Evaluating Particulate Emissions from Jet Engines: Analysis of Chemical and Physical Characteristics and Potential Impacts on Coastal Environments and Human Health

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The results of this study suggest that the range of size of particulate emissions from some jet engines clusters below 1.5 μm and that the emissions contain heavy metals. Therefore, jet exhaust particulates (JEPs) have the potential to adversely affect both the environment and human health. Little is known about the particulate component of jet engine emissions. Baseline physical and chemical data on JEPs were obtained to evaluate their potential effects on the environment. Particles collected from the exhaust stream of two types of jet engines were examined using scanning electron microscopy. Analysis indicated that 100 percent of the particles collected were below 1.5 μm in size. Particles in this size range can penetrate to the alveoli of human lungs. Chemical analyses of jet engine exhaust were conducted in an attempt to identify chemical fingerprints that would distinguish aviation emissions in the environment from other anthropogenic emissions. Certain heavy metals, especially vanadium, were found in jet exhaust and may be useful chemical fingerprints. Analysis of JP-5 fuel standards revealed a suite of alkylbenzene hydrocarbons, which may also aid in fingerprinting aviation emissions. Sediment samples taken at coastal wetlands near airports indicated the presence of the same heavy metals as those found in jet exhaust samples. Field sites exposed to higher volumes of air traffic contained higher levels of sediment heavy metals, supporting the hypothesis that aerial deposition of heavy metals is occurring in areas near some airports.

The aviation industry has committed substantial resources to studying and reducing the adverse environmental impacts of its activities. Most notably the problems of jet noise abatement and control of airport runoff have been addressed. Increased attention is being paid to jet engine emissions as airlines continue to upgrade their fleets to achieve full Stage 3 compliance with the 1990 Airport Noise and Capacity Act; concerns over emissions are not confined to noise, however. The latest challenge facing both the aviation industry and its regulatory agencies is to address the air pollution generated by air traffic. Until recently commercial air traffic had been mostly exempt from regulatory control of emissions. This is likely to change because the level of public concern about environmental and health issues remains high and many regions around the world are enacting more stringent air quality regulations.

Current fuel consumption as a result of aviation is 180 million tons annually (*1*). Airlines operating out of the five commercial airports in the Los Angeles Basin produce 28 tons of emissions daily. Three-fourths of this amount comes from airplanes, the remainder from ground support equipment (*2*). Fuel consumption is expected to increase. The International Civil Aviation Organization (ICAO) projects a 65 percent increase in aviation fuel consumption between 1990 and 2010 (*1*). Because of the predicted increases, pressure for further regulation of aviation emissions is also increasing. A recent meeting of ICAO's Committee on Aviation Environmental Protection resulted in a strong recommendation for increased stringency in the regulation of both noise and emissions from airports. In the United States, the recently proposed federal implementation plan of the Clean Air Act in California suggested instituting a sliding scale of reductions on aviation emissions beginning in 2001 (*3*). The plan proposed that airlines reduce emissions in the Los Angeles Basin by 35 to 45 percent by 2005 and that heavy fines, such as a fee of $10,000 per ton of excess emissions, be levied against parties exceeding the standards. The plan's standards applied to both airplanes and ground support equipment operated by the airlines. The plan was not implemented because of a variety of economic and logistic considerations, but it appears highly probable that regulation of airline emissions will increase in the future. It is vital that information on the effects of aircraft emissions be collected so that future efforts to reduce their impact can be as productive as possible.

Changes in jet engine technology intended to reduce noise have led to changes in emission profiles. New lower-noise engines have reduced emissions of hydrocarbons (HC) and carbon monoxide (CO) but have increased nitrous oxide (NO_x) emissions. Such tradeoffs are often made when the reduction of specific emission components is pursued. Reductions in engine noise generally require increased fuel burn, which also increases engine emissions. This paradigm of tradeoffs in engine design makes it vital to collect data on the relative environmental impacts of the chemical components of jet engine exhaust. The data will allow priorities to be set for the regulation of the most damaging emissions and will help guide the development of new engine technologies. For this study, information was collected on a relatively unstudied component of jet engine exhaust—particulate emissions.

The operation of jet engines results in the release of HC, CO, NO_x, sulfur dioxide (SO_2), and particulate matter. Assessments of the impacts of engine emissions and considerations of methods of reduction have focused more on the pollutants CO, HC, and NO_x

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because much more information is available on them. The 1994 EPA report *Air Pollution Mitigation Measures for Airports and Associated Activity* omits particulate matter from its discussion of airport emissions, stating, "little is known quantitatively about jet engine particulate emissions" (*4*). It is especially important to investigate the particulate component of jet engine exhaust because some studies of air pollutants have found that particulates derived from mobile sources have more serious adverse impacts on human health than other anthropogenic emissions such as ozone, nitrogen, and SO_2 (*5*).

