Title: A Personal Exposure Study Employing Scripted Activities and Paths in Conjunction with Atmospheric Releases of Perfluorocarbon Tracers in Manhattan, New York

Running Title: Prospective Urban Exposure Study


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Abstract
A personal exposure study was conducted in New York City as part of the Urban Dispersion Program (UDP). It examined the contact of individuals with four harmless perfluorocarbon tracers (PFT) released in Midtown Manhattan at separate locations, during two types of experiments, completed during each release period. Two continuous 1 hr release periods separated by a 1.5 hr ventilation time were completed on 3/10/2005. Stationary site and personal exposure measurements were taken during each period, and the first half hour after the release ended. Two types of scripted exposure activities are reported: Outdoor Source Scale, and Outdoor Neighborhood scale; requiring 1-minute and 10-minute duration samples, respectively. The results showed that exposures were influenced by the surface winds, the urban terrain, and the movements of people and vehicles typical in urban centers. The source scale exposure data indicated that local conditions significantly affected the distribution of each tracer, and consequently the exposures. The highest PFT exposures resulted from interaction of the scripted activities with local surface conditions. The range measured for one minute exposures were large with measured values exceeding 5000 ppqv (parts per quadrillion by volume). The neighborhood scale measurements quantified exposures at distances up to 7 blocks away from the release points. Generally, but not always, the PFT levels returned quickly to zero indicating that after cessation of the emissions the concentrations decrease rapidly, and reduce the intensity of local exposures. The near source and neighborhood personal exposure route results provided information to establish a baseline for determining how a release could affect both the general public and emergency responders, and evaluate the adequacy of re-entry or exit strategies from a local area. Finally, the data also show that local characteristics can produce “hot spots”.

Introduction
The exposure measurements reported here were part of the first New York City Urban Dispersion Program (UDP) study conducted in Manhattan during March, 2005 within an area that included the Madison Square Garden (MSG) (Figure 1). (1) A major purpose of the study was to examine the local horizontal and vertical dispersion of perfluorocarbon tracers (PFTs) released at specific points outdoors around MSG. During the development of the study, it was determined that the tracer releases could also be used to enhance our understanding of the nature of potential human contact with released material, and identify activities (in both space and time) that might lead to significant human exposures. To achieve this, a personal monitoring study was completed while the PFT tracers were being dispersed into the atmosphere. The exposure monitoring was feasible because the PFT personal samplers available from Brookhaven National Laboratory (BNL) were very sensitive and could be worn by individuals completing a set of
scripted tasks along specific near source and neighborhood routes. With a limit of quantification (See Table 1) in the parts per quadrillion (PPQV), the aim of the study was to collect the PFT personal samples for 1 and 10 minutes in duration, that were linked with specific activity patterns and distances from the release points. (2)

In contrast to typical urban air pollutant exposure measurement studies the MSG study involved specific paths associated with activity patterns (e.g. people evacuating, exiting or approaching the point of release, emergency workers remaining near the release, etc.) developed by the investigators. Each route was tailored to types of activities that could provide both source and neighborhood scale information about contact with each PFT. Subsequently, the results can be used with novel approaches to simulate contacts of individuals with actual chemical, physical or biological agents, and thus help evaluate and refine current practices for entry and exit of emergency personnel and individuals “in harms way” during a toxic release.

Based on the meteorology in the New York Metropolitan area and other local variables, (e.g. traffic, buildings) each activity route may or may not simultaneously yield intense integrated PFT exposures 0 to 7 blocks from a source. However, when meteorological conditions were favorable, each route was designed to provide maximal opportunities for contact with PFTs during one or more of the segments. Since the emission rate for each PFT was constant within two defined periods, the scripted activities were repeated to examine the changes in exposure over both space and time. The exposure encountered by each individual depended on many local variables, such as meteorology, traffic, and building geometries along the route. The release day had two “on” periods separated by a suitable ventilation time and the day was selected to achieve optimal and consistent meteorological conditions (clear days with NW winds). As a result, the data provides some indication of the variability that can be expected
under a specific scenario. Another advantage over previous exposure studies was the reduction in uncertainties associated with the timing and strength of PFT release from the source. The study also provided an ability to simulate exposure to biological, chemical or physical agents in the atmosphere, which during an actual event is an almost impossible task.

