

PORTABLE MOTOR VEHICLE CABIN AIR PURIFIER

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BACKGROUND OF PROJECT:

To paraphrase from Shakespeare, there is something rotten in our air, and it is encountered in driving along our highways. Consequently, in October, 1992, a research project was begun by Marie D. Lindsay, Manager/ Owner of what has now grown into Cabin Air Technologies, LLC, to determine what are the specific air pollutants that enter the passenger cabins of motor vehicles traveling on congested highways. The following questions were also asked:

- 1) Have there been scientific studies conducted that measured the concentration levels of specific air pollutants inside travelling vehicles? If so, what were their findings?
- 2) Do any of these pollutants present a health risk to the occupants of the vehicles?
- 3) If the answer to 2) above is positive, are there any filtration devices on the market (or shown in US Patents) that claim to reduce specific air pollutants to below the levels that present health risks?

The data gathered to answer the above questions came firstly from eight scientific studies that showed the results of measuring various gaseous and particulate air pollutants inside travelling cars. Two of these studies were conducted in vehicles in the Frankfurt area of Germany.¹ The other six studies measured pollution levels in the United States, including locations in the Boston,² New York/New Jersey (commutes),³ Raleigh, North Carolina,⁴ Washington, D.C./Reston, Virginia,⁵ Los Angeles⁶ areas, and also some “scattered” areas in a “TEAM” effort (New Jersey, North Carolina, North Dakota).⁷ Other background information came from the following:

- 1) Patent searches.
- 2) Papers printed and presented at Air & Waste Management Association and the American Filtration and Separation Society concerning the health effects of air pollutants and filter methodologies to capture these pollutants.
- 3) Health standards established by the US EPA, the State of California, and other government bodies for concentrations in ambient air for specific air pollutants, and

* We wish to acknowledge the advice and assistance given by a number of AFS members and sponsors. We were furnished sample filter media that were used in our prototype machines from the following companies: Pica USA, Inc. provided several types of activated carbon; non-woven particulate media (Technostat spun bond polypropylene) from Hepworth (now owned by Hollingsworth and Vose); catalyst media from Carus Chemical; and zeolite media from Zeochem.

the record (EPA Trend Reports) of attainment or non-attainment of those standards by communities across the United States.

- 4) A series of health effects-related studies published by Schwengels, *et al.*,⁸ Brandon,⁹ Becker,¹⁰ Maddison,¹¹ Schwela,¹² Hall, *et al.*,¹³ Kinney, *et al.*,¹⁴ and Detels, *et al.*¹⁵

Review of this information gave answers to the first two questions. Yes, there are good scientific test results that show the concentration levels found inside cars for the major pollutants. And yes, those studies had findings that agreed on one major point, namely, that the pollution concentration levels inside cars traveling on congested urban highways are typically 1 ½ to 10 times higher than the levels measured for the same pollutants at nearby, road side monitoring stations. Yes, many of these concentration levels are high enough to present serious health risks. This latter conclusion is based on a comparison of the measured concentration levels found inside traveling vehicles with the health standards set for ambient air by EPA, called National Ambient Air Quality Standard (NAAQS).

NAAQS have been established for six major air pollutants, or pollutant categories. These are the pollutants that are measured at multiple monitoring stations in all of the major U.S.A. cities, and most other large cities around the world. When measurements at these monitoring stations regularly exceed the NAAQS, by definition they present a human health risk, and local and state governments are required to take measures to reduce whatever pollutant is in “non-attainment.” We also compared concentration levels with standards set by the State of California, some European governments (especially for benzene) and Asian and South American governments.

The air pollution problem in many large cities in Asia and developing countries is far more extreme than anything experienced in the U.S.A. The World Bank has studied the economic consequences of the health effects of such pollution. The Fall, 1998, issue of “Environment Matters,” Annual Review, reported the following:

“A worldwide review of 126 cities in which high levels of particulates exceed World Health Organization (WHO) guidelines estimates that 130,000 premature deaths and 57-70 million incidents of respiratory illness occur each year due to air pollution. In East Asia alone, there are more than 10,000 deaths a year in Beijing, 3,000-6,000 in each of ten other Chinese cities, 6,000 a year in Jakarta, and 2,000-4,000 a year each in Bangkok, Seoul, and Manila. There are also 30,000-90,000 cases a year of severe chronic bronchitis in each of these cities. In monetary terms, these costs total 28 percent of urban GDP in Beijing, 8-30 percent in other Chinese cities, 7 percent in Manila and Bangkok, and 4 percent in Seoul. The costs in many cities, such as Jakarta and Bangkok, would be 20-40 percent higher if vehicle costs and the value of time lost in traffic congestion were included. Elsewhere in the world, air pollution impacts are

comparable: 40,000 premature deaths a year in India, 36,000 in the Newly Independent States, 4,000-6,000 in Cairo, 4,000 in Sao Paulo and Rio de Janeiro combined, and 6,400 in Mexico City. The economic value of this health damage represents 3-10 percent of urban income.”

The answer found to the third question above was “no.” Air filters currently being placed in the ventilation system of new cars, and those described in patents, do not claim to reduce specific air pollutants to below any government ambient air health standards, thereby to prevent health risk to human beings. Some effort has been made to provide air purification, or at least some attention to vehicle cabin air quality, in add-on or after-market devices.

The web site <http://www.realgoods.com/shop/shop.1.cfm?dp=107&ts=1053857> operated by Real Goods offers a three-stage auto air filter that employs activated carbon, an electret charged medium, and a Zeolite VOC ("Volatile Organic Compounds") filter for air purification, but the efficacy of the device is not known, other than that it is stated to recycle the cabin air in about six minutes. At the web site <http://www.realgoods.com/shop/shop.1.cfm?dp=107&ts=1053856> there is offered an auto ionizer to precipitate air pollutants. (Both sites visited Dec. 17, 2000.)

It thus became clear that the project should expand from research only to the research and development of a high performance air filter/purifier. By the mid-1990s various prototypes were being built and tested. Much was learned through trial and error, and through further search of the technical literature.

An article by Heinz H. Bitterman entitled "History and World Wide Trends in Cabin Air Filter Testing," was published in Fluid/Particle Separation Journal, Vol. 3, No. 2, Aug. 2000, pp. 152 - 155. This article notes the air test standards being employed in Europe, which were then compared to the less stringent U. S. standards. (The article also notes that General Motors vehicles for the European market will have filtration for both particles and odors, whereas the American versions of such vehicles will only have particle filters.) The article also remarks that "if it could be managed to provide filters being effective with diesel soot, a major step to recognizable air quality improvement inside cars would be made," but only the use of activated carbon as a filter material is proposed to reach that goal. No mention is made of the HEPA filter, which appears, from the data reported in the present paper, to be the one dependable way to remove the fine particulate matter onto which it is now thought that many other pollutants adhere.

The web site <http://www.epa.gov/ttn/amtic/pmspec.html>, under the heading "A final draft copy of the "Particulate Matter (PM-2.5) Speciation Guidance Document," at pp. 24 - 31 (pp. 15 - 22 as printed), describes in detail the general characteristics of PM2.5 particles, identifies the "target species" for which speciation of the chemical components in test analyses of air is sought by the U. S. Environmental Protection Agency, and in particular identifies a very wide

range of pollutants and their sources that become a part of the ambient air. (Site visited Dec. 17, 2000.)

An article by Tadeusz Jaroszczyk *et al.* entitled "Filtration Performance of High Efficiency Cabin Filters for Operators' Protection in Dusty Environments," published in Fluid/Particle Separation Journal, Vol. 3, No. 2, Aug. 2000, pp. 156 - 164, discusses the cabin air filtration systems of mobile mining equipment with respect to the efficacy of particular filter types, and also both recirculating and air intake ventilation systems. The test data include information with respect to air flow rates and pressure drops, and the same data are cited as to the aforesaid existing ventilation systems, and these data will be referred to below in connection with the present experimental results.

Another article by Tadeusz Jaroszczyk *et al.* entitled "Media Needs for Automotive Cabin Air Treatment" published in Proceedings, Filtration '94 Conference, American Filtration and Separations Society, pp. 123 - 147, sets out criteria that filter media should meet if they are to be used in cabin air filtration. Particular stress is given to the constraints thought to be present in filter design, in light of the limited space available for such filtration in the ventilation systems of automobiles, as well as the need in such systems to maintain a high air velocity, with the resultant short residence time of the air within the filter system reducing filter effectiveness. The article indicates, for example (p. 125), that "conventional high efficiency filters operate at low filtration velocities and excessively large spaces would be required to accommodate these filters in a car," and also (p. 126) that "current ventilation system designs do not allow for the incorporation of conventional high efficiency filters (HEPA) typically required if 'lung damaging' particles have to be removed." The proposed solution, but for which no specific means are given, is (p. 130) as follows: "An independent car ventilation system with recirculating air flow should be used to control contaminants from internal sources. Filters in this system can be installed in the trunk, under the roof (in the headliner), or under the seats. Since there is more space in these locations, such filters can be larger than ventilation system filters. A low flow velocity in these filters can be maintained so that high filter and adsorber efficiency can be achieved." Even so, one version of the Car Air Purifier reported on herein, and which includes a HEPA filter, is located within an armrest/ console disposed on the vehicle back seat.

This second Tadeusz Jaroszczyk *et al.* article also discusses odor reduction and air velocity values used in laboratory tests, which will be discussed further below in terms of passenger acceptance data and air velocity values collected in the course of testing different prototypes of the Car Air Purifier. The data cited in the article with respect to odor control indicate (pp. 145 - 146) that "under the flow conditions common in this application, adsorbent media did not have sufficient efficiency and life to remove challenge substances."

The major goal of this R & D project was thus to design and build an apparatus capable of bringing the concentration level of the major air pollutants inside vehicle cabins to below the

health standards for ambient air established by government agencies around the world. The specific pollutants are shown in Fig. 18: Concentration Chart -- Major Pollutants Targeted, with the targeted health standards shown in bold print under the columns titled "Government Ambient Air Health Standards." Evidence of the Car Air Purifier's effectiveness is shown in the rightmost two columns, labeled "Typical Performance with Purifier." These are field test results achieved in the real world, inside the passenger cabin of sedans and an SUV traveling in extremely heavy traffic in some of the most polluted highway conditions in the world. These data generally show a reduction of air pollution to below governmentally defined standards when one or the other version of the Car Air Purifier was in operation, but pollution concentration values in excess of those standards when the device was not in operation. Measurements were made in a vehicle that had a filter system built in to its ventilation system, and in most cases was in operation, but was not effective since the measured pollution levels as shown in the graphs to be presented still exceeded those standards.

A secondary goal of the project had been to design a machine that can be placed quickly and securely in any vehicle, in a position that is non-obtrusive and which will not interfere in any way with the use of the car's ventilation system. One location selected was an armrest/console position in the center of the rear seat of a sedan, secured by the center seat belt as a preferred location in a sedan, and a second location was in the vehicle trunk, with air ducts connecting to that same armrest/console position. Analogous locations were used in an SUV. Although the goal of proven effectiveness is primary, without achieving this secondary goal the Car Air Purifier would be far less acceptable to the public.

Prior to September 11th, it was thought that the public's greatest interest in using the Car Air Purifier would be to protect themselves and their families from the pollutants that cause respiratory illness and cancer. The primary carcinogens are diesel exhaust fumes in the PM-2.5 category, and the hydrocarbons in both diesel and gasoline exhaust. Benzene is a proven human carcinogen (Class A). It was also expected that people with asthma would want protection from ozone as well as the fine particles (PM-2.5). The HEPA filter, a component of the Car Air Purifier, is used to capture the PM-2.5 particles with high efficiency for extended periods of time. This category of pollutant also includes viruses and bacteria. But given now the anthrax attacks that were carried out through the mail shortly after Sept. 11, it would appear, fortuitously, that the Car Air Purifier could be used successfully to protect vehicle occupants from a bioterrorist, as well as chemical or nuclear radiation-producing (e.g., a "dirty bomb") attacks. (HEPA filters are in fact used in nuclear power facilities for the protection both of workers and the general public.¹⁶ The anthrax virus falls within the particle size range at which the HEPA filter is most efficient – it is known to capture particles in the 1 - 5 micron size range, which includes such bacteria and some viruses, to the extent of 99.99%. And, of course, by its own standard the HEPA filter captures particles measuring 0.3 microns in diameter at efficiencies of 99.97% or greater.

A ninth scientific study that measured specific air pollutants inside travelling cars was published by the California Air Resources Board (ARB) recently, and has been included in Fig. 18 “Concentration Chart” in columns headed “Ten In-Car Studies, without Purifier”. Those results, from field tests in Sacramento and Los Angeles, show concentration levels that are similar to the present test results, i.e., measurements taken in the Los Angeles area with the Car Air Purifier turned off. The ARB web page <http://www.arb.ca.gov/newsrel/nr061099.htm> has an Executive Summary shown as News Release N. 99-18, dated June 10, 1999, which states as follows:

“Dr. Alan Lloyd, ARB Chairman, said ‘We’re learning that peoples’ highest daily exposure to air pollutants may be during their commute to and from work. Also, we have concerns about the potential impact on bus riders, especially children’ Researchers found levels of hydrocarbons and carbon monoxide were between two and ten times higher inside vehicles than at roadside or fixed monitoring stations. Researchers also found similar levels of toxic compounds such as benzene, 1,3-butadiene, ethyl benzene, toluene, xylene and MTBE, all considered toxic by the ARB and USEPA.”

THE APPARATUS

The Car Air Purifier, the performance of which was the subject of the experimental data presented herein, is shown in Fig. 1. (The drawings of the apparatus and the graphs of experimental data are taken from a patent application filed in the United States, but under the Patent Cooperation Treaty so as to encompass other countries.) When the lid is lifted up as shown by the dotted lines, one sees a motor/blower under the exit marked by an upwardly pointing arrow, and at the other end, behind the grate and the horizontal arrow, there is a sequence of filter media packets having the construction shown in Fig. 2, that sequence then ending near to the motor/blower with the HEPA filter. The device as normally installed in a car is shown in Fig. 3.