Internal combustion engines are not the only sources of atmospheric particulates, but previous research indicates that they may be one of the most damaging. A study comparing the toxicity to humans of particulates from wood smoke and automobile exhaust found that particles derived from the exhaust, a mobile source, had a 3.6-fold higher mutagenic potency than did particles from wood smoke (*6*). Mobile source emissions are estimated to compose the single largest source of health risk from airborne toxic pollutants (*7*).

Particulates in engine exhausts form because of incomplete combustion. Particulate emissions are higher at low engine powers because combustion efficiency is lower. Particulate emissions from jet engines are highest at takeoff and climbout, operations that require very high fuel flow rates. Therefore, data would be expected to show high particulate emissions around airports. Aerial deposition of exhaust particles from air traffic may have impacts on human health and the environment. High levels of ambient particulate matter have been found to adversely affect human respiratory systems, causing the development of asthma, lung cancer, and chronic bronchitis, among other problems (*5*,*8*,*9*). Particle size is an important factor in determining particulates' toxicity to organisms. Particles smaller than 10 μm (PM_{10}) are considered to be respirable. After a particle is inhaled by an organism, size determines how far into the lungs it is likely to penetrate and can affect its chemical toxicity. Previous work has indicated that the fine fraction of PM_{10} is often more toxic than the coarse fraction (*8*).

Aerial deposition of particulates from jet exhaust may adversely affect the environment, as well as human health. Previous studies of particulates derived from automobile exhaust have documented the deposition of such particles on vegetation. Heavy metals associated with these aerosols have been shown to adversely affect several plant species (*10*) and some animals (*11*,*12*). Because of the gaps in knowledge about particulate emissions from airplanes, such emissions' potential negative effects on human health and the environment and the probability of increased regulation of air traffic emissions, data have been collected to evaluate the physical and chemical characteristics of jet exhaust particulates (JEPs). The data have been used to assess the potential impacts of JEPs on humans and the environment. The focus has been on evaluating the role of JEPs in coastal regions. A large percentage of the world's airports route jet traffic over water, making a study focused on coastal airports relevant to many airports worldwide.

Assessments of the potential for chemical fingerprinting of jet engine emissions in the environment were also made. Such fingerprinting techniques would be especially valuable tools for assessing the impacts of JEPs because most areas adjacent to airports are subject to a variety of anthropogenic inputs and deposition from many emission sources. Levels of impact on the environment from aviation sources and the necessity for regulation of those sources cannot be successfully assessed until the levels can be reliably distinguished from the background of impacts from other emission sources such as automobile exhaust.

MATERIALS AND METHODS

Three primary lines of inquiry were pursued in investigating jet exhaust particulates: physical, chemical, and biological. Results of the biological phase of the research will be discussed in a future paper.

Techniques were designed to provide basic information on the morphometrics of JEPs; results will allow predictions to be made about the behavior of the particles in the environment and their potential effects on human health. Two methods were employed to examine the physical qualities of JEPs: scanning electron microscopy (SEM) of exhaust particles and measurement of mass of aerial deposition at field sites. The measurements will help determine whether particulates are reaching ground level and if so, in what quantities this occurs.

Other techniques were designed to determine the chemical composition of JEPs and to assess whether they pose any health risks to humans or other organisms. Two groups of chemicals were investigated: heavy metals and HC. Levels were measured in samples of jet engine exhaust and in the sediment of field sites near airports. Information on the physical and chemical characteristics of JEPs will eventually be combined with biological data in order to evaluate whether they have adverse environmental impacts.

Study Sites

Data were collected at two coastal wetland field sites, both of which contain tidal creeks and are subject to different levels of jet traffic. Goleta Slough is located directly beneath the flight paths of the Santa Barbara Regional Airport. The tidal creeks of the wetland are within 200 m (219 yd) of the runways and were considered to be a proximal area subject to a lower volume of jet traffic than the Ballona wetlands, which are located 4.83 km (3 mi) north of Los Angeles International Airport (LAX). The LAX site was considered to be a lower-proximity site subject to much greater air traffic volume. Both wetlands are located near urban areas, which subjects them to a variety of anthropogenic impacts. Data from these two field sites will eventually be compared with those from a reference site that is not subject to any aviation activities. Reference site data are not yet available because finding coastal wetlands in Southern California that are not near airports or highly degraded by other impacts has been difficult. The nearest suitable reference site located so far is in Baja, Mexico. All field sites are being sampled to measure amounts of aerial deposition, HC, and trace metals in the sediment.