In most circumstances, personal monitoring measurements are completed in locations: a) close to the source or b) that would experience high exposures based upon past practice. The latter would include anticipated frequency of emissions or accumulation patterns.(3) The measurements in such studies are coupled with the activities of individuals who may frequent the area of concern, which could lead to various levels of exposure based upon the dynamics of the contact in both space and time. However, in such circumstances neither the emissions nor the patterns of participant exposure can be controlled by the investigator. (4)

Exposure science studies provide valuable information regarding the contact of individuals with a source, which is useful information for human health studies (5). Even though the measurements are related to specific hypotheses, they are still somewhat opportunistic when attempting to define high exposure conditions. (6) Further, many times these measurements cannot be directly coupled to specific source emissions since one does not control the activities of the individuals, nor the presence or absence of emissions from the source of concern on a particular day. (3) These types of difficulties are reduced in a prospective personal exposure monitoring study with a constant PFT release rate if realistic scripts are developed for the individuals wearing the personal monitors and they are repeated during the sampling period.

Methods

Objectives and Approach
The specific science objectives for the Urban Dispersion Program (UDP) in NYC were to: understand flow and dispersion in deep urban canyons within a large urban area; understand rapid vertical transport and dispersion in re-circulating eddies adjacent to very tall buildings within a large urban area; carry out tracer experiments with concurrent detailed meteorology to aid in this understanding and in development and evaluation of models; obtain a high quality field measurement data set that can be distributed to others for evaluation in modeling studies to evaluate the distribution of exposure to the tracers outdoors, and indoors away from release points. (1) The last goal mentioned above is the ultimate focus of the exposure science experiment.

All scripted activities were completed in the field by trained EPA emergency response personnel directed by J. Daloia, USEPA, Region II. The approach included: 1) measurement and characterization of integrated personal exposure to the PFTs in the MSG area, and 2) examination of the PFTs data, a “quasi-ideal gas” for simulations of a highly toxic substance. The latter will yield detailed exposure characterizations and generalization to a much larger group of individuals within MENTOR-2E (Modeling Environment for Total Risk – Emergency Event) system. (7)
Design of the Exposure Monitoring Study

Approximately 800,000 daily commuters pass through Pennsylvania Train Station, New York City, which is located under the Madison Square Garden building. The building is located in the center of Manhattan and therefore we expect highly diurnal variability in pedestrian and vehicular traffic. Outdoor releases were timed to start in the early morning before the peak of the morning rush and when meteorological conditions were stationary. Investigators developed the scripts by walking the streets and timing exactly how a person might move through the city at these times of day. Information were acquired on pedestrian and vehicular traffic patterns in mid-town Manhattan, and experiences of the emergency response members on our team. The potential exposure patterns were defined through reconnaissance that identified pedestrian and vehicular traffic patterns, major points of interest and activity, and types of activities that might lead to high exposures. The latter was coordinated with other MSG team members in terms of the exact locations and times of the PFT releases. All of the information was used to develop the scripted movements of the personnel taking samples representing one or ten minute exposures, respectively, that could occur downwind, upwind, and crosswind of the four PFT release points.

During the walk-through, the spatial and temporal aspects of the prospective exposure monitoring were defined for the individual routes. Each route accounted for: 1) the time of day for the release; 2) foot traffic and motor vehicle traffic in the personal sampling areas; 3) the potential wind directions; and, 4) the nature of the physical structures surrounding the release points. Examples of the pedestrian and motor vehicle traffic encountered in two locations around the MSG are shown in Figure 2a and b.

Advice from EPA emergency responders was used in constructing the final scripts to evaluate personal exposure issues, and/or activities associated with an accident or other type of
acute exposure event. The specific scripted outdoor routes and activities used are shown in Figure 3 and 4, for near source and neighborhood activities patterns, respectively.

In summary, the first set of activity patterns targeted near-source exposures as represented by 1-minute contact with one or more PFTs within 10 to 20 feet of an individual PFT release point. The second set of activity patterns represented neighborhood movements of an individual and were comprised of ten-minute integrated exposures. Each was designed to enhance our understanding of the variability of the exposure caused by the PFTs in space and time both during and after each release period.

**Source Scale Personal Exposure Monitoring**

The source scale (1-minute) scripted personal monitoring tasks (Figure 3) were completed by four different individuals. In each instance a team member implemented his/her scripted tasks in an area associated with one of the four MSG outdoor PFT release points. However, the power of the data analysis was improved because each personal monitor was capable of simultaneously collecting all four PFTs. As illustrated in Figure 3, four identical near-source routes were completed at each corner next to the MSG building, and each release location was defined by the release of a specific PFT tracer (one of four) at each corner of MSG (See Figure 3).