The preferred sequencing of the filter media packets was identified through repetitive testing, although the sequence can be modified to treat a less demanding pollutant mix targeted in certain geographical areas during particular seasons of the year:

1. Desiccant packet containing various types of silica gel, zeolite and/or molecular sieves, within a gross particulate envelope.
2. Nitrogen and sulfur oxides and ozone adsorbent packet containing various types of packed activated carbon granules or pellets, within a gross particulate envelope.
3. Catalyst packet to break down carbon monoxide, within a gross particulate envelope. To function properly the catalyst packet must be preceded in the air flow stream by desiccants to reduce moisture and by adsorbents to capture sulfur and other acids which could poison the catalyst and make it inoperative.

4. Benzene and other hydrocarbon adsorbent packet containing various types of coconut based activated carbon granules, beads, and/or powder, within a gross particulate envelope.
5. HEPA filter (tested to remove 99.97 % of particles measuring 0.3 microns in diameter, and more efficient for both smaller and larger particles), approximately three inches deep.
6. A carbon impregnated fiber (“CIF”) sheet to capture any residual gases and odors.

The gross particulate medium envelope referred to consists essentially of a sheet of non-woven particulate filter material onto which the various filter media are poured as the sheet lies within one of the grates shown in Fig. 2; another such sheet is placed over the filter medium material, and then another grate. The structure is then held together using the U-shaped sliders also shown in Fig. 2.

The resultant structure provides a “packed bed,” whereby the filter medium will be so tightly packed that it cannot vibrate (as a result of jolting of the vehicle as it is being driven) and settle towards the bottom when the filter medium packet is placed vertically within the Car Air Purifier. That such tight packing has been accomplished evenly throughout the area of the filter is evidenced by the “bubbles” shown in Fig. 2: an excess of medium material forces the envelope sheet to become distended outwardly through the holes within the grate, and an even distribution of such “bubbles” over the grate area on both sides confirms that the desired tight packing has been achieved.

When vehicle cabin air enters the Car Air Purifier, the desiccant - adsorbent packet acts to reduce the humidity of the incoming air and thereby to protect the effectiveness of the later carbon particle packet and the catalyst packet. The desiccant - adsorbent packet preferably contains 50% silica gel and 50% zeolite. The silica gel was obtained from Silica Gel Desiccant Products Company and the zeolite was Zeochem® 24-01, 4 X 8, type 4A. The carbon particle packet will contain packed coal based activated carbon pellets to adsorb ozone along with many other gases including sulfur oxides, the particular type of coal-based carbon used being pelletized type G352-60 made by the PICA company (France). Acidic gases such as sulfur oxides that contaminate the air can also contaminate the catalyst, so for effective operation of the catalyst those pollutants are preferably to be removed from the air before that air reaches the catalyst packet. The activated carbon so employed in the carbon particle packet may also contain impregnates to act as chemisorbents.

The catalyst packet contains catalysts, specifically including a base metal catalyst that is somewhat moisture tolerant and effective at ambient air temperatures to break down carbon monoxide. The CARULITE® 300 12X20 mesh catalyst made by the Carus Chemical Company was used for this purpose because of its applicability to carbon monoxide oxidation. The coconut-based carbon packet, which follows the catalyst packet, is intended to adsorb benzene

and other hydrocarbons, and contains coconut-based, activated carbon granules and/or beads necessary to adsorb the smaller hydrocarbon molecules, for which 50% PICA Nacar P - 20x50 and 50% PICA G55-C were used.

With respect to coconut based carbon products in general, care should be taken in the selection of the supplier, since some of these products have been derived from coconut trees around which the ground has been treated with insecticides or similar agents that contain substances that will have been conveyed upwards into the coconuts, and because of the presence of those substances, such as arsenic, the carbon products from any such coconuts may themselves act as a pollutant source.

The HEPA filter that next follows was the HEPA PLEAT II®, a 2.5" (6.35 cm) deep pleated, high efficiency particulate filter, rated at 100 FPM (feet per minute), the metric equivalent being 30.48 meters per minute, and having an FPD (Filter Pressure Drop) of 0.53 W.G. (Water Gauge) mounted in an aluminum frame, and has been tested to remove 99.97% of particles measuring 0.3 microns in diameter, being generally more efficient for both the smaller and larger particles. A carbon impregnated fiber ("CIF") filter sheet that follows the HEPA filter employs coconut carbon wrap from Hepworth, and serves to capture residual gases and odors. This filter is formed simply by loosely folding the indicated fiber and taping the resultant folds of fiber together, and is thus distinct in structure from the filter media packets previously discussed (and of course from the HEPA filter).

EXPERIMENTAL DATA

Field test results are shown in figures 4 - 17, in graphical form to illustrate the most significant findings during tests taken of in-vehicle cabin air quality during 1999 and 2000. Figures 4 and 5 give experimental results from testing done in the Los Angeles area in August of 1999. This testing was conducted in a 1998 Honda Accord sedan with two to four passengers traveling on major freeways (such as I-5) during heavy traffic. The Car Air Purifier (with a 7 m³/min (250 CFM) rated motor/blower) was located in the trunk of the sedan, with an intake opening and an outlet duct between the back seat and the trunk. The measuring instrument used in the vehicle was a MIE DataRAM, equipped with nozzles for both PM-10 and PM-2.5 particle sizes. The DataRAM operated on a battery and displayed real time concentration levels in micrograms per cubic meter (µg/m³) every 10 seconds. The readings were recorded every few minutes, or whenever there was a significant change in the reading or the conditions inside the vehicle.

The conditions recorded included whether or not the ventilation system of the car was in operation and at what setting (including the recirculate mode) and fan speed; whether or not windows were open; and whether or not the Car Air Purifier was in operation. Temperature and humidity conditions also were noted. Also noted were the subjective evaluations of people in the car of the air quality. The human testers used a scale of 0 – 5, with the lower numbers indi-

cating low or moderate odor and 5 meaning unbearable bad odor. The effect of the Car Air Purifier on odor was easily detectable, the differences being more intensely reported by women than by men.

Generally, there was a close positive correlation between higher measured concentration numbers for PM-10 and PM-2.5 and the higher numbers given by the human testers. However, there were exceptions, when the testers expressed higher numbers without a corresponding increase from the machine. This result suggests that human noses can detect odors from gases whereas the DataRAM was measuring only particles. However, some noxious gases such as the hydrocarbons attach themselves to fine particles, which would explain the generally close correlation otherwise found.

As can be seen in Fig. 4, and as will be true also as to the other figures to follow, these figures do not show all of the conditions recorded as mentioned above. For the sake of clarity and objectivity, these graphs only show the most significant findings, i.e., the differences between measured particulate matter when the Car Air Purifier was in operation and when it was not. It thus seems appropriate to stress at this point what was the fundamental purpose of these tests.

That purpose, in short, was simply to find out whether or not the Car Air Purifier could reduce the pollutant levels present in the air of a motor vehicle cabin to levels below the NAAQS and other health standards. In conducting these measurements, however, the other information mentioned was recorded and studied to see if there were any other conclusions that might be drawn, and indeed there were: it was found out that (a) the best conditions for use of the Car Air Purifier were when the vehicle ventilation system, if on, was in its recirculate mode; (b) when using a higher capacity motor/ blower, while the ultimate result did not appear to be altered, the “bottom” level of pollutant achievable by the Car Air Purifier seemed to be reached more rapidly; (c) any air filtering carried out by the vehicle air conditioning system itself was essentially undetectable; and (d) operation of the Car Air Purifier itself was unaffected by whether or not the air conditioning/ventilation system was on or off.

Returning again to Fig. 4, it presents measurements for PM-10, and Fig. 5 shows the PM-2.5 results. With the Car Air Purifier in use, the concentration levels were reduced below the annual mean as well as the 24-hour mean NAAQS for both categories of particulate. The reductions were indeed in the 10-fold plus range. Of additional interest in Fig. 4, however, are data that show specifically the effect of switching the ventilation system into or out of its recirculate mode.

Specifically, in the time period from about 11:42 AM to 12:18 PM, during all of which time the Car Air Purifier was operating, there were two upward excursions from very low levels, the first of which occurred at 11:52 AM to give a value of $24.4 \mu\text{g}/\text{m}^3$, up from a value of $4.3 \mu\text{g}/\text{m}^3$ at 11:47 AM, and again at 12:18 PM to give a value of $22.5 \mu\text{g}/\text{m}^3$, up from a value of 1.9

$\mu\text{g}/\text{m}^3$ at 11:57 AM. These were brief periods in which the ventilation system was taken out of, and then put back into, the recirculate mode. That result is not surprising, since the recirculate mode reduces the amount of (polluted) air that is being brought into the cabin from the outside. What is particularly encouraging from these data is the short period of time within which the Car Air Purifier can cause the pollution level to drop back down when the amount of pollutant having to be removed is reduced (i.e., when the recirculate mode has been turned back on). An interesting question (among a very many not addressed completely in this initial data survey) is whether or not the Car Air Purifier could, after a few more minutes of operation, bring about those lower readings of $4.9 \mu\text{g}/\text{m}^3$ or $1.9 \mu\text{g}/\text{m}^3$ when the ventilation system was *not* in its recirculate mode.* What is *most* significant in these data, of course, are the reduction in the PM-10 concentration level from $309.9 \mu\text{g}/\text{m}^3$ at 11:40 AM to $10.2 \mu\text{g}/\text{m}^3$ at 11:42 AM, i.e., in two minutes, and analogous results are shown at the times 12:23 PM ($241 \mu\text{g}/\text{m}^3$) and 12:28 PM ($6.8 \mu\text{g}/\text{m}^3$) (five minutes).

The NAAQS for PM-10 is $150 \mu\text{g}/\text{m}^3$ for 24 hours and $50 \mu\text{g}/\text{m}^3$ for the annual mean. The State of California uses $50 \mu\text{g}/\text{m}^3$ for its 24-hour health standard. Thus, Fig. 4 shows how much higher the PM-10 levels in a motor vehicle cabin will be, when passing through Los Angeles, than the government health standards, and how far those levels can be reduced with the use of the Car Air Purifier. It also shows some effect when the vehicle ventilation system is in the recirculate mode rather than just the air-conditioning mode.

The air-conditioning system of the vehicle employed was equipped with a built-in particulate air filter. Because the weather was warm during these field tests, the A/C system was in use most of the time. What that means, of course, is that the particle density measured when not in the recirculate mode (e.g., at 11:52 AM and 12:18 PM) was measured on air that had passed through that built-in vehicle particulate air filter. The increase in the particle density when turning off the recirculate mode indicates how less effective that built-in filter is than the Car Air Purifier. To evaluate that comparison fully, however, would require a set of tests on the A/C system alone, i.e., with that filter in place and with the filter removed, and the present experimental data were not able to include such a test.

Fig. 5 shows experimental results of PM-2.5 testing in Los Angeles on August 3, 1999. Again there were dramatic drops in the PM-2.5 levels when the Car Air Purifier was in use, especially during the 7:42 AM – 7:48 AM period when the amount of PM-2.5 particles became too low to measure. In the $0.2 \mu\text{g}/\text{m}^3$ reading at 7:33 AM, the Purifier was operating but the ventilation system was turned off. The next reading of $12 \mu\text{g}/\text{m}^3$ occurred at 7:34 AM, when the windows were open and the Purifier was off. A minute later the reading was $19.2 \mu\text{g}/\text{m}^3$, under the same conditions. At 7:42 AM the windows were closed and the Purifier was operating, but the A/C and recirculate modes were not in use, and the reading was $0 \mu\text{g}/\text{m}^3$ (i.e., too low to detect). The next two readings ($0.7 \mu\text{g}/\text{m}^3$ at 7:45 AM and $0 \mu\text{g}/\text{m}^3$ at 7:48 AM) were taken when the Purifier, the A/C and recirculate modes were all in use. At 7:52 AM the read-

ing was $23.3 \mu\text{g}/\text{m}^3$, with both the Purifier and the vehicle ventilation system turned off. At 7:55 AM the reading was $6.2 \mu\text{g}/\text{m}^3$ with the Purifier, A/C and recirculate mode all operational. That same pattern is repeated further along the graph. These data show that the PM-2.5 levels inside the car, without the use of the Purifier, happened to exceed the annual NAAQS ($15 \mu\text{g}/\text{m}^3$), but not the 24 hour NAAQS ($65 \mu\text{g}/\text{m}^3$). With the Car Air Purifier in use, even under the varying circumstances indicated, the concentration levels in the cabin were reduced to well below both standards.

The next five figures (Figs. 6 -- 10) present field test results obtained in Bangkok, Thailand, in March of 2000. The experiments were conducted in a rental car, with a driver. The car was a late model Japanese sedan that carried three people during the testing. The variable conditions under which these measurements were taken in Bangkok were essentially the same as was described above for the field testing in Los Angeles. The measuring instrument was an MIE DataRAM, with separate nozzles for PM-10 and PM-2.5. There were two Car Air Purifier prototypes tested, one with a $7 \text{ m}^3/\text{min}$ (250 CFM) rated motor/blower, and the other with a $5 \text{ m}^3/\text{min}$ (176 CFM) rated motor/blower. Both of these prototypes are portable units that can be placed on a seat, secured by a seat belt, and plugged into a power outlet such as a cigarette lighter plug as previously shown in Fig. 3.