Scanning Electron Microscopy of Jet Engine Exhaust Particulates

JEPs were collected at jet engine test cells at Miramar Naval Air Station, San Diego, California, from two different engine types, the TF-30-P-414-A and the F110-GE-400. Both engines were burning JP-5 fuel. The TF-30 is an older engine, typically used to power the F-14A Tomcat and the Air Force F-111. The F110 engine is typically found on the F-14D "Super" Tomcat. Exhaust particulates were sampled using a modified EPA Method 5 apparatus. A stainless steel probe with an internal diameter of 12.7 mm (0.5 in.) was inserted through a port in the wall of the test cell, which was located approximately 15.25 m (50 ft) behind the engine, in the

exhaust stream. A pump was used to draw exhaust gases through the probe and into copper tubing that directed the exhaust into the Method 5 apparatus. Within the Method 5 apparatus exhaust is first pulled through an EPM 2000 glass fiber filter and then passed through two impingers containing distilled water. Exhaust then passes through a dry impinger and finally through a fourth impinger filled with 250 g of desiccant agent.

The particulates collected on the filter were later viewed using SEM. Portions of the filter were cut out and glued to an SEM stub. The samples were sputter-coated with gold for SEM viewing.

After scanning electron micrographs of a filter segment were obtained, particle sizes were measured by hand as they appeared on the micrographs. A centimeter ruler was used. Each particle was measured across its longest axis and scored as part of an aggregate or not part of an aggregate. Aggregates were defined as clumps of particles with no visible breaks between particles. Each aggregate was also measured across its longest axis and for the purposes of data analysis was considered as one large particle. The measurements obtained were converted using the micron scale on the micrograph to obtain actual particle sizes.

Heavy-Metal Analysis of Jet Engine Exhaust Samples

An engine run was performed without an EPM 2000 filter in front of the Method 5 impingers to collect exhaust samples for heavy-metal analysis. Sterile filtered seawater instead of distilled water was exposed to the unfiltered exhaust stream. Seawater was used to better model the chemical effects of JEPs for the investigation of the effects of JEP deposition in coastal areas. Seawater from the impingers was analyzed for heavy metals using the protocols established by Martin et al. (*13,14*). Eight grams of each sample was analyzed in duplicate. The samples were digested overnight with 2 mL each of nitric acid. Each sample was then analyzed for heavy metals by an inductively coupled argon plasma emission spectrometer (ICP) from ARL Accuris Mody Fison's Instruments, Inc.

Measurement of Mass of Aerial Deposition

Aerial deposition was measured under the flight path of LAX. Settling plates (n = 4) were deployed at random intervals along a transect perpendicular to the runways. The plates were located approximately 100 m (328 ft) from the end of the runways. Deposits were collected by exposing plastic petri dishes to ambient air at each site. All petri dishes were coated with a thin layer of silicon grease to facilitate the retention of particles. Before exposure, coated dishes were desiccated for 8 hr and weighed. Plates were collected after 48 hr of exposure. After collection, the samples were again desiccated for 8 hr and weighed to determine the mass of particulate deposits collected.

Collection and Analysis of Field Sediment Samples

Four transect lines 30 m long were laid at each study site. Along each transect 10 quadrats, each delineating an area 0.25 m square, were sampled for the biological phase of the research. Random numbers were used to select 4 of the 10 quadrats as sediment sampling stations. At each station two sediment samples were collected, one for the purposes of trace metal analysis and the other for HC analysis. Samples for heavy metal analysis were collected using a plastic template to isolate a standard surface area of sediment. A random subsample of the top 6 cm of this isolated area was scraped into a polyethylene sampling jar using a plastic measuring spoon. Samples for HC analysis were isolated in a similar way, except that a galvanized steel template was used to isolate the standard surface area. All sediments were collected in amber glass jars to reduce light exposure, because photooxidation of HC can change their chemical signature. To avoid sample contamination only plastic collection and measuring devices were allowed to contact sediments slated for heavy metal analysis, and sediments for HC analysis were handled only with metal implements. All collection containers used for sediment samples were certified cleaned to EPA Superfund standards.

After collection samples were placed on ice in coolers, transported to the laboratory, and frozen within 8 hr. The trace metal content of sediment samples was determined by ICP using the methods established by Martin et al. (*13,14*). Samples of 0.5 g were weighed in triplicate and heat-digested overnight with 3 ml of nitric acid. They were then diluted and centrifuged to remove any undigestable particulates, and the supernatant was analyzed for heavy metals by ICP.