The first one-minute integrated exposure task consisted of walking back and forth in a semicircular path at a distance of 10 ft (3 m) from the source. The second one-minute task was walking another semicircular path, but at a distance of 20 ft (6 m) from the source. The third one-minute task was walking a transect in a straight line from the building until the individual passed the source. The four individuals collected individual samples along the three separate paths every 15 minutes (four samples per hour) for each task during source “on” sampling, and two per hour for each task during the ½ hour of source “off” sampling.)
The three different paths taken by each member of the field team at release location A, B, C, or D are shown in Figure 3. For each path, the integrated personal sample was one-minute in duration to minimize the risk of saturating the personal monitor because of potentially high concentrations near the source. Each individual first completed the inner semi-circle path (10 ft (3 m) from the source), then the outer semi-circular path (20 ft (6 m) from the source), and finally the transect from the outside wall of the MSG to just past the source.

Within the first release hour (0900 to 1000) and the second release hour (1130 to 1230) four replicates were collected at each location. During each non-release period two sets of samples were collected within the period between 1000 and 1030, and approximately 1230 and 1330. This resulted in a total of 12 samples of one minute durations being collected at each release location, A through D during an “on” period, and six samples, two per route, collected during each “off” period. Each individual produced a time series of the integrated one-minute samples that defined the intensity of contact (exposure) with each of the four PFTs released around the MSG (see Figure 3).

*Neighborhood Scale Personal Monitoring*

Each of the neighborhood personal monitoring routes (10-minute samples) was coupled to a specific PFT source location (See Figure 4). The goal was to include directions of motion that cover two to three specific walking activities that would lead to ten-minute integrated exposure. The first activity was movement away from the source location, the second activity was movement at a distance from the source, and the third activity was movement toward the source. For each route, activities 1 and 3 were completed by all team members. The number of activities included along each route (AA through DD) were dependent upon the building, traffic patterns, and distance from the source. Each member of the neighborhood exposure sampling
team collected continuous ten-minute samples (two or three per route) throughout the sampling period. A duplicate sample collected by another individual was assigned to the one member of the group for quality control. As shown in Figure 4, each of the four routes (AA through DD) for the neighborhood scale sampling started immediately adjacent to the source release point for one of the four PFT tracers. As noted by the arrows, each member of the personal monitoring team moved in a direction that took each individual away from the source. At the ten minute mark, post start time, the first sample tube was capped and a second sample tube was opened to complete the next leg of the script. In some cases (AA and DD), this second sample moved the individual to a point that was farthest away from the source in an upwind, downwind or crosswind direction. For other members of the neighborhood exposure field team (BB and CC) the second sample collected along the route brought the individual back to a point near the start position (see Figure 4 for details). Thus, the concentration measured at each sampling route was the 10-minute integrated concentration of each PFT collected along the path from the start of the sample to the changing of the sample. Interpretation of the data is based upon the direction and the proximity to a source when leaving or approaching a particular point. Similar to the source scale field sampling, the individuals completed repeats of the activities during both the “on” and “off” PFT release periods.

**PFT Sampling Technology**

The PFT sampling and analysis technology was developed at Brookhaven National Laboratory (BNL). (2) PFTs have been used worldwide as tracers and in many other applications for decades by both government and private organizations. The compounds are fully fluorinated (saturated with fluorine), contain only carbon and fluorine, and have no unsaturated bonds. For these reasons, these compounds are extremely stable, chemically and physically. In the pure state,
PFTs are clear, slightly viscous liquids, boiling between 45 to 130 °C, with a density about 1.75 times that of water. Being extremely stable chemically also makes them biologically very inert. PFTs can be inhaled and ingested without resulting in adverse effects.

The BNL Tracer Technology Center PFTs are used for leak detection, atmospheric tracing, and building ventilation are in the generic class of perfluoroalkylcycloalkanes, that is, typically four (4), five (5), or six (6) carbon member ring compounds with one (1), two (2), or three (3) methyl groups attached to the ring. The tracers themselves have regulatory acceptance and are used commercially (e.g., detecting leaks in underground power cables).

Advantages of PFTs are that they: have the ability to be measured at very low concentrations and to operate at low release rates; have negligible background concentrations; are non-toxic, non-reactive, and nonflammable; and are commercially availability. (2) PFTs are the most sensitive of all non-radioactive tracer technologies and samples can routinely be detected at concentrations in the range of 10 parts per quadrillion of air (ppqv); six to eight different PFTs can be released from the same location with different sequences, or from different locations; and each PFT can be detected in the same gas sample. The release equipment consisted of six gas cylinders (one for each PFT) similar in size to a 1A cylinder.

