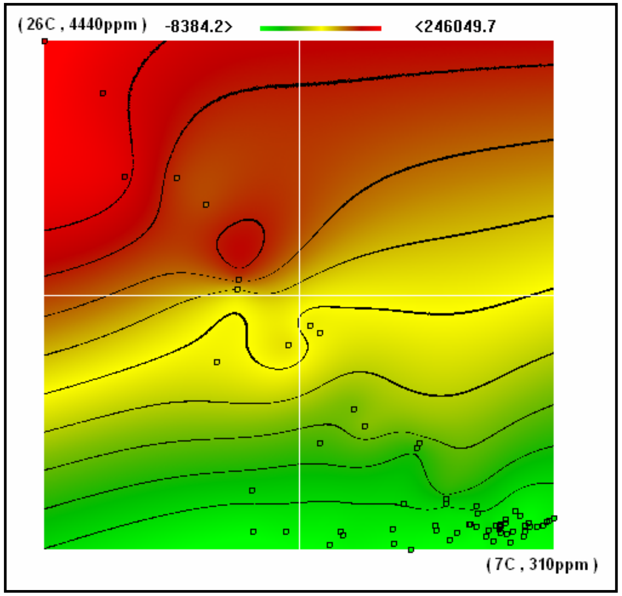




Results

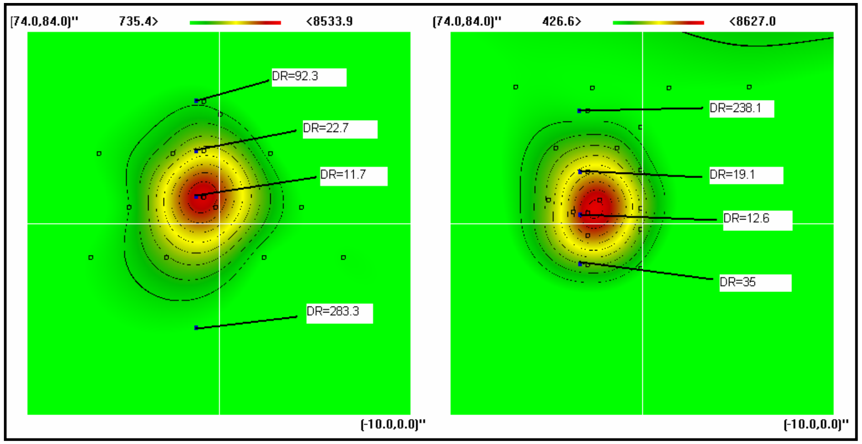
- To investigate potential issues caused by temperature and CO_2 concentration contour dissimilarity, the maps were compared to their spatial relationship to aerosol concentration.
- Comparisons were made through a uniform spatial grid applied to each of the maps in order to pull out natural groupings of CO_2 concentration, temperature, and aerosol concentration.
- The resulting coordinates of CO_2 concentrations and temperature were ordered and mapped for aerosol concentration. A stronger spatial connection to CO_2 was observed.
- As such, CO_2 concentration became the primary parameter used for placing aerosol size distribution samples.



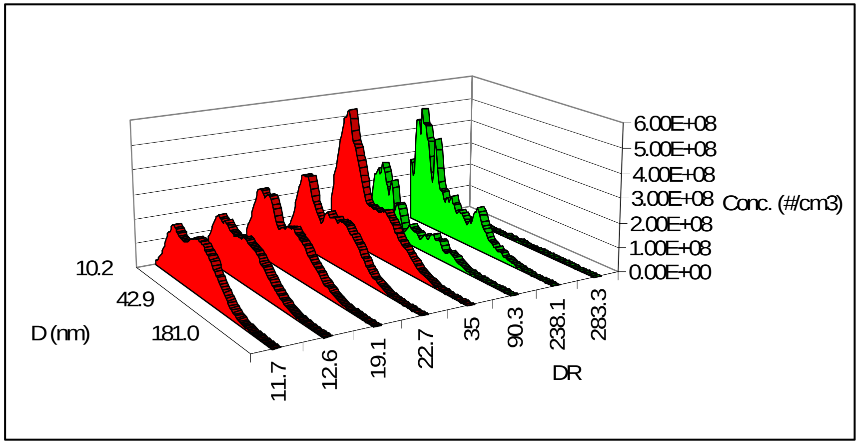


Results (6 feet)

- The results of measurements at the 6-foot station indicate increase in a concentration of aerosols in the nuclei mode towards the edges of the plume and a relatively invariant concentrations of aerosols in the accumulation mode.