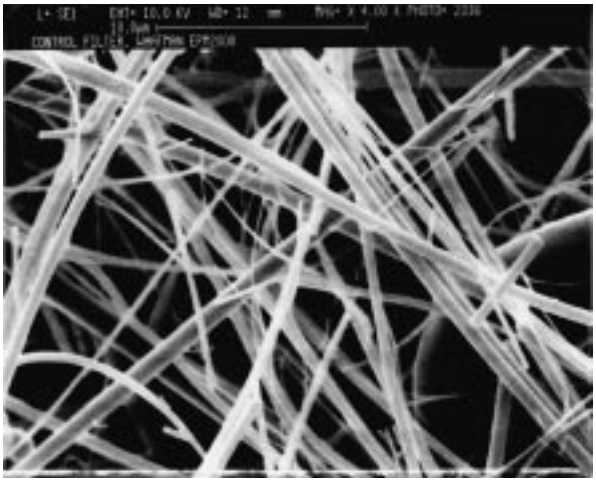
Sediments analyzed for HC were extracted and analyzed with gas chromatography/mass spectrometry (GC/MS) using the methods established by Venkatesan et al. (*15*). Forty grams wet weight of thawed sediment was extracted using methanol and methylene chloride. After a series of back extractions and precipitations, the extract was separated into aliphatic, aromatic, and polar fractions. The aliphatic fractions were analyzed in a Varian 3400 gas chromatograph equipped with a flame ionization detector and a Septum programmable injector. Helium was used as a carrier gas. The data were processed using a Varian Star Integrator. Both the aliphatic and aromatic fractions were analyzed by GC/MS using a Finnegan 4000 with a Varian 9610 gas chromatograph. Standard quality-control procedures were followed in the analysis of all samples.

RESULTS

Scanning Electron Microscopy of Jet Exhaust Particulates

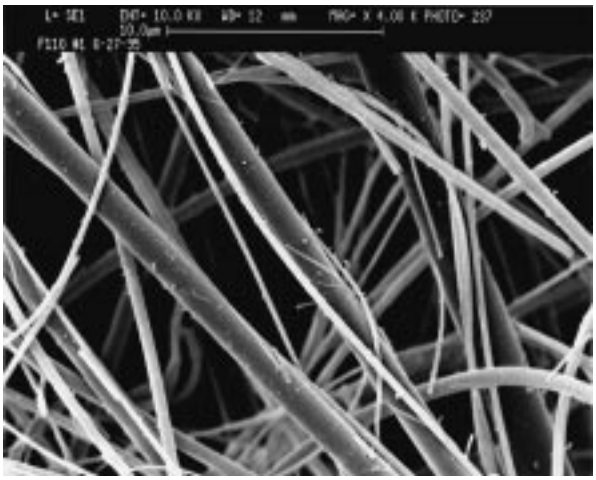
Observation by SEM of filters exposed to jet engine exhaust indicated that particles were present in the exhaust stream and that both their quantity and average size varied by engine type. The older engine type, the TF-30, emitted approximately three times more particles than the F110. Over a 2-hr run a total of 317 particles was collected on a 521.4-μm^2 surface area from the TF–30 engine, as shown in Figure 1(*a*), whereas the newer F-110 engine emitted a total of 106 particles on the same surface area over the same time period, as shown in Figure 1(*c*).

These particle densities are equivalent to 330 million particles/cm^2 (2.13×10^9 particles/$in.^2$) for the TF-30 engine and 260 million particles/cm^2 (1.68×10^9 particles/$in.^2$) for the F110 engine. Size frequency distributions of the particles for both engine types indicate that 100 percent of the particles emitted were less than 1.5 μm in size, as shown in Figure 2. The average size of a particle from the TF-30 was 0.01 μm larger than the average F110 particle size. The differences in size frequency between the two groups of particles may be attributed in part to an interesting aggregating property exhibited by the exhaust particles. When the exposed fil-



(*a*)

(*b*)



(*c*)

FIGURE 1 Scanning electron micrographs showing effect of jet engine exhaust on strands of glass fiber filter paper magnified 4,000 times: (*a*) control filter not exposed to jet engine exhaust, (*b*) filter exposed to exhaust stream of TF-30 jet engine for 2 hr, and (*c*) filter exposed to exhaust stream of F110 jet engine for 2 hr. (Scale = 10 μm.)

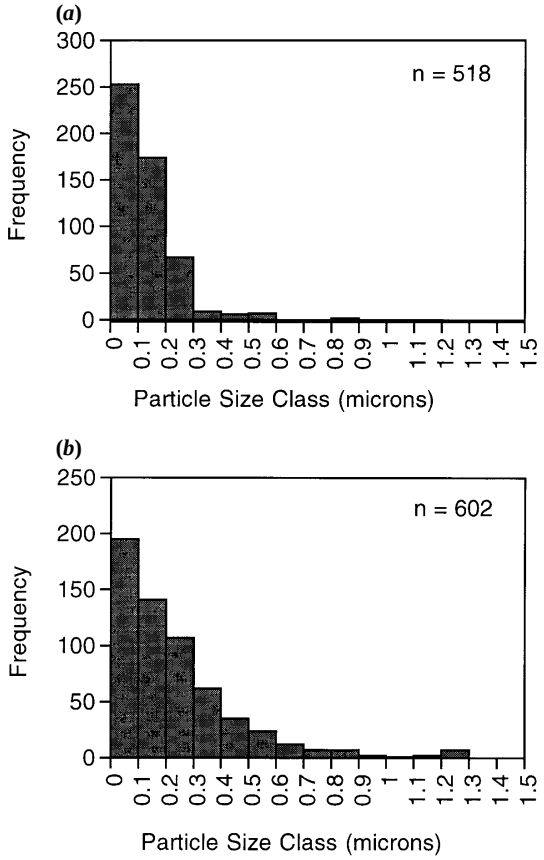


FIGURE 2 Size frequency distributions for jet engine exhaust particles collected from 2-hr runs of two engine types: (*a*) F110 jet engine and (*b*) TF-30 jet engine.