Six different PFTs were simultaneously released, near ground level, at five locations during the overall UDP MSG experiment but, only four release points were placed around MSG, and only the results for these PFTs were analyzed for current study (See Figure 3). All PFTs released during the UDP were: PMCP (perfluoromethylcyclopentane), oc-PDCH (perfluoro-1,2-dimethylcyclohexane), PMCH (perfluoromethylcyclohexane), PECH (perfluoroethylcyclohexane), i-PPCH (perfluoro-iso-propylcyclohexane) and PTCH (perfluoro-1,3,5-trimethylcyclohexane). The tracers (released at the four points around MSG) were as
follows: ocPDCH at point A; PMCP at point B; PMCH at point C; and PECH at point D. The plumes from the four locations were transported and dispersed differently since they were affected by wind patterns at the surface and aloft (details are found in Watson, et al, 2006). (2)

The PFT personal samples were collected using BNL personal air samplers (PAS) that were carried on the upper body (i.e., in the shirt pocket) by the EPA field personnel. The PAS is a pocket-sized air sampling unit that is nominally 1” wide x ¾” thick x 4” high and holds a capillary adsorbent tracer sampler (CATS) tube for sampling tracer. The CATS tube is a ¼ inch (0.6 cm) diameter × 2 inch (5.1 cm) long glass tube filled with sorbent to capture the PFTs. Duplicate samples were worn by individuals completing some of the scripts, and the results are shown in Figure 5. Pre-test background levels of the PFTs selected were also tested and those results are shown in Table 1 and details are found in the report of Watson et al. (2006). (2)

**Field Experiment**

Continuous PFT releases were made at the four locations around MSG for two separate one hour periods from 9:00 to 10:00 am (0900 to 1000), and 11:30 am until 12:30 pm. (1130 to 1230). All sampling was conducted over five hours, between 0900 to 1400, spanning both release periods. During each one-hour release period, the direction and speed of the tracer plume varied according to mesoscale wind fluctuations, as well as the influence of the streets, the traffic, pedestrian loadings and the surface winds. On March 10, 2005, the general (rooftop) wind direction was from the west, but at the surface (street level) the wind direction was variable. At 0900, the general movement of air at the surface and at the rooftops is illustrated in Figure 6. The wind vectors for the rooftop winds were primarily coming from the western direction. In contrast, the winds at street level near each of the release points were quite variable, with directions that spanned 360 degrees around the compass. (8) Figure 6 has been compared to
high-resolution numerical models and is a good picture of the mean winds over each 10 minute averaging period. However, during any ten-minute period the winds at a location show great variation and high gustiness. Thus the dispersion is dependent on both transport and extremely high levels of turbulence.

**Analytical Methods**

The PFTs were analyzed using a gas chromatograph with an electron capture detector (ECD). The samples were desorbed from the collection tube by heating it to 400° C into a 5% Hydrogen, and nitrogen carrier gas stream. The air stream was separated on a 1/8 in o.d., 18in. precut column packed with a 0.1% SP – 100 mesh Carbopack-C (Superlco, Inc. Bellefonte, PA). The flow was directed to the atmosphere or through a heated palladium (Pd) reducing catalyst on to a Florisil (Superlco, Inc. Bellefonte, PA) packed trap. The air stream was switched between the vent to the atmosphere and the trap windows where the perfluorocarbons were separated and the eluting interfering compounds directed out the vent. The Pd catalyst combined with the 5% hydrogen also reduced co-eluting gases to a form that were detected by the ECD. After the PFTs were trapped, the column was back flushed to remove any remaining high molecular weight compounds. The sample was then desorbed through a second Pd catalyst trap and dryer. This completed the cleanup, and the sample was passed to the main column. The PFTs were then separated and passed to the ECD detector for quantification. Calibration was achieved using standards prepared by the BNL Tracer Technology Group. A total of 146 calibration standards were run for each PFT during the experiment. (2) The PFT detection limits are presented in Table 1.
Results

On March 10, 2005 the PFT releases started at 0900 at all four MSG locations associated with the exposure experiments. At that time both the source and the neighborhood prospective personal integrated PFT monitoring commenced simultaneously at all eight locations adjacent to the PFT release locations around MSG (See Figures 3 and 4). The plumes from the four release locations were transported and dispersed differently and were affected by wind patterns at the surface and aloft (see report by Watson, et al, 2006). Further, the concentrations along the street were affected by the presence of buildings and other structures. Therefore, these are only a semi-quantitative representation of the surface PFT levels present at any specific point in space and time.