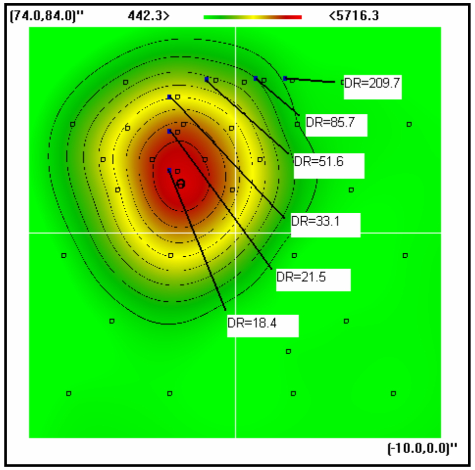


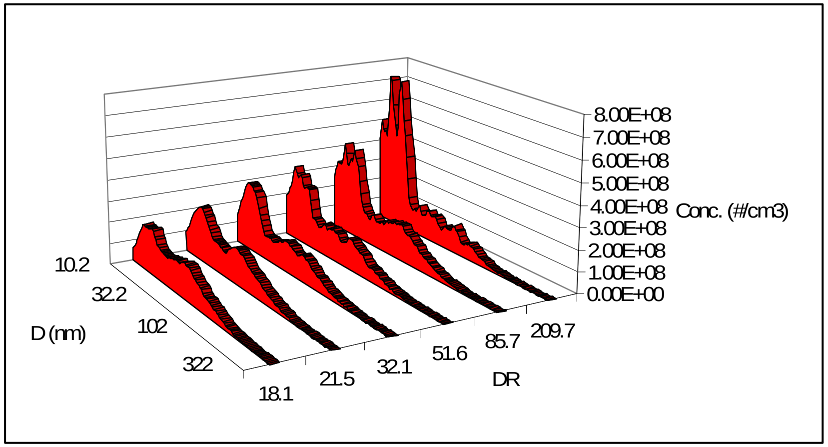
- The measurements in the outer region of the plume were found to had a larger amount of uncertainty.



Results (10 feet)

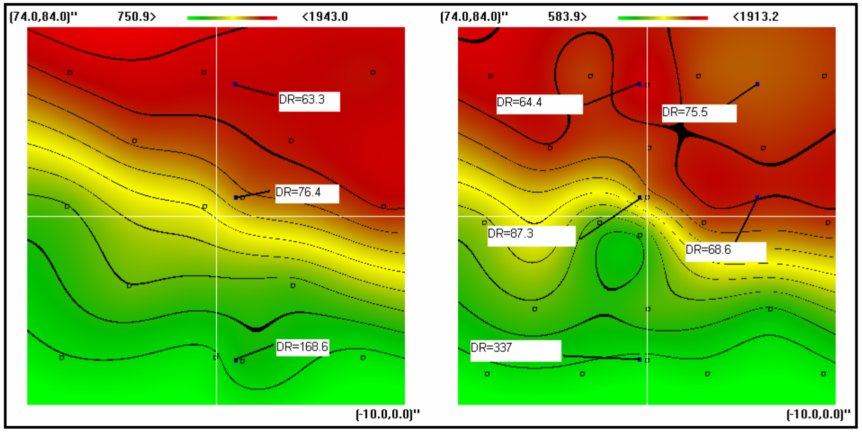
- **The results found at the 10-foot station are similar to those found at the 6-foot station.**
- **However, the peak particle concentrations of the nuclei mode are noticeably larger than at 6 feet, suggesting a continued particle growth.**
- **This may be an indication of residence time effects and/or continued dilution.**
- **It is apparent that relatively strong correlation between CO_2 and aerosols field has held for this particular axial distance.**