ters in Figure 1 are viewed at higher magnification, as in Figure 3, some particles were observed to clump together into aggregates. The reason for the aggregate formation is unknown. It is possible that some sort of charge attraction exists between the particles. Aggregating behavior also varied by engine type, with 35 percent more of the particles from the TF-30 occurring in aggregates, as shown in Figure 4.

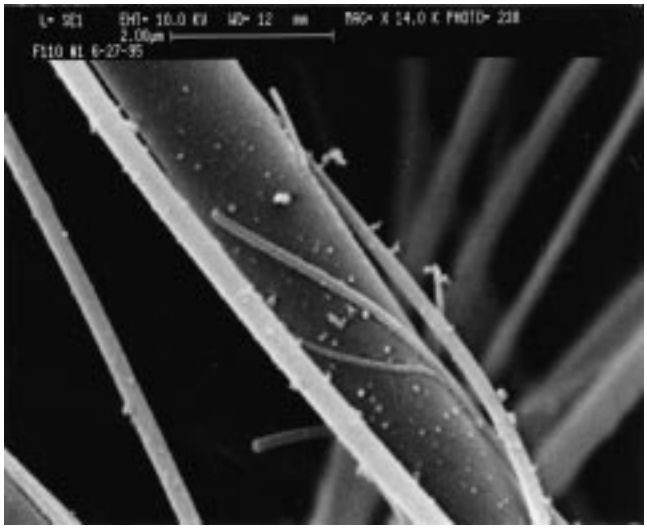
Aerial Deposition at Field Sites

Preliminary measurements of aerial deposition at field sites around LAX have indicated measurable levels reaching the ground at sites near runways. Settling plates deployed directly under the take-off path of LAX received an average of 10.6 g/m²/day of deposits. Chemical analyses of deposits collected in this manner are in progress and will eventually help to determine what percentage of the deposits is derived from jet emissions.

Metal Composition of Jet Engine Exhaust

Chemical analyses of jet engine exhaust samples indicate that the exhaust contains heavy metals. Exhaust samples collected at the jet engine test cell showed substantial increases in metal concentrations above the control sample, as shown in Figure 5. Zinc, copper,

(*a*)



(*b*)

FIGURE 3 Scanning electron micrographs showing aggregating behavior of jet engine particles for two engine types: (*a*) TF-30 jet engine and (*b*) F110 engine. (Exposure time, 2 hr; magnification, 14,000 times; scale = 2.0 μm.)

and beryllium were all observed at levels 100 percent above the control. Lead levels were 50 percent above the control; cobalt and vanadium were observed at less dramatically increased levels—25 and 28.6 percent, respectively. After establishment of this baseline metal signature for JEPs, sediment collected at field study sites was analyzed for heavy-metal content. Results indicate that all of the heavy metals found in the samples of jet exhaust were present in the sediments of field sites near airports, as shown in Figure 6. Sediments from the site near LAX contained higher levels of all the potential aviation fingerprint metals than did sediments from the study site near Santa Barbara Regional Airport. Whereas zinc, copper, and beryllium levels were equal in exhaust collected from the test cell, copper and especially beryllium levels were substantially lower than that of zinc in field sediments. This may be because of chemical transformations or preferential biological uptake of these metals in the wetland environment.

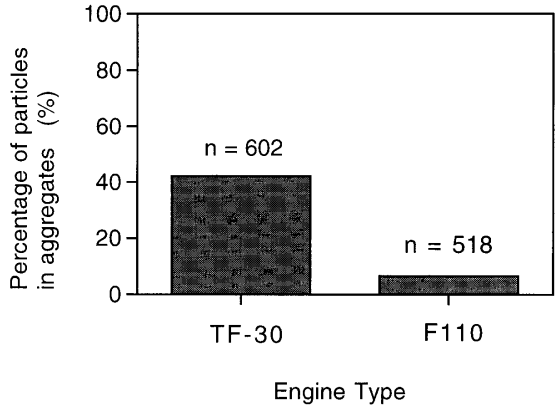


FIGURE 4 Aggregation frequency of jet engine exhaust particulates.