In addition to the personal samplers, Brookhaven Atmospheric Tracer Samplers (BATS) were deployed at 19 ground locations, and seven locations on the roofs of buildings and collected half-hour integrated samples from 0900 to 1400. Isopleths constructed from the stationary monitoring data for each MSG tracer plume, and for each 1-hour release period are found in Figure 7a and 7b. They illustrate that the plume associated with each point was somewhat different but overall the pattern for each tracer had a west to east trajectory for each release period, 0900 to 1000 and 1130 to1230. However, the width of each dispersed plume, and the distance and area covered in the north direction, was different for each PFT release location. Further, the isopleth for the first release period, Figure 7a, had a wider spatial extension to the south and south east for release points A, B, and C. During both release periods, the plumes associated with release points A and D significantly influenced points directly to the north. The plume from release point B, however, actually reversed direction and the flow significantly influenced both the westerly and northerly locations. The isopleth profiles shown in Figures 7a
and 7b will be used in the overall analysis of the personal monitoring results, and in the evaluation of any changes in the isopleth structure based upon the personal monitoring data.

Source-Scale Personal Exposure Measurements.

The time series obtained for each of personal exposure measurements is shown in Figure 8, and arranged according to the elapsed time associated with each release. The highest concentrations were normally observed for the PFT released at a specific location. PMCP, PMCH, and PECH were released at points B, C and D, respectively and the highest exposures for each were associated with the three activities completed at that location. Specific PFTs were detected at multiple locations, but the one-minute exposures were usually much lower than the levels of PFT released and sampled at points B, C, and D (e.g., PMCP at location D < than PECH at location D). The results obtained at release point A, however, provided a different picture. In fact, during one sampling period at release point A, high values were measured for PMCP, the PFT released at point B.

The actual paths traversed for each route during both the release and non-release periods did not appear to significantly influence the intensity of exposure, indicating the local turbulence dominated the concentration variations and not the direction of motion of the individual. This observation is re-enforced by the fact that the range in concentrations found for each one-minute personal monitoring sample was different at each location. The largest variation was observed at point A (NE corner) and the smallest variation was observed at Point C.

Neighborhood Scale Exposure Measurements

To make the neighborhood scale exposure more manageable, the results are presented as three dimensional plots of the 10-minute integrated samples. Each Figure, 9 through 14, includes the data collected for all tasks during one of the four designated sampling periods. Thus, Figures
9 through 14 provide a time series representation of the neighborhood personal exposures to all four PFTs. Since a goal was to examine the relative magnitude of integrated exposure while moving away and coming toward the source, the loop was completed to ensure that each member of the field team could complete one pass of a route in less than or equal to 30 minutes. Thus, to increase the size of the dataset there would be one repeat of the route during each 1 hour release period. Subsequently, there would be a single traverse of the same route during the ½ hour immediately after the source of each PFT had been turned off. Since routes AA and DD had three 10-minute samples taken during the task, and routes BB and CC had two 10-minute samples taken during the tasks, the following results sections were first analyzed according to each sampling route (e.g. AA) across all sampling periods. Then the results obtained along each route (AA through DD) during an individual sampling period were analyzed across all routes results during that single sampling period.

**Results Obtained for Each Neighborhood exposure Route and the Entire Sampling Period (0900—1330)**

**Route AA. (Upwind on 3/10/05)**

The data reported in Figures 9 through 14 show the highest 10-minute exposure occurred during the first release period (Figure 9) when a team member approached the return point (between release points D and A on 8th Avenue). In contrast, the integrated exposures were non-detectable at up wind locations (e.g. the second exposure period, 33rd Street to 9th Avenue) during all “on” sampling periods. Very low PFT levels were measured at all locations during the “source off” periods except for PECH (released at point B) which yielded a high concentration near Point A during the first 10 minutes of the “1000 hour off period. This was attributed to a backwash plume that moved along 33rd Street.
Since route AA could not exclude interaction with the emissions at point D during a return, the one personal sample during the first “on” period had quantifiable PECH exposures when the team member returned (30 minute time point) passing point D and moving toward point A. A similar concentration was measured for ocPDCH. These results are fairly consistent with the plume results found in Figure 7, since concentrations of most PFTs were present at various distances away from their release points. The concentrations detected during the first 10-minute exposure sample would have been primarily from contact with ocPDCH and PECH that were released from points A and D, respectively, and resulted from contacts that occurred as one moved immediately away from the starting point on 8th avenue and not while the individual walked west along 33rd Street.