The most obvious difference between the findings in Bangkok and Los Angeles was the much higher level of ambient particulate matter pollution in Bangkok. In summary of the full set of measurements in Fig. 6 - 10, the high readings without the use of the Car Air Purifier were $1044 \mu\text{g}/\text{m}^3$ for PM-10 and $382 \mu\text{g}/\text{m}^3$ for PM-2.5. The high readings in Los Angeles were $309.9 \mu\text{g}/\text{m}^3$ for PM-10 and $30.2 \mu\text{g}/\text{m}^3$ for PM-2.5. When the Car Air Purifier was in operation, the readings ranged as follows:

	<u>Los Angeles</u>	<u>Bangkok</u>
Lowest PM-10	$1.9 \mu\text{g}/\text{m}^3$	$24 \mu\text{g}/\text{m}^3$
Mean PM-10	$9.14 \mu\text{g}/\text{m}^3$	$37.4 \mu\text{g}/\text{m}^3$
Lowest PM-2.5	$0.0 \mu\text{g}/\text{m}^3$	$15.7 \mu\text{g}/\text{m}^3$
Mean PM-2.5	$1.2 \mu\text{g}/\text{m}^3$	$20.3 \mu\text{g}/\text{m}^3$

Therefore, concentration levels for PM-10 were below both the annual ($50 \mu\text{g}/\text{m}^3$) and 24-hour ($150 \mu\text{g}/\text{m}^3$) NAAQS when the Car Air Purifier was in operation. The PM-2.5 levels were brought down below the 24-hour NAAQS ($65 \mu\text{g}/\text{m}^3$), but were higher than the annual NAAQS ($15 \mu\text{g}/\text{m}^3$). These results suggest that in a sense, when severely challenged in an environment such as Bangkok, the Car Air Purifier can be “overwhelmed,” at least temporarily. When encountering pollution levels actually over $1000 \mu\text{g}/\text{m}^3$ for PM-10 (Fig. 8), however, the reduction in that particular case down to $15.7 \mu\text{g}/\text{m}^3$ suggests that one is certainly better off having a Car Air Purifier in the car, since Fig. 8 also suggests that by continuing the measurements, a level

below that $15.7 \mu\text{g}/\text{m}^3$ might well have been achieved. (Also, the prototype being tested in the Fig. 8 data actually had the smallest size motor/blower ($5 \text{ m}^3/\text{min}$ –176 CFM)). The highest ambient pollutant levels were found at around noon, and lowest levels in early morning.

Figs. 6 and 7 show results from the use of the $7 \text{ m}^3/\text{min}$ (250 CFM) motor/blower powered Car Air Purifier for PM-10 and PM-2.5, respectively, measured on March 13, 2000. Figs. 8, 9, & 10 present results recorded on March 14 and March 15, 2000, using the prototype with a $5 \text{ m}^3/\text{min}$ (176 CFM) rated motor/blower, all of which can be seen to be essentially mutually consistent. One feature of these measurements is brought out quite clearly in Fig. 9, however, which is that there was no control whatever over the ambient pollution levels encountered, which would depend entirely upon where one was driving at the time and what was the traffic level. In Fig. 9, in the time period from 2:36 PM to 2:49 PM, there was substantial variation in the measured PM-2.5 when the

Car Air Purifier was not running, which was thus not to be accounted for by anything done by the experimenter. Even so, these data show quite unambiguously that in spite of such variations, when the Car Air Purifier was turned on at about 2:50 PM, the ambient pollution level, whatever it may have been, was quite rapidly reduced within the cabin to numbers around $40 \mu\text{g}/\text{m}^3$ in lieu of a peak of $400 \mu\text{g}/\text{m}^3$, i.e., a reduction of about 90%. This type of result is consistent with the stated purpose of the research, namely, to determine the extent to which, as a practical matter, the Car Air Purifier was capable of providing clean air in a dirty environment. You are never so much at risk as when you are in your car.

The next set of Figures (11 – 17), which now address the gaseous chemical pollutants, show experimental test results obtained in Los Angeles on September 1, 2000. Air samples were drawn into summa canisters inside a Nissan 2000 SUV, driving on the I-5 freeway during heavy late afternoon traffic. Three samples were taken: the first was a grab-sample of air with neither the Car Air Purifier nor the vehicle ventilation system in operation, and with the windows partially open. The second grab-sample was taken 5 minutes after the Car Air Purifier and A/C (with recirculate mode) were turned on, and with the windows closed. A third sample was drawn into a summa canister, under those same conditions, over a continuous 90-minute period. There were four people in the SUV during this sampling. The summa canisters were sent to Performance Analytical, an independent certified laboratory that did the analysis of the samples, using GC/MS apparatus and an EPA approved test method (TO-14).

Although the research and development project had initially targeted only benzene among the hydrocarbons, the analysis of the summa canister contents was requested to include all four of the BTEX hydrocarbons (benzene, toluene, ethylbenzene, and the xylenes) plus butadiene and MTBE. Figures 11 - 17 show the analytical results for each of these toxic pollutants. The reason that benzene was initially singled out as a targeted pollutant is that it is the one hydrocarbon in this group that is identified as a proven human carcinogen (Class A), while the others are considered to be lesser carcinogens. It was specifically sought to determine, or ensure that in-

deed the Car Air Purifier *was*, a filtration method that would reduce benzene concentrations in traveling cars to below the European health standards. Fig. 11 shows quite clearly that this was accomplished.

Because of the chemical similarity among the aromatic hydrocarbons, it is not surprising that similar results were found as to toluene (Fig. 12), ethylbenzene (Fig. 13), *m*- & *p*-xylenes (Fig. 14), and *o*-xylene (Fig. 15). 1-3-butadiene, although not aromatic, is nevertheless unsaturated and will have substantial electron density extending beyond the molecular skeleton, and thus should be susceptible to adsorption by the same filters that capture the aromatic hydrocarbons. That is rather difficult to confirm from Fig. 16, since the levels are in any event extremely low, but even so it is clear that some amount of reduction was taking place. As to *t*-butyl methyl ether (commonly called MTBE), the results for which are shown in Fig. 17, the reduction in the pollution level is quite substantial, possibly attributable to the fact that the molecule is quite asymmetrical, highly strained, and as a result the oxygen atom will have an electron pair “sticking out” that, so to speak, will be ready to “grab onto” anything. (The second author’s prior experience in studying dielectric relaxation in dissolved molecules brings forth the recollection that in that context also, relatively large ethers tend to behave like aromatic hydrocarbons, for reasons that so far are evidently unknown.)

A summary of these results is shown in Fig. 18, in which the data of major interest appear in the two pairs of columns on the right that are marked off by the darker lines. (The leftward columns, after the designations of the particular pollutants, simply list the governmental standards against which the performance of the Car Air Purifier was to be checked.)

The first of those two pairs of columns, labeled “Ten In-Car Studies: Without Purifier,” set out in terms of peak and mean range values a summary of the data that were reported in the nine articles mentioned earlier, and which are listed under footnotes 1 – 7, along with the data obtained in the present work at those times when the Car Air Purifier was not turned on. The second pair of columns, labeled “Typical Performance: With Purifier,” shows mean values for the measurements reported herein when the Car Air Purifier was turned on, together with identification of the geographic location at which the respective measurements were made. Those mean values are lower than the corresponding standards for each of the pollutant species studied, and it is that which the present work sought to determine. In almost all cases, the Car Air Purifier reduced the pollution levels to below standards that are actually more stringent than had originally been targeted. (For example, for ozone the 100 ppb NAAQS had been targeted, but the results more than achieved the 80 ppb NAAQS.)

As to the nitrogen dioxide, sulfur dioxide and lead listed in Fig. 18, graphs that would show those experimental results are not included because they would be quite uninformative. These data were collected using glass tubes and analyzed by Assay Technology Labs., in either Los Angeles or Portland using NIOSH method 6014 as to nitrogen dioxide, OSHA method ID-200 as to sulfur dioxide, and OSHA method ID-125 as to lead. The measured values (a) were almost uniformly the same, whether the Car Air Purifier was turned on or not, were so because the values fell below the lower limit of the analytical technique(s); and (b) in any event were well below the relevant health standards.

As to carbon monoxide, a single 5-minute mean concentration was obtained in Bangkok, Thailand on March 14, 2000, using the Dräger Gas Analyzer to yield a value of 11.9 ppm, well below the one-hour EPA standard of 30 ppm and the California standard of 20 ppm. Similarly as to ozone, a four-minute mean concentration measurement was made in Los Angeles on August 2, 1999, using the Ozone Spot Checker to yield a value of 2 ppb, well below the one-hour standards of the EPA (120 ppb) and California (100 ppb), and a 14-minute mean concentration measurement was made in Bangkok on March 14, 2000, using the Dräger Gas Analyzer to yield a value of <25 ppb, which is well below the 8-hour EPA standard of 80 ppb. The effectiveness of the Car Air Purifier against these chemicals also appears to have been demonstrated.

CONCLUSION

The Car Air Purifier that has resulted from this project and on which this paper reports is the first filtration device to be field tested in motor vehicles for effectiveness against all of the US EPA criteria pollutants. In addition to those air pollutants (carbon monoxide, ozone, nitrogen dioxide, sulfur dioxide, lead, and particulate matter), the field testing included benzene and other toxic volatile organic compounds. The Car Air Purifier also is the first device, to our knowledge, that was specifically designed to reduce the concentration levels of these specific pollutants inside traveling cars to meet the health standards for ambient air set by the U.S. government and most governments around the world. These are the major air pollutants for which monitoring stations are operating in most of the large and medium sized cities in the world. These health standards are set at a concentration level, for each pollutant, above which there is risk to human health.

The experimental results show the Car Air Purifier to be capable of reducing all of these pollutant levels to meet the prescribed health standards. Because of the very high particulate levels found in Bangkok, Thailand before the Purifier was turned on in the car cabin, the challenge to the Car Air Purifier was clearly significant enough that additional particulate matter testing is not needed. The same can be said, it would seem, for the levels of hydrocarbons that were encountered and tested in the Los Angeles area. However, additional field testing should be carried out in geographical areas where the ambient carbon monoxide and ozone levels will be higher than those encountered thus far, whereby a greater challenge to the Car Air Purifier

can be tested.

This study provides additional verification of previous studies showing that the concentration level of these major air pollutants inside vehicles traveling on congested highways is elevated 1.5 to at least 10 times above the levels measured at near-by monitoring stations. Even the levels found at the monitoring stations are high enough in many of the cities in the U.S. to place those areas in “non-attainment” status with the EPA, especially for particulate matter throughout the year and for ozone in the summer, and as is now quite clear, the person driving a vehicle through those cities is at much greater risk. In many cities outside of the United States, the ambient levels of these major pollutants are many times higher than what is experienced within the United States, as reported in the literature and confirmed by the levels measured in Bangkok.

The “good news” is that when the Car Air Purifier becomes available for purchase in the market place, people will no longer have to put up with that “something rotten in the air” experience when driving in heavy traffic. The human testers who gave their subjective evaluation of air quality in cars, both with and without the Purifier in operation, were uniformly consistent in the better ratings given for the purified air. There was no question that they were able to tell the difference that the Purifier made. What this means is that by using the independently operated Car Air Purifier, it is quite possible to satisfy customer demand with respect to “dust, pollen and some odors” being sought for marketing purposes, while at the same time to protect the vehicle users from more noxious air pollutants that might otherwise shorten their lives.