HC Characteristics of Jet Fuel Standard

Analysis of a laboratory standard of JP-5—the same fuel that was run in the jet engines used in test-cell trials—indicated a suite of compounds that may prove useful in fingerprinting aviation inputs in the environment. A characteristic group of peaks that appear to be alkylbenzene compounds were identified. Those peaks are shown in the GC/MS chromatogram in Figure 7.

The alkylbenzene compounds are particularly useful for fingerprinting purposes since they do not naturally occur in sediments. Sediment samples from field sites have not yet been evaluated for HC because they would be subject to deposition of exhaust particles derived largely from Commercial Jet A fuel instead of JP-5. The process of identifying HC signatures for Jet A is ongoing. Because JP-5 is primarily used in naval flight operations, many of which occur on aircraft carriers, it is less volatile than Jet A for safety reasons. Its lower volatility made extracting and analyzing for HC easier. Adjustments are being made to the extraction protocols for Commercial Jet A, and the process of identifying a potential HC fingerprint for this fuel is continuing. If one is identified, sediment samples from field sites will be analyzed to determine if they contain a similar HC profile.

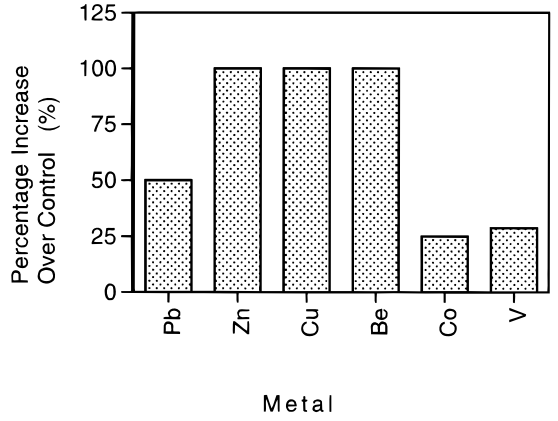


FIGURE 5 Heavy-metal content of seawater after 2-hr exposure to TF-30 jet engine exhaust.

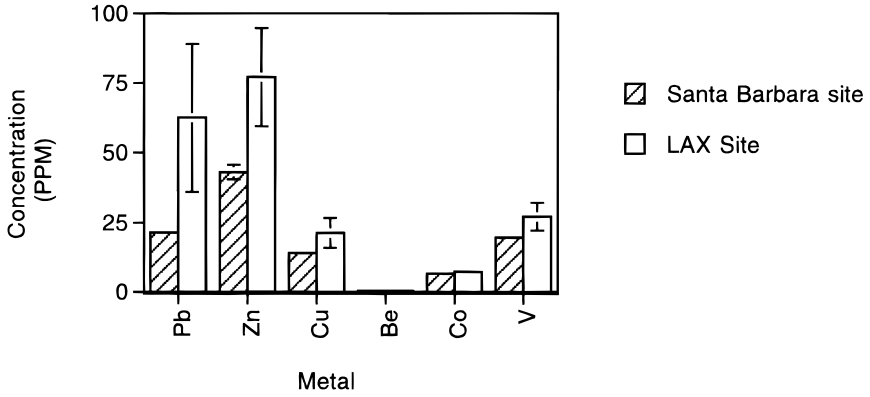


FIGURE 6 Trace metals in field sediment.

DISCUSSION OF RESULTS

It has been known for some time that particulates are present in the exhaust of some jet engines, but quantitative data on their emission is lacking for most engine types (*4*). The majority of studies on the impact of aviation emissions focus on emissions' effects in the atmosphere. It appears that the possible environmental impacts of aerial deposition of JEPs have never previously been studied. Previous work using Electrical Aerosol Analyzer data to determine size ranges of JEPs from military engines found high concentrations of submicron particles in the exhaust of jet engines for the engines' entire power range (*16–19*). Those studies found no particles larger than 1 μm in jet emissions and found particle concentrations ranging from 10^5/cm^3 for newer jet engines to 10^6 to 10^8/cm^3 for older engines.

The data collected agree with these previous findings and are apparently the first SEM photographs to be obtained for JEPs (personal communication, Everett Douglas, North Island Naval Air