**Route BB (CROSSWIND on 3/10/05)**

The team member associated with route BB went north of the MSG to 39th or 40th St, and then returned south and west to approach MSG. In this case the two sampling routes during the first hour were not totally identical since the starting and ending point shifted one block when the team member completed a repeat of the route during each “on” (release) period. Many of the highest 10-minute exposures occurred as the team member either left or returned to the area, i.e. those nearest the release points for a specific PFT tracer. Figures 10 and 13 show high egress values for ocPDCH, during the second release periods and PECH during the second release period, and very high return values for PMCP (>43,000 ppqv). The latter would be logical since the field person would be approaching a point of emission for PMCP, location B, the value was actually in the same concentration range as the near source exposure value for the one-minute sampling period at point B. The results again showed the rapid decay of all PFTs values during the source “release off” periods.
Route CC (DOWNWIND ON 3/10/05)

The exposure samples taken along this route represented contact that would have been affected by the dispersion caused by the winds generally affecting the area, west to east, in addition to the influence of the local street canyon. In contrast to the previous results, (route BB) the egress samples did not immediately return to zero during the “off” period. In fact, the levels of PMCH, and PECH, released at points C and D, remained detectable for the egress sample (from the SE corner of the MSG to Broadway) for route CC during both the source “off” and “on” periods. Thus, the individual was walking through a portion of the plume that was still in the area as the release ended at source point C. During the source “on” period, the results reflected movement of air downwind from an individual PFT source, but the highest exposures occurred as a team member approached source location B. This result was observed for all “on” sampling intervals. The fact that the exposures did not go to zero quickly, during the “off” period was due to the bolus of material that was still in the plume near street level as the “off” period began.

Route DD (CROSSWIND ON 3/10/05)

The exposures derived for this route during the source “on” periods were among the lowest recorded during the entire day of sampling, especially for the samples collected between 0900 and 0930, and 1130 and 1200. For example, the second 10-minute sample collected to the south and southeast of all points of release, reflecting walking from 26th Street to the Avenue of the Americas, the team member recorded exposure levels that were close to the limit of detection for each PFT. In contrast, the first sample collected which represented movement away from source D to 26th Street, recorded exposures to PMCH and PECH occurred during the second sampling period and the last sampling period. The result for PECH is easily understood since the field person was leaving the source area D, however, the levels for PMCH indicate rapid movement of
PMCH from point C around buildings and through the streets, which would be caused by surface winds and turbulence.

**Integrated Analysis of the Results for Routes AA through DD within Each “On” or “Off” Sampling Segment**

*Sampling period 9:00 AM. – 10:00 AM. (0900-1000) – Source On*

Figures 9 and 10 provide a picture of the types of neighborhood exposures that occurred for each PFTs emitted during the first release period. The results showed that multiple PFT tracers could be detected in the area around the MSG during completion of specific portions of each activity. The characteristic exposure during each 30-minute release period demonstrated that as an individual re-entered a source area the exposures were the highest, and that somewhat lower values were seen while an individual was exiting from source locations A and D. Further, based upon the surface and the mesoscale winds encountered that day (see Figure 6), the hot spot for the experiment was the NE corner of the MSG, especially for PMCP. The winds in combination with the height of the buildings and the traffic contributed to the highest exposures encountered at that corner. Another observation was that PMCH released at point C could be detected in multiple types of samples, indicating that due to the spatial location and meteorological conditions the PMCH distributed fairly uniformly throughout areas north, east and south of the SE corner MSG release point. This was supported by the isopleths shown in Figure 7a and 7b.

*Sampling Period 1000-1030 – Source Off*

At almost all locations each PFT rapidly retuned to background concentrations. The only sample that had relatively high values was the exit sample for route C. As stated earlier, this was due to material that had not dispersed immediately upon cessation of the emissions, and could be attributed to the local meteorology.

*Sampling Period 1130-1230 - Source On*
Similar to the first “on” period, the highest levels were observed during the return for each route, with the highest exposures occurring again at release point B. In contrast to the first release period, detectable levels from the release at point D were measured in a number of exposure samples to the east, north, and south. However, the north and south levels associated with release point D could just be due to contact with the plume during the first couple of minutes as the field team members moved away from either release point D or A. This could explain the levels of the PFT emitted at point A detected during the first leg of route AA.

**Sampling Period 1230-1300 –Source Off**

The PFT levels all returned rapidly to below the detection limits except for the egress sample collected along path C. This was again due to the remaining levels in the plume after cessation of emissions.

**Discussion**

The results of the personal exposure study provided important information on the spatial and temporal exposures that could occur in an urban center like New York City after a street level release of a gas or fine particles. The local conditions that affected exposure were clearly driven by the low surface winds, the high turbulence, the complexity of the urban terrain (e.g. the street and the downwash of Two Penn Plaza), and the activities that typically occur in an urban center. A general observation was the presence of a “hot spot” for exposure at the northeastern PFT release point, B on this date. The nature of the local conditions mentioned above led to elevated PMCP exposures at both the source and neighborhood scale which were a factor of 10 greater than observed for the other PFTs. These also led to high levels of exposure to PMCP at release point A (west of the PMCP release).
The source scale exposure data showed that local conditions associated with geometry and small length eddies (e.g. 10’s of meters) affected the distribution of each tracer, and consequently the exposure received by each individual. The different 1-minute source scale paths did not show either a semi-circle path or the transect paths yielding higher exposures. In fact, the results indicated that higher or lower exposures were not characteristic of any of the three paths. This reinforced the conclusion that the influence of local surface conditions, including building characteristics and dynamics, traffic, and meteorology, influenced the potential contact with an individual PFT. The range measured for one-minute concentrations/ exposures was quite high.