Fig. 1

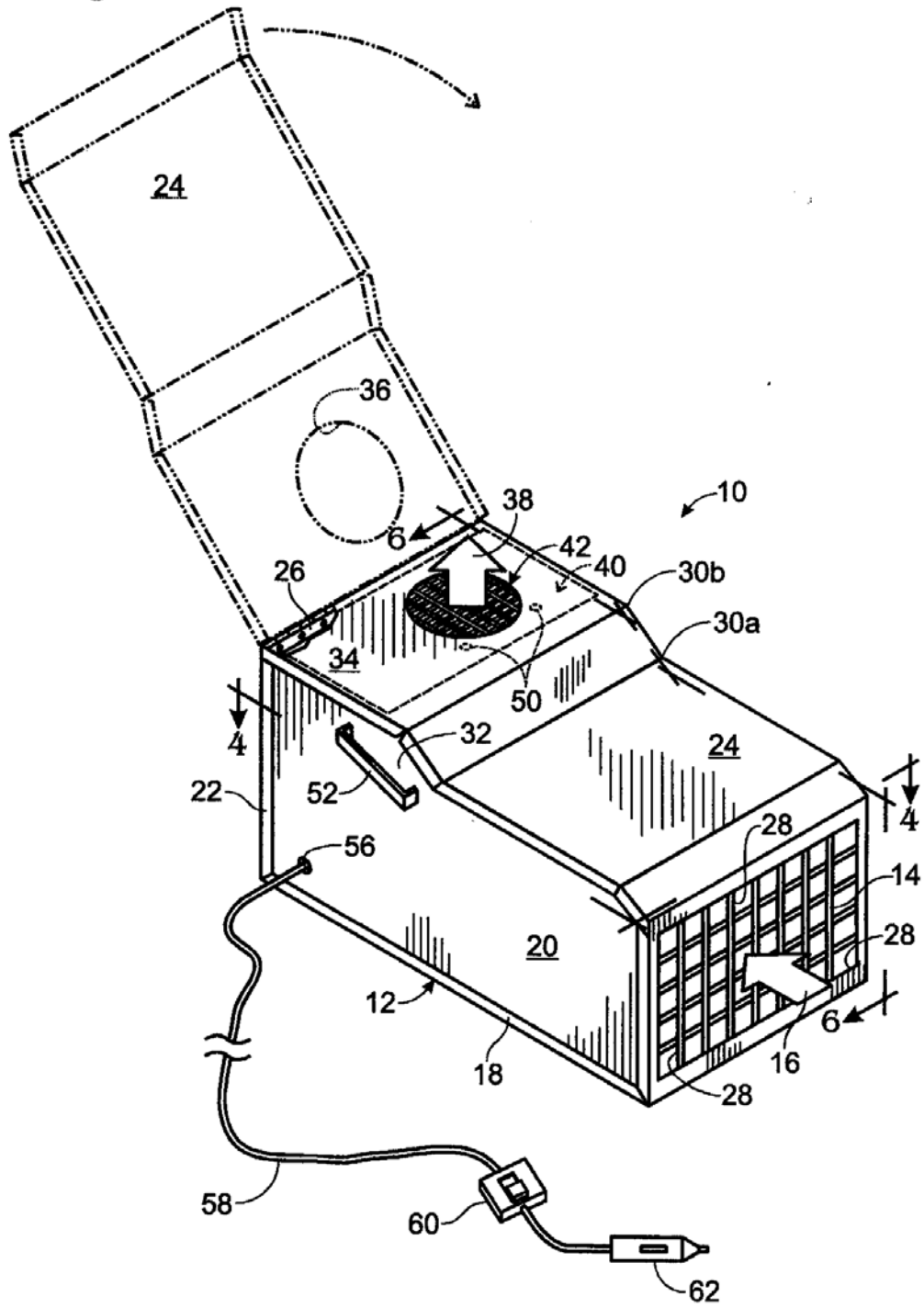


Fig. 2

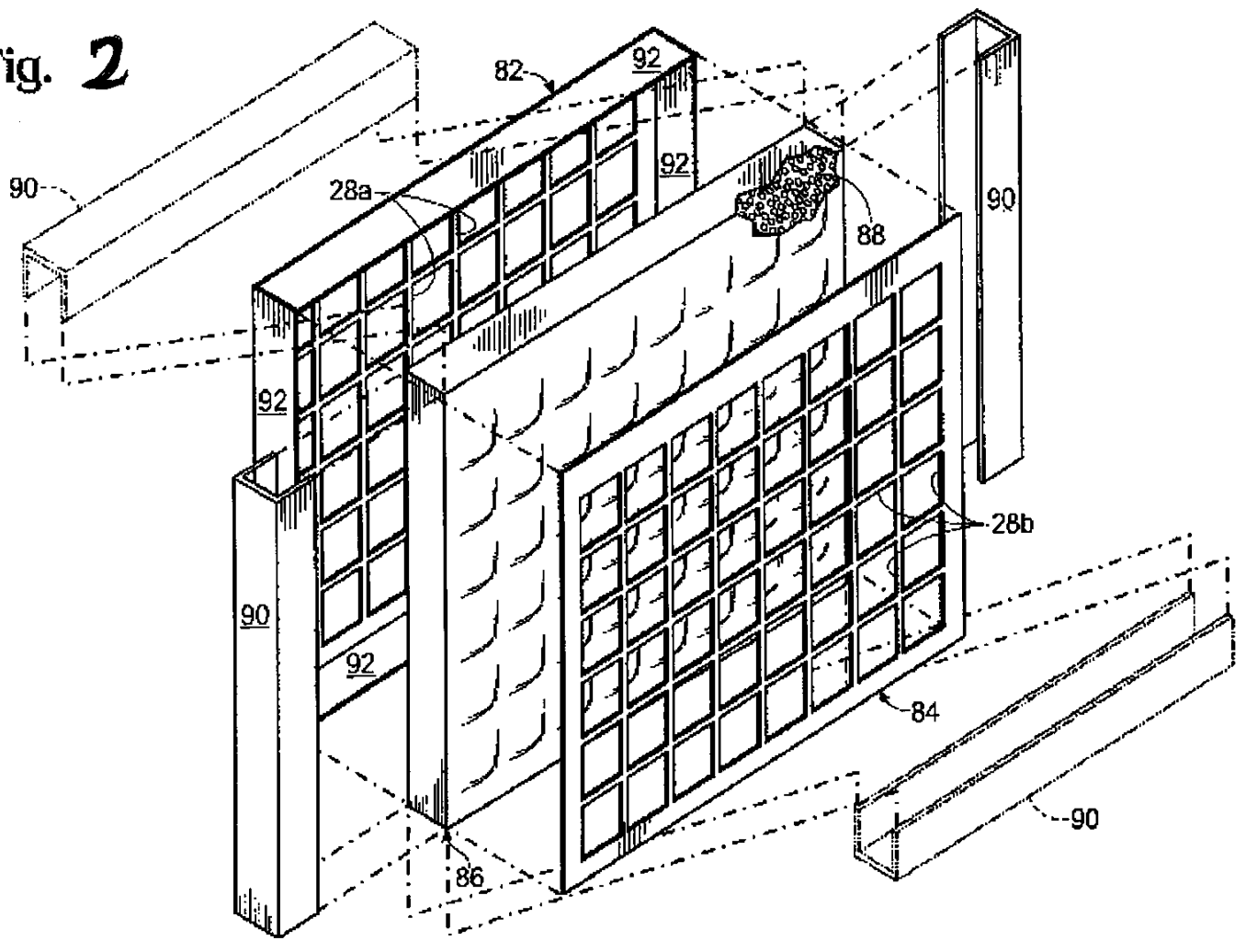


Fig. 3

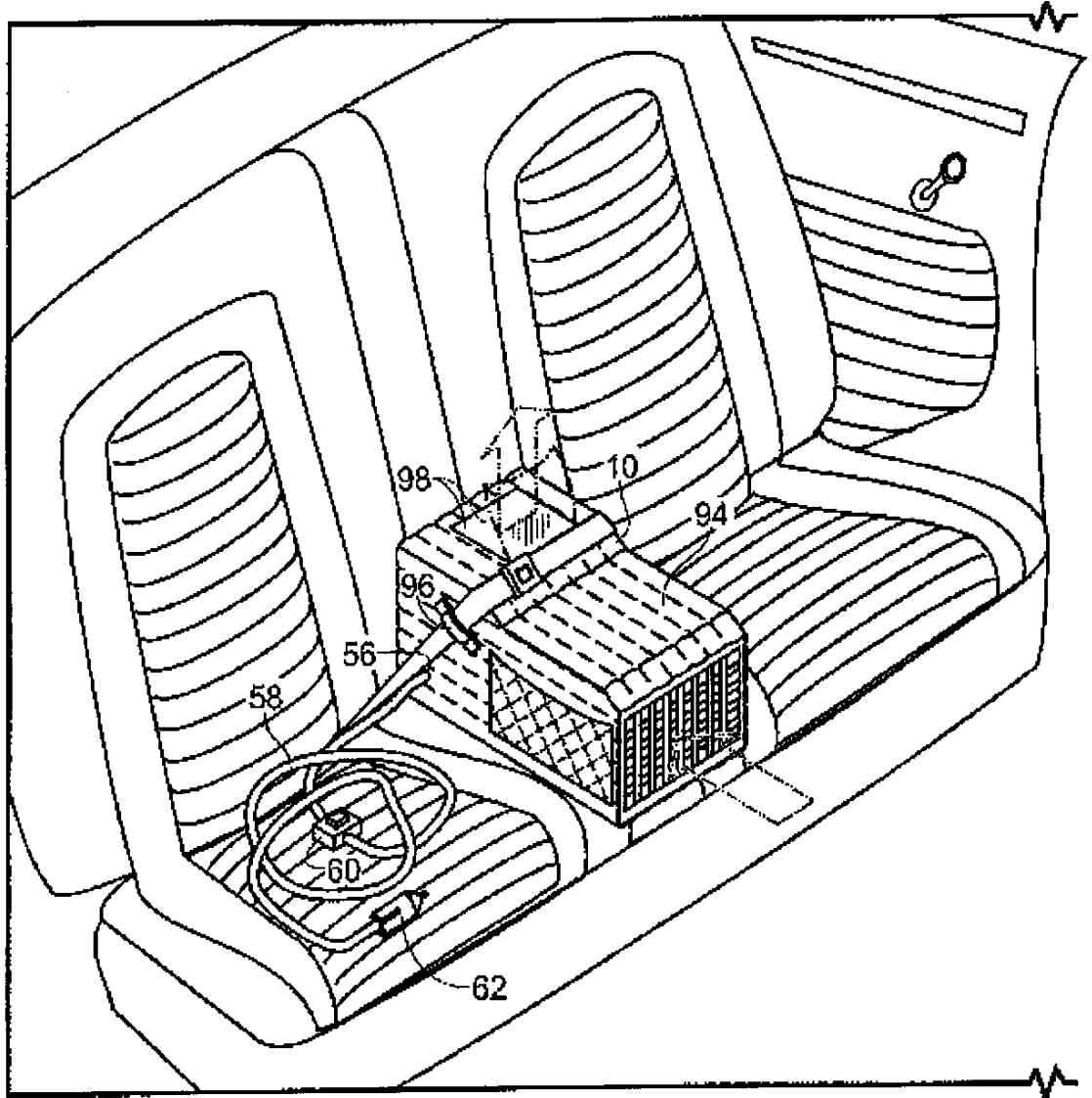


Fig. 4
 PM-10. 250 CFM --Trunk
 Los Angeles, Calif. August 2, 1999.