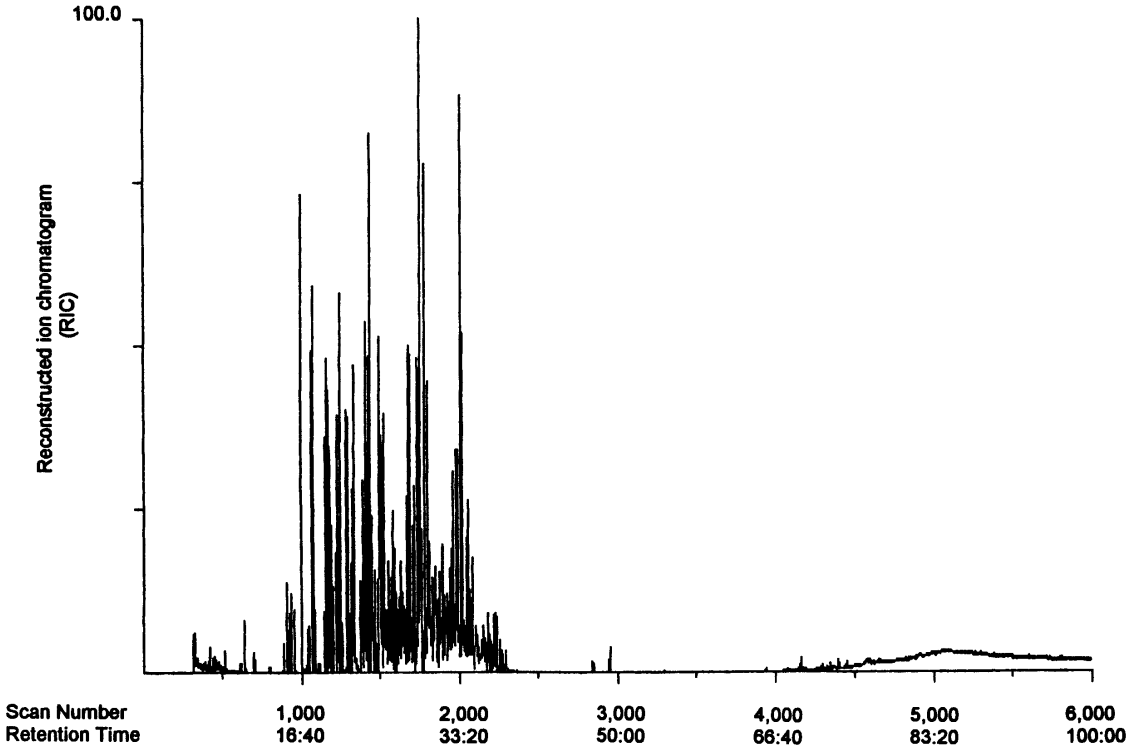


FIGURE 7 GC/MS chromatogram showing the presence of a group of alkylbenzene HCs in aromatic fraction of standard sample of JP-5 jet fuel; represents 1.5 μL of total 1,400 μL of aromatic fraction run. Each peak on graph represents concentration of given compound. Temperature program run for sample was 6 min at 35°C, then 4-degree increases per minute to 280°C, followed by 2-degree increases per minute to 310°C. Samples were run on DB-5 fused silicon capillary column 30 m long with an internal diameter of 0.25 mm.

Station). Data obtained thus far on both the size and chemical composition of these particles indicate that they have the potential to adversely affect human health, environmental quality, or both. Based on the results of the investigation, it is possible to make some preliminary assessments of the behavior of JEPs in the environment.

Potential Chemical Fingerprints for Aviation Emissions

Some of the heavy metals found in jet exhaust may prove useful in fingerprinting jet emissions in the environment. Vanadium appears especially promising because it does not normally occur in high levels in most natural sediments and, unlike lead, is not typically found in automobile exhaust. A similar signature may be obtained for HC. Results isolated a potential HC signature for JP-5 jet fuel. The distinct suite of alkylbenzene HC that was found may be very useful in distinguishing aviation inputs in the environment, because these HCs never occur naturally in sediments. Alkylbenzene HCs have been used successfully in the past to fingerprint domestic waste inputs in the environment. If a grouping of certain types of alkylbenzenes, or a combination of alkylbenzenes and some heavy metals, proves to be specific to aviation emissions, it may be possible to identify the component of urban impacts in an area that is attributable to aviation activities. An HC signature is being sought for Commercial Jet A fuel and will be compared with HC levels found in sediments at field study sites and at a reference field site. As more chemical data are collected, a signature combination of heavy metals and HC highly specific to aviation emissions may be identified. This would provide a tool for the collection of useful data on the relative contribution of aviation emissions to overall urban emission loads and would give the airline industry and regulatory agencies more specific data to use in evaluating that contribution.