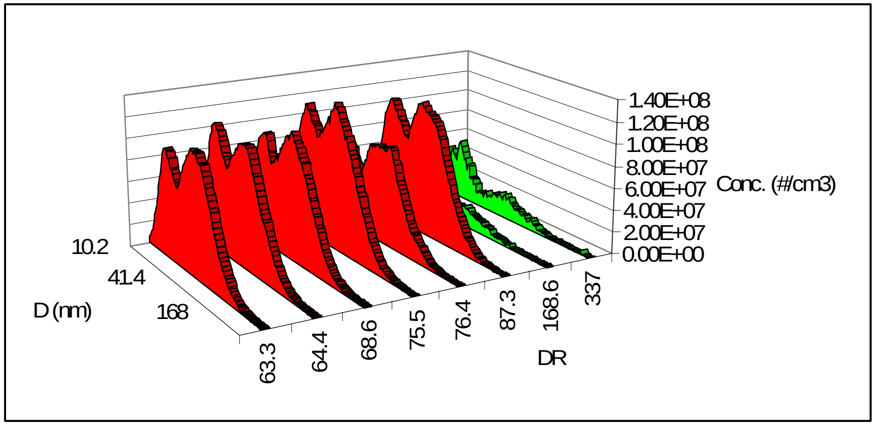




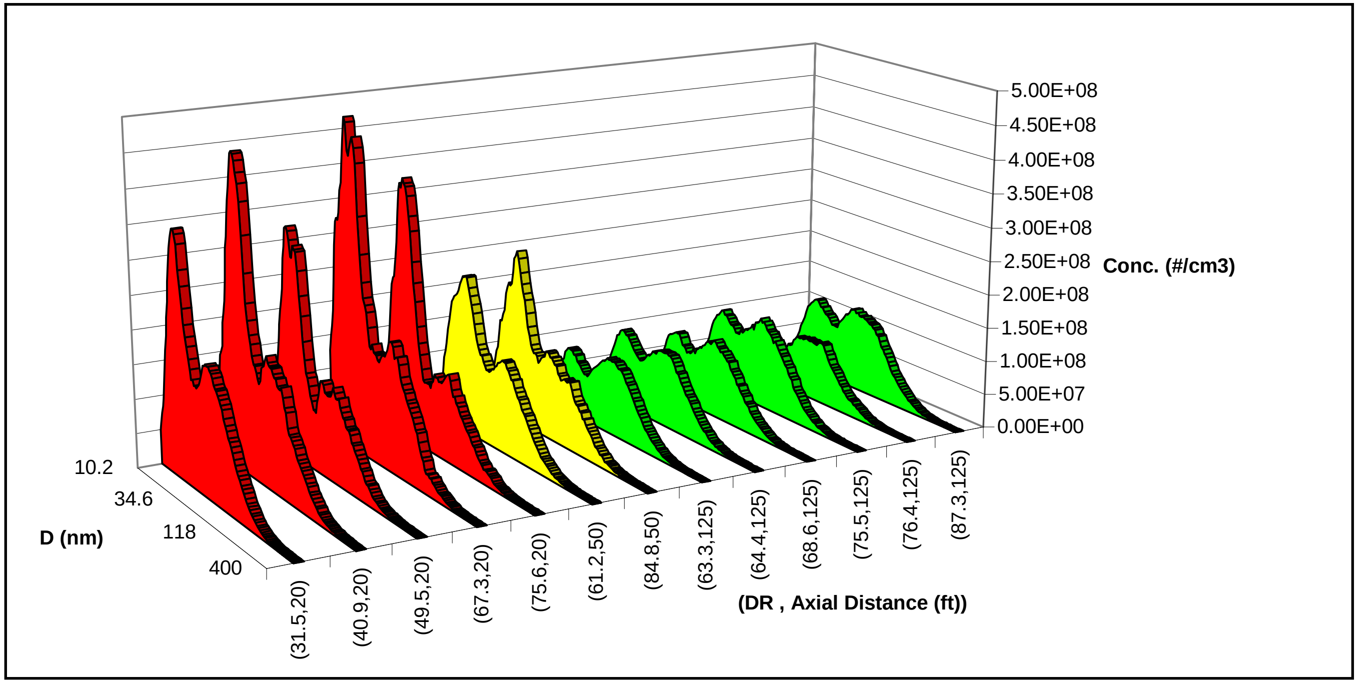
Results (125 feet)

- The plume was found fully stratified at 125-foot station (continued from an axial distance of ~20 feet).
- As in the 6 foot case, scalar maps and aerosol size distributions of the 125-foot station were taken on two different test dates.
- Waviness in the second map was triggered by work being performed during the scan, which required frequent travel by personnel through the tunnel test region during the second test.
- A slanting of both contours was due to tunnel slope and leveling of the test apparatus. However, this does not affect the overall characteristics of the maps and can be resolved in the future through a coupled calibration of the encoder inputs.
- Aerosol size distributions at 125-foot station were relatively constant and unbiased towards dilution ratio. However, the most diluted regions of these maps still contain aerosols with noticeable concentrations of particles in nuclei modes whose overall concentrations are reduced.





Results



- Dilution ratio specific size distributions of aerosols measured on the locations beyond 20-foot section were found to have reduced concentrations of aerosols in the nuclei mode.
- The dilution ratio specific concentrations of aerosols in the accumulation mode are much less variable throughout the test section (125 feet).

Conclusions

- **The testing procedures developed during this study have proven to provide a fairly efficient means of obtaining relatively detailed information on aerosol evolution.**
- **These characteristics were taken from a naturally occurring plume in contrast to forced laboratory mixing.**
- **The results demonstrate a relatively invariant dilution-specific accumulation mode throughout the entire 125-foot test region.**
- **However, nuclei mode concentrations changed for almost an order of magnitude over the distances spanning just a few feet.**
- **In addition, the concentrations of aerosols in nuclei mode were found to have a much stronger spatial correlation to the concentrations of CO_2 than any other recorded exhaust variable.**
- **The results of this study also shed light into the complicated paths traveled by aerosol particles as they develop under natural mixing.**
- **These paths are marked by continually changing exhaust states which are known to affect particle evolution.**