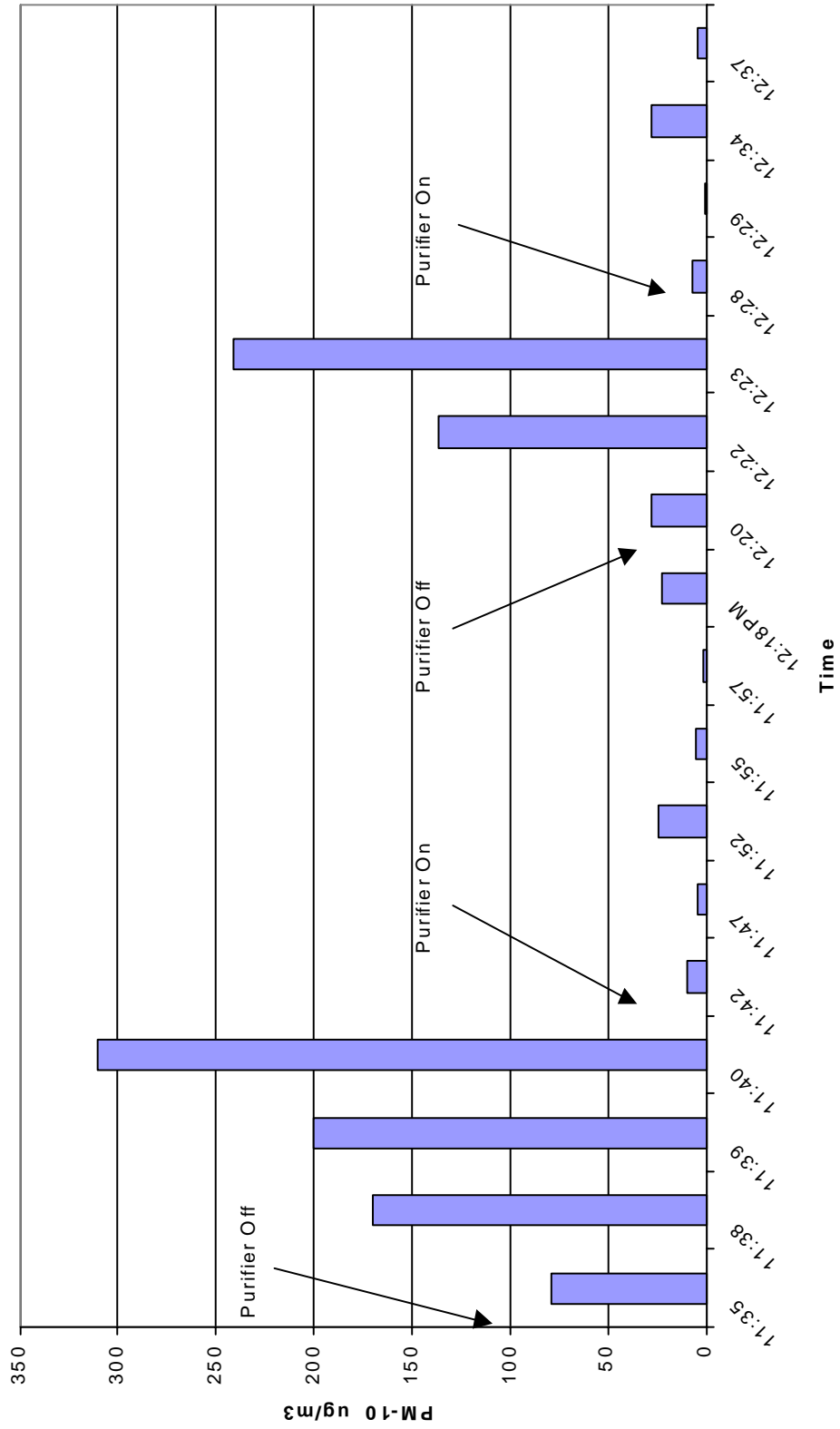


Fig. 5
PM-2.5 250 CFM - Trunk
Los Angeles, Calif. August 3, 1999

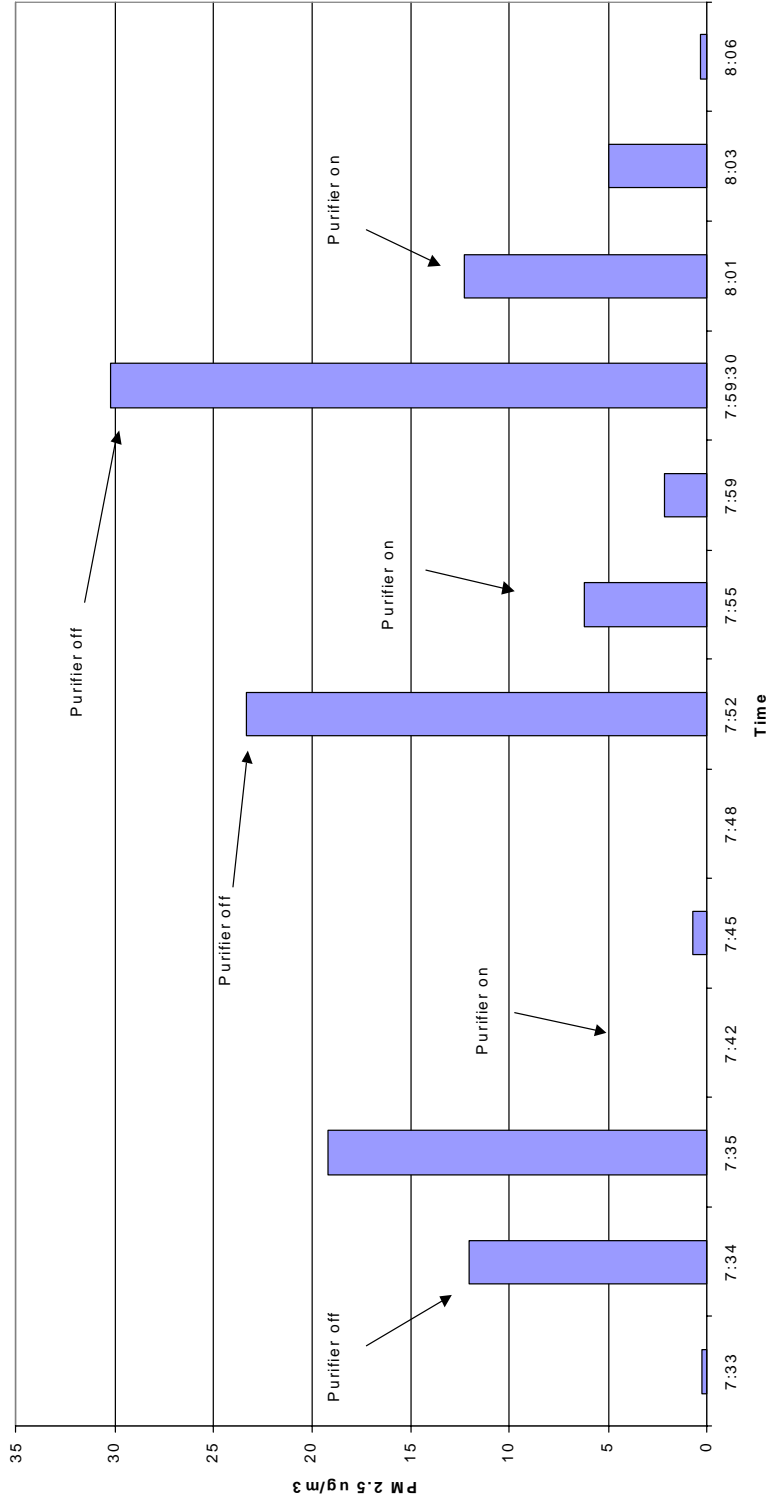


Fig. 6
PM-10. 7 m³/min (250 CFM)
Bangkok, Thailand, 13 March, 2000

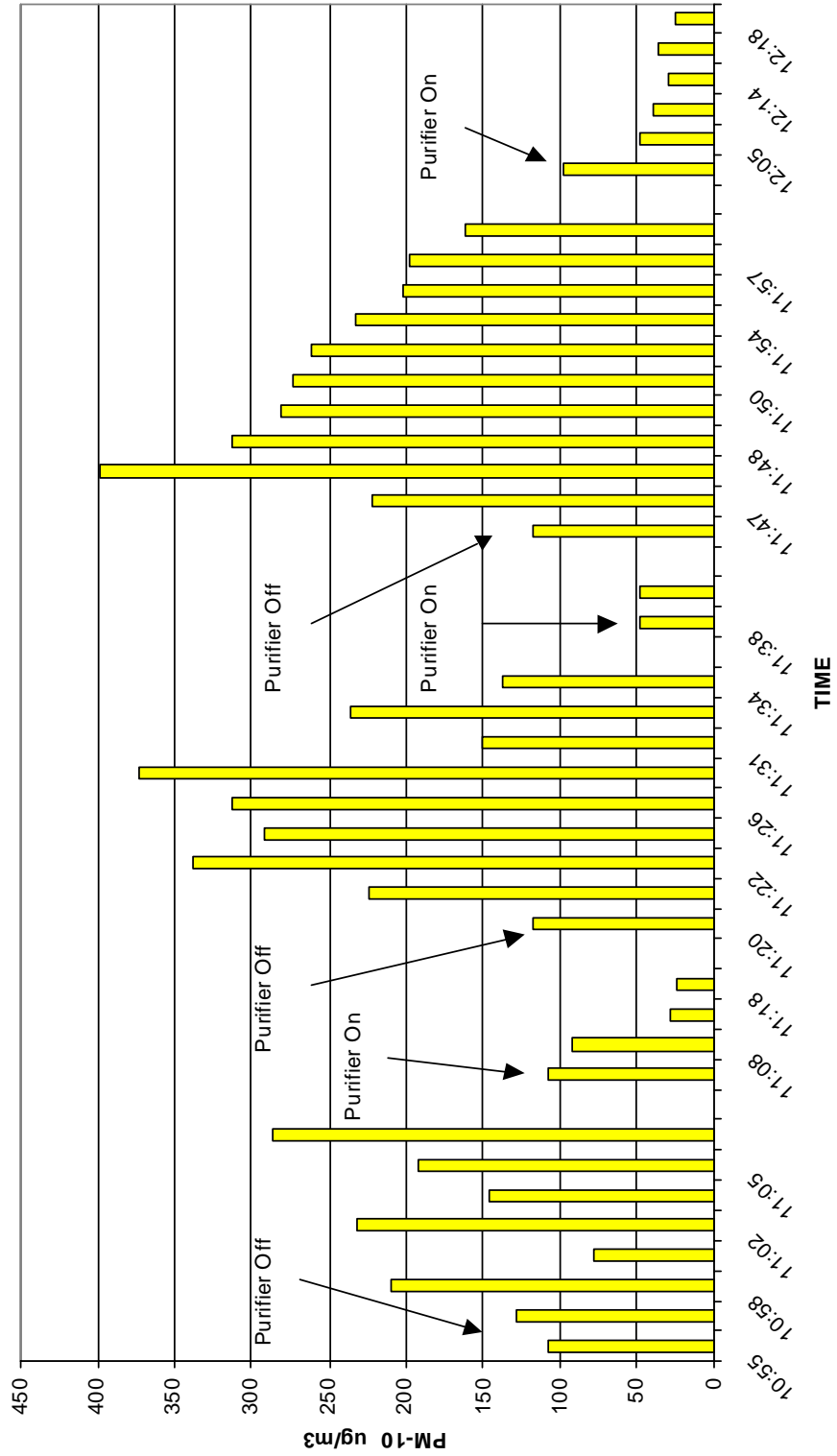


Fig. 7
PM-2.5. 7 m³/min (250 CFM),
Bangkok, Thailand, 13 March, 2000

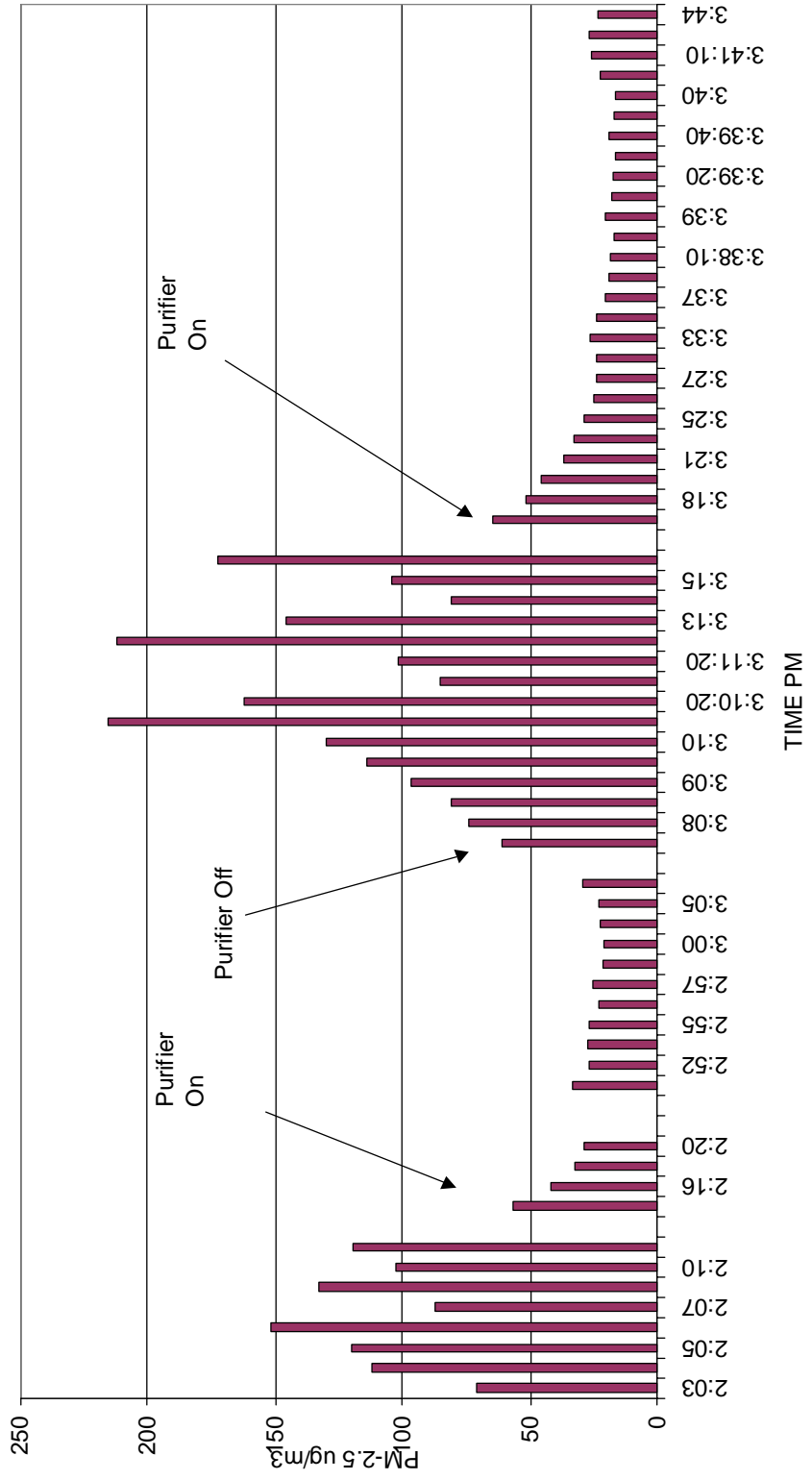


Fig. 8
PM-10.5 m³/min (176 CFM).
Bangkok, Thailand, 14 March, 2000

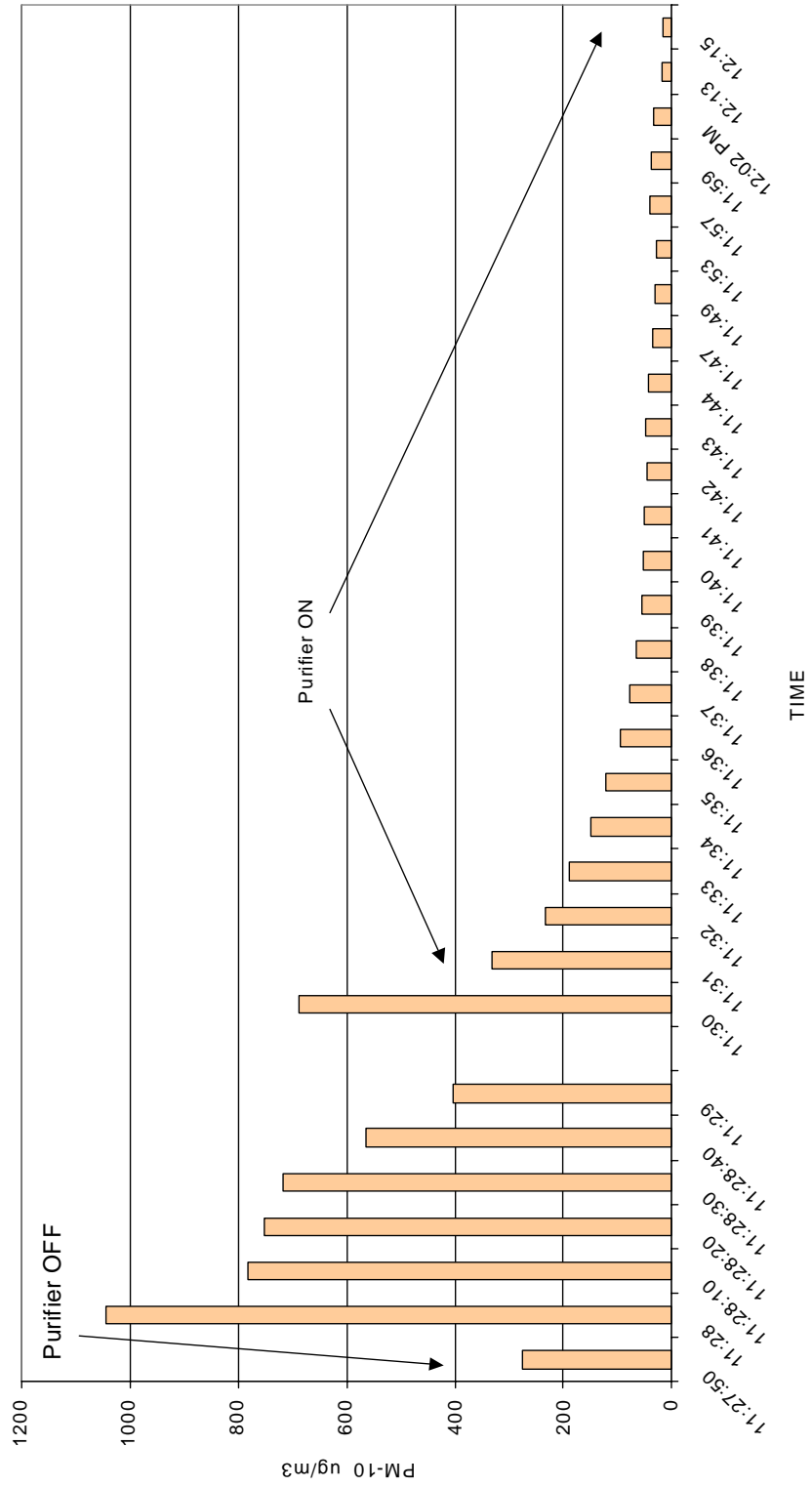


Fig. 9
PM-2.5. 176 CFM
Bangkok, Thailand, March 14, 2000.