The neighborhood scale exposures provided a different set of information that is important for quantifying exposures at distances which, based upon the study design, could be as far as six to seven blocks away from the individual release points, i.e. A through D. The stationary monitor comparison data provided a spatial footprint for the space time relationship defined by the individual scripts along paths AA through DD. The individual results were analyzed for each route over the course of the experiment, and then as a composite of all routes for each of six time intervals within the 0900 to 1400 time period defined for the experiment. The exposures derived from the neighborhood routes yielded three general observations:

1. The highest concentrations were associated with the 10-minute time interval samples that were collected as a member of the sampling team returned to a source location. The exposures were, however, not consistently high. In fact, the northeastern corner, which was the location of release point B, always yielded the highest exposures to the PMCP emissions during the source “on” period. In some ways this was expected since the general wind direction was from West to East, and the individuals completing paths BB, and CC would return from East to West and at a location near release point B.
2. The local meteorology and street activities influenced the magnitude of the exposures as an individual returned along a route. The levels for the return from path AA to point D, and the return from route CC to point C recorded detectable exposures during at least one sampling interval. In contrast, the very high exposures were primarily recorded at point B during all sampling intervals. The high exposures recorded at release point B for the neighborhood scale exposure return routes are supported by the near source exposure data which showed comparable values for multiple 1-minute samples.

From the standpoint of all PMCP exposure measurements the area between 8th and 7th Avenue on 33rd street was the most dynamic and will be used in predictive modeling. In addition to the above observations, the measurement of high levels of PMCP during the first off period sample (i.e. 1000) at point A was due to the transport of PMCP west caused by surface level turbulence. Since this would be in a direction opposite to the general wind direction (east to west rather than west to east), therefore, the local street canyon turbulence influenced the exposure. This result was supported in part by the stationary monitoring results (See Figure 7a and b).

3. For the majority of all source and neighborhood scale exposure samples, the exposures of the field team members quickly returned to below the detection limit during both PFT “off” periods. This is illustrated in Figures 11 and 14. The result is somewhat surprising, but indicates that even within a major urban area, a release of a gaseous material, and possibly very fine particles will disperse rapidly after cessation of the source, reducing the intensity of local exposures. From Figures 9, 10, 12, and 13, it is clear that there will still be a bolus of a PFT, or other material in a “real” situation at downwind locations, especially along the first 10-minute sample for route CC. The detected levels along route
AA would be consistent with the point of departure being on 8th Avenue, and the local wind directions encountered at the surface. The emission of each PFT would have stopped; however, the levels would dissipate quickly within the first 10 to 15 minutes. Obviously, in situations with inversions this may not be the case, and exposures would probably be similar to the situation described above for the off period peak of PMCP at release point A, which resulted in increased concentrations in an area other than immediately around the original release point. In this case, the levels of PMCP were still elevated at point A; although, quickly reducing to background around its release point B. In such instances, the residual levels would be highly dependent upon the local physical boundary conditions, local turbulent eddy, and the depth of the inversion.

The data collected during the UDP is unique because of the ability to collect exposure data using a defined set of repeatable activities. Previously, tire fires of any sizable quantity (10,000 or more) provided opportunities for long term air monitoring and sampling not available at typical responses because of their scope and duration. In some cases there has been evaluation of personal exposures to the many chemical compounds that evolve from the combustion or incomplete combustion of scrap vehicular tires. For example, on October 31, 1983 a major tire fire occurred in Winchester, Virginia, that resulted in the combustion of more than 5 million automobile and truck tires. (9) The fire produced a thick black smoke plume that extended 30-50 miles from the source and rose 3000 feet above the tire piles. Fallout from this plume affected 3 states. During this multi-week response; federal, state, local responders and their contractors, were involved in this operation. Early on in the response, EPA Region 3 asked NIOSH for technical assistance to evaluate personal protective equipment usage and the potential exposures resulting from the containment and on-going cleanup efforts. NIOSH technical staff deployed
three air sampling stations to evaluate the smoke plume. In addition to the stationary air sampling stations, 19 personal air sampling pumps were used to measure air in the breathing zone areas of the responders that were conducting different job functions at the fire scene. They included the decon workers, firemen, heavy equipment operators and cleanup technicians. Personal air sampling pumps were attached to responders who were wearing this sampling equipment in addition to their respiratory protective equipment. Results of the personal sampling revealed that workers who were working at various locations were exposed to low levels of many chemical compounds. Such information was very useful because it gave the responders timely data on what they were being exposed to and prescribe the proper protective equipment, procedures and protocols. The results have been of value to EPA Regions 10 and Region 2 to develop their own site specific personal air monitoring program (9,10). However, the data was still obtained from uncontrolled and associated with a large ongoing event and over multiple days.

The UDP prospective exposure data used a controlled and constant release, and had both near source and neighborhood personal exposure routes. This design provided a unique opportunity to establish repeated baseline dataset for use in the evaluation of EMS procedures and the extent of population exposures. The field data simulated how the gaseous material release could affect both the general public and emergency responders within minutes to hours after a release for multiple and repeatable releases and release periods, and for multiple periods of sampling along the same paths. The results indicated that the surface level structure of the area affects the dynamics of contact with the released PFTs, and that these dynamics can produce significantly high exposures. The MSG results point to the potential for a “hot spot” in a release area depending upon the boundary conditions and the near-source flux or turbulence, which would be plausible in many locations within cities having large buildings or congested streets.
However, the variability that may be introduced by gases, fine and coarse particles released during a fire, accident, or terrorist event in the same or similar manner will need to be evaluated in modeling applications. The results for this scenario can indicate locations where a first responder must be wearing personal protective equipment, i.e., an area that was about one to three blocks radius from an active source. However, the details on the levels of protection would be dependent upon the agent of concern.

The Isopleths in Figures 7a and 7b were constructed using only the stationary site data collected during the UDP (2). The prospective exposure study added another dimension to the experiment by specific scripts. When these results were incorporated in the original Isopleths (Figures 7a and b) the impact zones for each tracer were slightly expanded (see Figures 15a and b) for specific source releases, e.g. A and B. The isopleths indicate a wider area of influence of the PFTs for locations that were either downwind or in other directions away from a release, e.g. the northerly direction for release point A. These stationary data were very useful in helping understand the interaction of the personal monitoring results with general conditions around the release. However, the stationary data could not be effectively used as a surrogate for the intensity and variability of the measured exposures.

Summary and Conclusions

The PFT monitoring results provide baseline results for emergency events involving release of gaseous chemical agents. These can be used by the emergency medical services (EMS) and other responders. For example, the results show that depending on the local meteorology, the personnel can wait for relatively short period of time after the release is stopped (e.g. forced intervention or when the entire amount has been released). Then they can enter the area for rescue or recovery operations. However, future modeling these results to simulated toxic
exposures will determine whether or not the distribution of materials changes significantly based upon the weight of the gas or the form of the release, e.g. larger particles. These data also reinforce the utility of many of the current practices employed by emergency response, and provide additional data for establishing more effective guidelines of hot and warm zones for entry, and location of potential victims. For the latter, these data will be applied within different types of modeling analyses. The goal will be to evaluate variability and overall impacts on individual exposures to highly toxic substances or general air pollution at near roadway locations based upon the patterns of concentrations and exposures determined for the PFTs measured in this prospective exposure study.

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Figure 3. Source scale personal exposure monitoring scripts for PFT release points A through D adjacent to MSG

Figure 4. Neighborhood scale personal exposure monitoring scripts for the four paths (AA through DD) linked to a starting location adjacent to PFT release points A through D.

Figure 5. Correlation plot of duplicate samples; number of points is 36 (N=36) and include data for all six PFTs

Figure 6. Actual winds at 9:00 am on March 10, 2005 (Courtesy of M. Reynolds, Brookhaven National Laboratory)

Figure 7. One hour average isopleths for tracer releases points adjacent to Madison Square Garden using only UDP stationary monitor data: (a) first release period, 9:00-10:00 am; (b) second release period, 11:30 am-12:30 pm

Figure 8. Source scale personal monitoring results for each PFT (NW, NE, SW, SE) release location next to the Madison Square Garden as a function of time for all “on” and “off” release periods. The “x” axis of each graph starts at 9:00 a.m. on March 10, 2005.

Figure 9. Neighborhood scale personal exposure monitoring, PFT release at 9:00-9:30 am, March 10, 2005

Figure 10. Neighborhood scale personal exposure monitoring, PFT release at 9:30-10:00 am, March 10, 2005

Figure 11. Neighborhood scale personal exposure monitoring, PFT release at 10:00-10:30 am, March 10, 2005

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