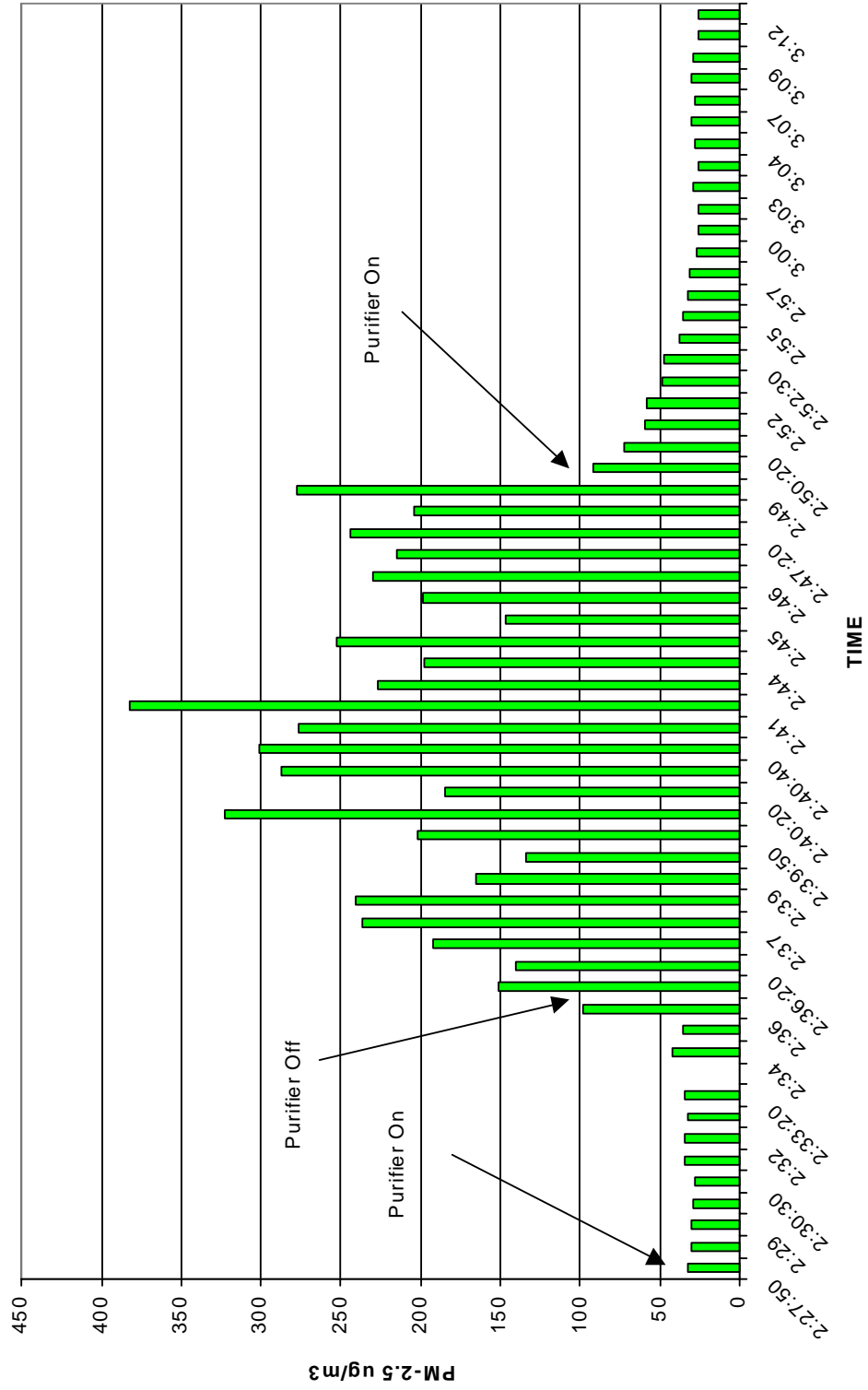


Fig. 10
PM-2.5. 5 m³/m In (176 CFM)
Bangkok, Thailand, 15 March, 2000.

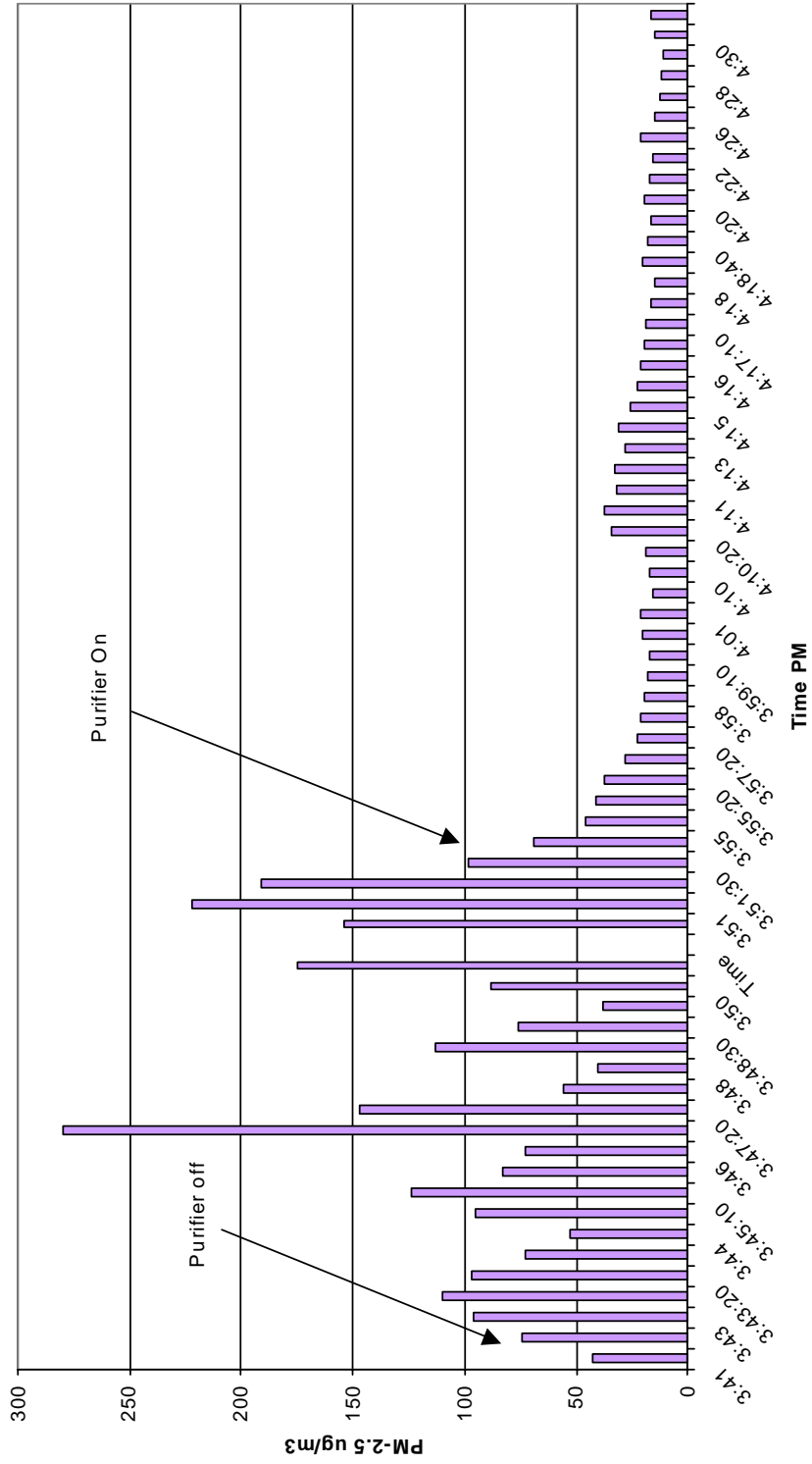


Fig. 11
Benzene. 7 m³/m In (250 CFM). Los Angeles, September 1, 2000. EPA Method TO-14A,
performed by Performance Analytical Inc., Simi Valley, Ca.

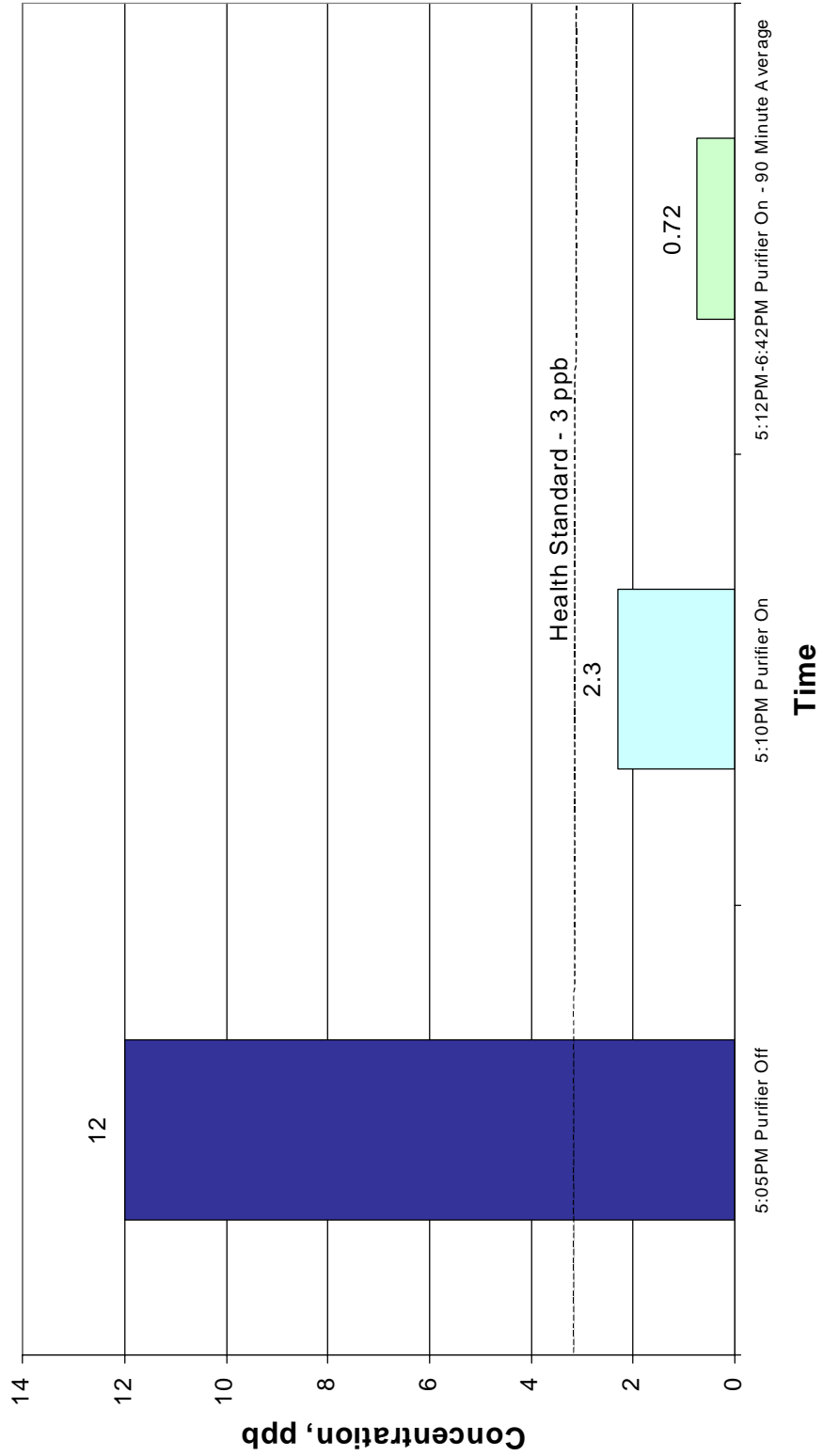


Fig. 12
Toluene. 250 CFM. Los Angeles, September 1, 2000. EPA Method TO-14A,
performed by Performance Analytical, Inc., Simi Valley, Ca.

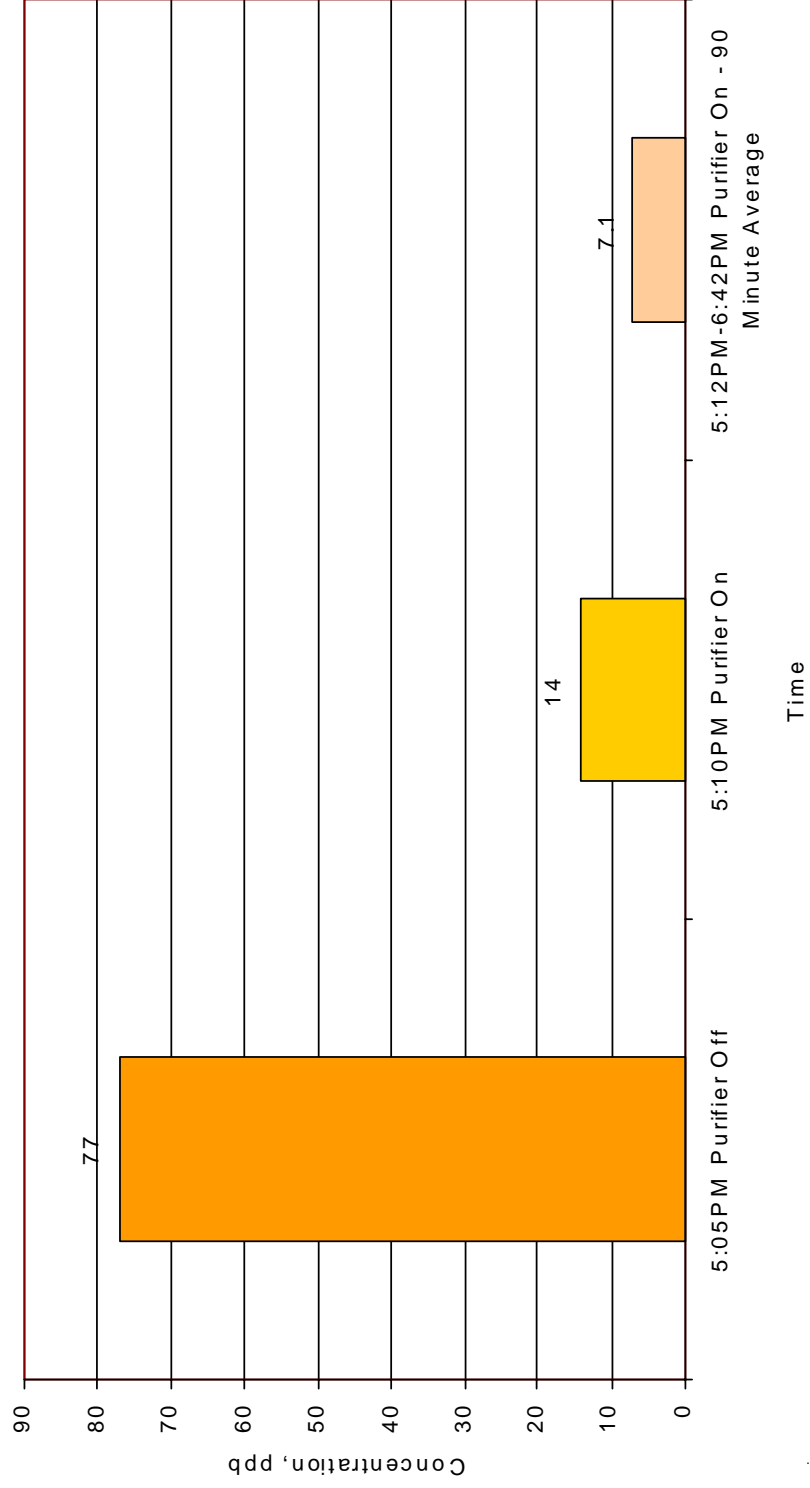


Fig. 13
Ethylbenzene. 250 CFM. Los Angeles, Sept. 1, 2000. EPA Method TO-14A,
performed by Performance Analytical, Inc., Simi Valley, Ca.

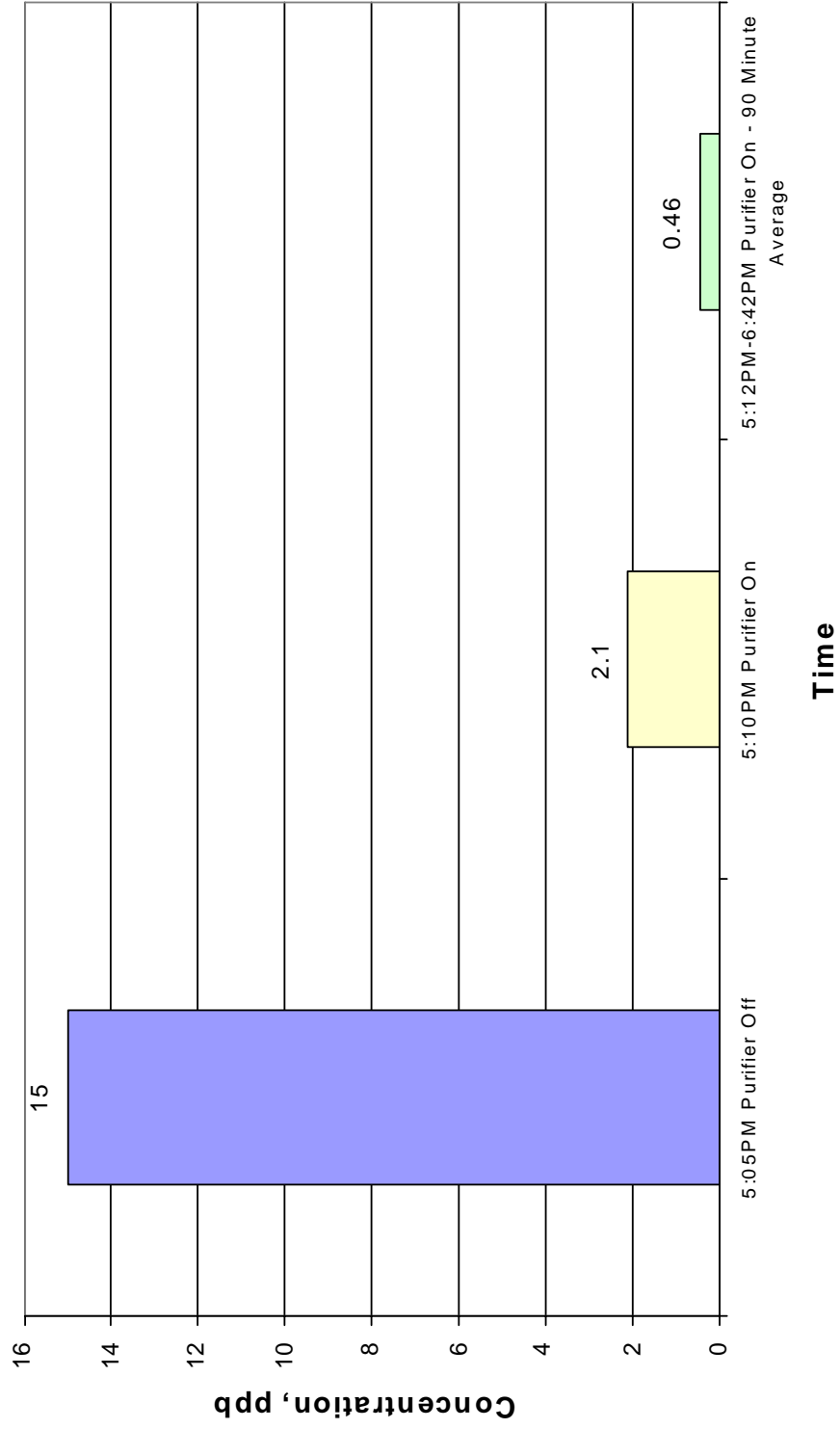


Fig. 14
m- & p- Xylenes. 250 CFM. Los Angeles, Sept. 1, 2000. EPA Method TO-14A,
performed by Performance Analytical, Inc., Simi Valley, Ca.

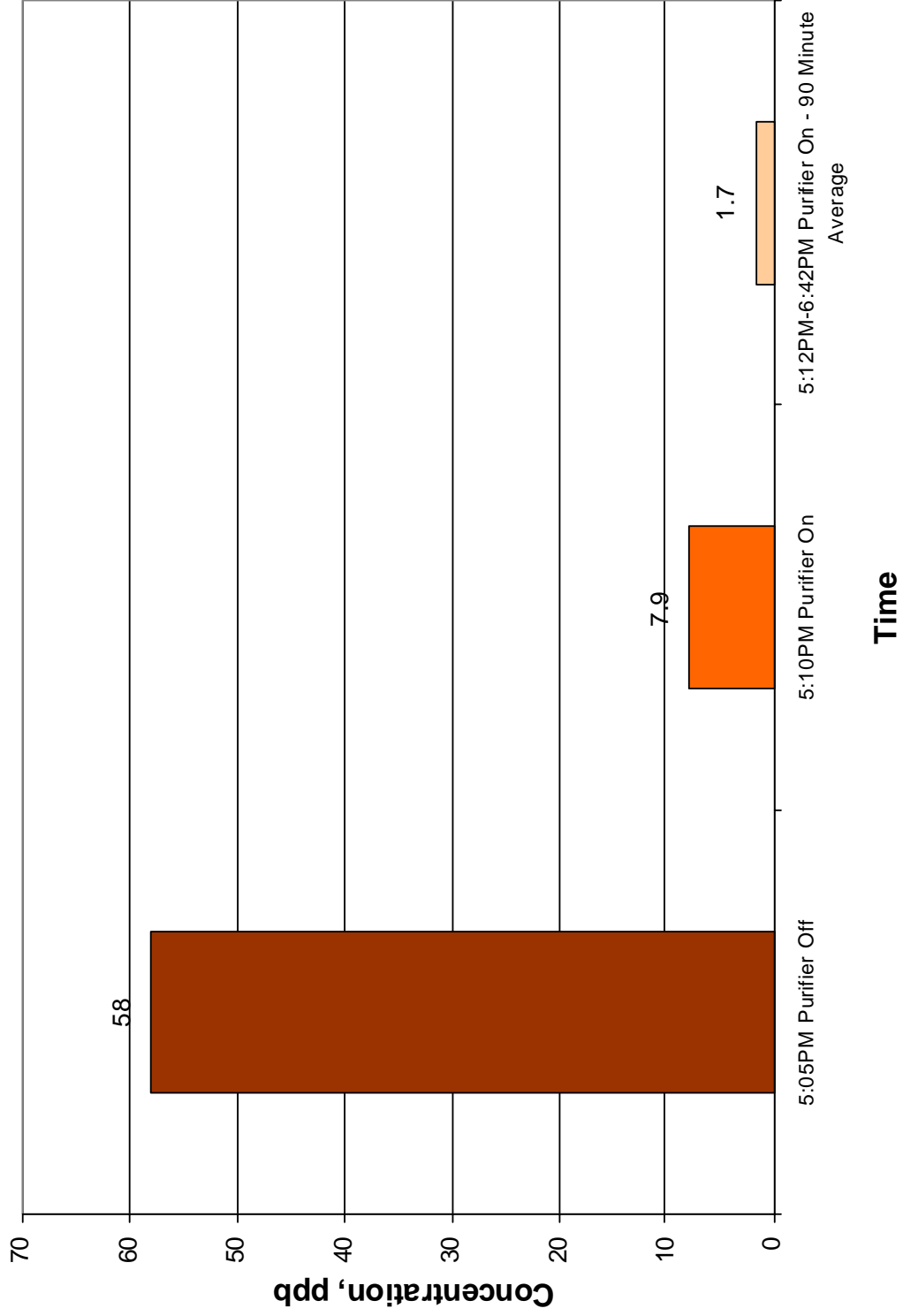


Fig. 15
o-Xylene. 250 CFM. Los Angeles, Sept. 1, 2000. EPA Method TO-14A, performed
by Performance Analytical, Inc., Simi Valley, Ca.

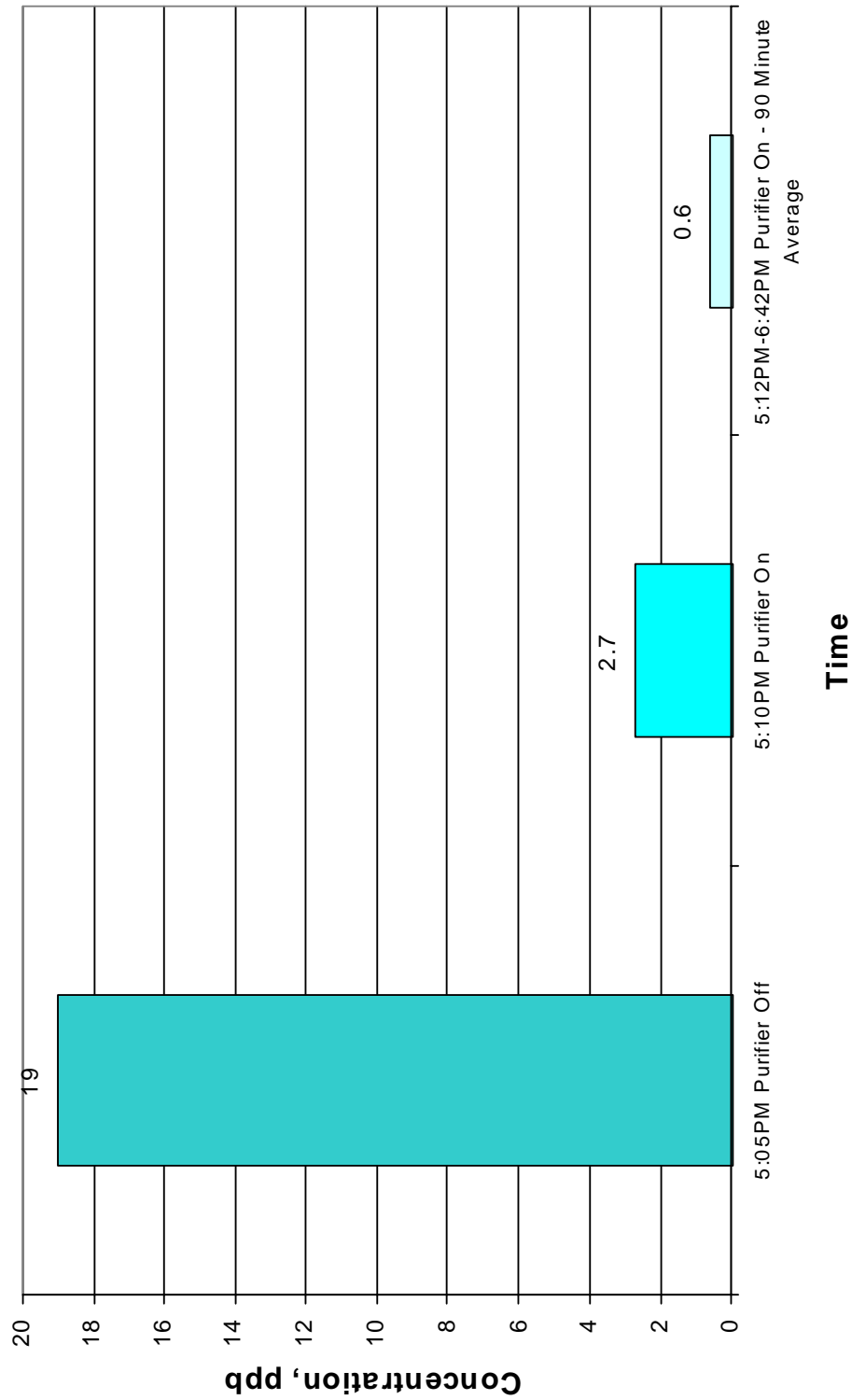


Fig. 16
1,3-Butadiene. 250 CFM. Los Angeles, September 1, 2000. EPA Method TO-14A,
performed by Performance Analytical, Simi Valley, Ca.

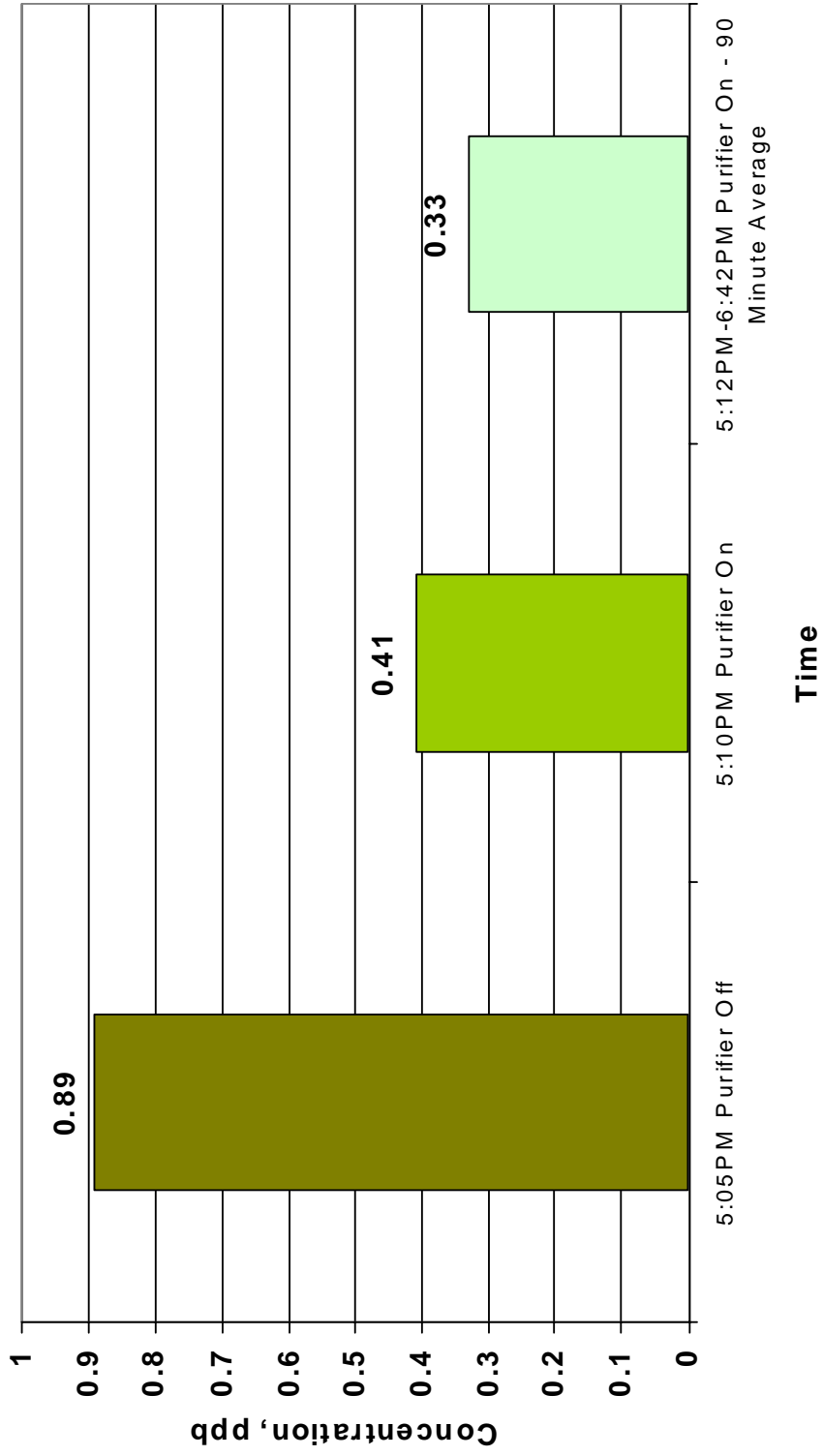


Fig. 17
t-Butyl Methyl Ether. 250 CFM. Los Angeles, September 1, 2000. EPA Method TO-14A, performed by
Performance Analytical, Inc., Simi Valley, Ca.

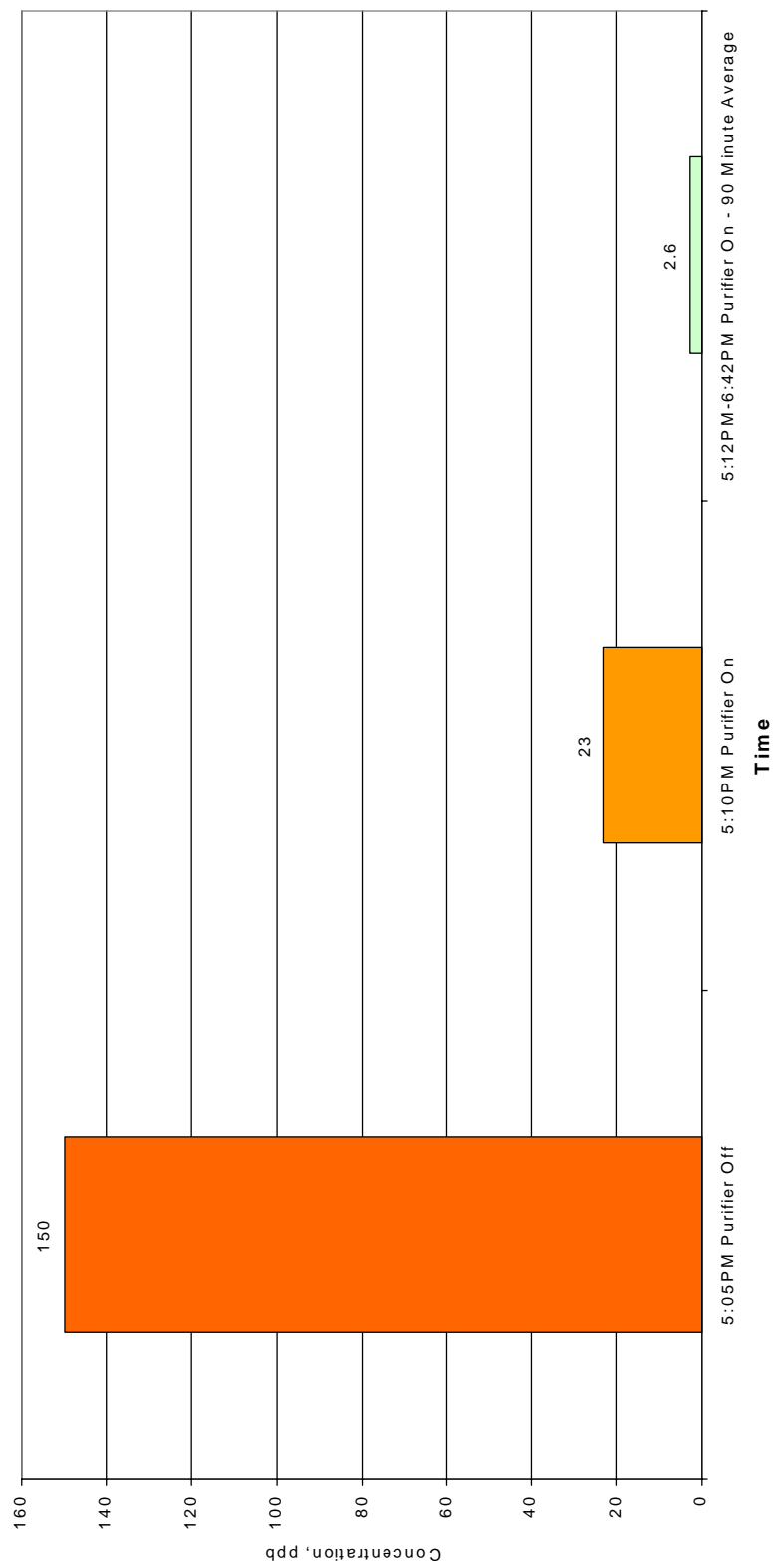


Fig. 18

**CONCENTRATION CHART -- MAJOR POLLUTANTS TARGETED
HEALTH STANDARDS VS. LEVELS FOUND IN THE PASSENGER CABINS OF TRAVELING CARS**

Pollutant:	Government Ambient Air Health Standards:			Ten In-Car Studies:			Typical Performance:	
	Averaging Time:	Holland	US EPA	California	Without Purifier	With Purifier	Test Site	Mean **
BENZENE	annual	10 µg/m ³ (3 ppb) *	none		Peak 766 µg/m ³ (240 ppb)	Mean Range 8 - 380 µg/m ³ 5 - 240 ppb	Los Angeles	2.3 µg/m ³ (0.72 ppb) 1)
CARBON MONOXIDE	1 hour		30 ppm (40,000 µg/m ³)	20 ppm (23,000 µg/m ³)	100 ppm	3 - 46 ppm	Bangkok	11.9 ppm 2)
	8 hours		9 ppm (10,000 µg/m ³)					
OZONE	1 hour		120 ppb	100 ppb *	350 ppb	10 - 177ppb	Los Angeles	2 ppb 3)
	8 hours		80 ppb				Bangkok	<25 ppb 4)
NITROGEN DIOXIDE	Annual 1 hour		100 µg/m ³ (52ppb)	481 µg/m ³ (250 ppb) *	290 ppb	20 - 140 ppb	Los Angeles Portland	<100 ppb 5) <100 ppb 6)
SULFUR DIOXIDE	Annual		80 µg/m ³ (140 ppb)					
	24 hours		365 µg/m ³ (636 ppb) *		400 ppb	<320-400 ppb	Los Angeles Portland	<320 ppb 7) <320 ppb 8)
LEAD	3 months		1.5 µg/m ³ *		3.1 µg/m ³	.2--1.3 µg/m ³	Los Angeles Portland	<1.0 µg/m ³ 9) <0.65 µg/m ³ 10)
PARTICULATE:								
PM 10	24 hours Annual		150 µg/m ³ * 50 µg/m ³	50 µg/m ³	1044 µg/m ³	20--370 µg/m ³	Los Angeles Bangkok	9.14 µg/m ³ 11) 37.4 µg/m ³ 12)
PM 2.5 ***	24 hours Annual		65 µg/m ³ * 15 µg/m ³		382 µg/m ³	29--220 µg/m ³	Los Angeles Bangkok	1.2 µg/m ³ 13) 20.3 µg/m ³ 14)

Fig. 19

FOOTNOTES TO THE CONCENTRATION CHART (Fig. 18)

*-- Government standards in bold print on the previous page (Fig. 18) are the targeted concentration levels attained by the tests described below.

** -- The numbered footnotes below describe the date and type of test for each of the pollutants.

- 1) Benzene: 90 minute mean concentration on September 1, 2000, using EPA method TO-14A, GS/MS, by Performance Analytical, Inc., collection by summa canister in Los Angeles.
- 2) Carbon Monoxide: 5 minute mean concentration on March 14, 2000, using Draeger Gas Analyzer, in Bangkok.
- 3) Ozone: 4 minute mean concentration on August 2, 1999, using Ozone Spot Checker in Los Angeles.
- 4) Ozone: 14 minute mean concentration on March 14, 2000, using Draeger Gas Analyzer in Bangkok.
- 5) Nitrogen Dioxide: 60 minute mean concentration on September 22, 2000, in Los Angeles using NIOSH method 6014 by Assay Technologies Lab., limit of detection.
- 6) Nitrogen Dioxide: 60 minute mean concentration on September 25, 2000, in Portland, using NIOSH method 6014 by Assay Technologies Lab., limit of detection.
- 7) Sulfur Dioxide: 60 minute mean concentration on September 22, 2000, in Los Angeles, using OSHA method ID-200 by Assay Technologies Lab., limit of detection.
- 8) Sulfur Dioxide: 60 minute mean concentration, on September 25, 2000, in Portland, using OSHA method ID-200 by Assay Technologies Lab., limit of detection.
- 9) Lead: 30 minute mean concentration, on September 22, 2000, in Los Angeles, using OSHA method ID-125 by Assay Technologies Lab., limit of detection.
- 10) Lead: 45 minute mean concentration on September 25, 2000, in Portland, using OSHA method ID-125 by Assay Technologies Lab., limit of detection.
- 11) Particulate (PM-10): 15 minute mean concentration on August 2, 1999, in Los Angeles, using a MIE DataRAM with a PM-10 nozzle.
- 12) Particulate (PM-10): 35 minute mean concentration on March 15, 2000, in Bangkok, using a MIE DataRAM with PM-10 nozzle.
- 13) Particulate (PM-2.5***): 9 minute mean concentration on August 3, 1999, in Los Angeles, using a MIE DataRAM with PM-2.5 nozzle.
- 14) Particulate (PM-2.5***): 33 minute mean concentration on March 15, 2000, in Bangkok, using a MIE DataRAM with PM-2.5 nozzle.

*** -- Pollutants in this size category include sulfates, nitrates, elemental carbon (diesel soot), asbestos, lead, cadmium, mercury, fungi, bacteria, viruses, and volatile organic compounds (such as hydrocarbons) attached to sub-micron sized particles.

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