Human Health Risks from Particulates

Physical data showed that 100 percent of the exhaust particles collected were less than 1.5 μm in size. This indicates that they have the potential to adversely affect the human respiratory system. For the purposes of air quality assessment, airborne particulate matter is classified according to size. PM_{10} are considered to be in the respirable range; that range has been demonstrated to have the most significant effects on human health. Air quality monitoring devices and EPA regulations focus on particles in this size range. Particle size remains important within the PM_{10} category, because size in this range determines the location in the human respiratory system where a particle will be deposited. The EPA recommends that "inhalable particulates" (those less than 10 μm) be separated into two size classes, above and below 2.5 μm. Particles larger than 2.5 μm tend to be deposited in the airways, whereas particles smaller than 2.5 μm penetrate deeper into the lungs, depositing primarily in the alveolar regions (*20*). The SEM data from this study indicate that 100 percent of the particles collected from the jet engines are below this 2.5-μm threshold, and therefore have the potential to penetrate to the alveolar region. Previous work has indicated that some of the more toxic elements in urban air pollution, such as lead, and strongly acidic aerosols tend to be concentrated in the submicrometer fraction of airborne particulates (*21*). The majority of the JEPs collected in this study were smaller than 1 μm. This concentration suggests that these particles have the potential to cause physical damage to respiratory systems by penetrating deeply into the alveoli, as well as to cause chemical toxicity by carrying compounds into alveoli, from which they can diffuse into the bloodstream more easily. Toxic chemicals associated with particulates can be present on the particles at the time of their emission or can be present in the ambient air and be adsorbed by particle surfaces. In the collected particles, potentially toxic metals such as lead were present as the particles were emitted from the jet engine. The particles sampled therefore have the potential to act as both physically and chemically toxic agents to humans.

In addition to its implications for human health, particle size also affects how these emission products will behave in the environment. Particles less than 0.1 μm have a settling velocity in still air of only 0.3 mm/sec (*22*) and therefore remain suspended in the atmosphere for a long time. The increased atmospheric residence time increases organism exposure times, because the particles are airborne and respirable for a longer period. The primary process by which particles between 0.1 and 5 μm are removed from the atmosphere is wet deposition in clouds and fog (*23*). Coastal regions such as LAX are frequently subject to fog, which would result in the deposition of these fine particles and their chemical constituents, such as heavy metals, on the land surrounding flight paths.

Potential Environmental Effects of Particulates

Coastal wetlands have been shown to be extremely important habitats in the life cycle of a variety of organisms. They provide breeding and feeding habitats for many species of birds and nursery areas for many species of fish. The wetlands surveyed provide habitats for several species of endangered birds, including light-footed clapper rails and Belding's savannah sparrows. Field data indicated that measurable aerial deposition occurred at the study site near LAX. The chemical analysis of test cell exhaust suggested that this deposition would contain heavy metals. Levels of heavy metals detected in field sediments supported this hypothesis, showing the presence of all of the heavy metals that had been detected in test cell exhaust samples. In addition, levels of these metals were higher in all cases in sediments from the site subjected to more air traffic, which would be expected if these metals were derived from jet emissions. Automobile emissions at LAX are greater than at the Santa Barbara field site, a difference that could affect the relative amounts of elements such as lead and zinc found at the sites. However, the fact that vanadium, which is rarely associated with automobile emissions, is present in higher levels in areas with high air traffic supports the connection between sediment heavy metals and jet engine emissions.

The observed effects of JEPs deposited on the coastal wetland habitats would include increased exposure of plants and animals in the habitat to the heavy metals and HC that are associated with these particulate emissions. In addition, a similar toxicity risk from inhalation of submicron particles would apply to organisms with respiratory systems similar to humans, including mammals and birds. Upon settling in a wetland the exhaust particles would likely partition into both the sediment and water. A previous study of a lake system subject to chronic contamination from the atmospheric emissions of nearby metallurgic industries found low concentrations of trace metals in water and higher metal concentrations in sediment (*24*). Aerial deposition from air traffic is a similar chronic exposure and would be expected to result in comparable partitioning of the metals in the environment.

It is difficult to make general predictions about effects of heavy-metal exposure on the variety of organisms living in wetlands, but heavy metals are generally accepted to have toxic effects. Previous studies of heavy-metal exposure in marine species indicated that the effects vary depending on the species' living and feeding habits and physiology. For example, deposit-feeding organisms that live in closer association with the sediment than filter-feeding organisms have been found to have higher levels of lead, zinc, and copper in their bodies (*25*).

A major concern associated with heavy metals in the environment is that they have the potential for biomagnification, a process that occurs when animals higher in the food chain feed on contaminated prey. Animals in lower trophic levels, such as snails, may have relatively low body levels of metals. However, a bird that feeds on snails will eat many in the course of a week. The amount of metal in each individual prey combines, giving the predator a much higher pollutant residue level than that found in the species it feeds on. A classic example of the bioaccumulation of heavy metals is the case of Minamata disease in humans. The disease is named for a city in Japan where a factory released mercury-contaminated effluent into Minamata Bay from 1932 to 1968. Methyl mercury accumulated in fish and shellfish, which were eaten by the local population. The population's consumption of contaminated seafood over a long period of time resulted in over 2,000 cases of a toxic central nervous system disease, of which roughly 900 have been fatal (*26*). Because heavy-metal toxicity and susceptibility to bioaccumulation varies from organism to organism and by type of metal, more detailed studies are needed for specific habitats before the precise environmental effects of metal deposition from air traffic emissions can be assessed. Data from the biological phase of research and comparisons with an unaffected reference site should help to clarify the effects. At this time data show that particulate deposition from airplanes can result in increased levels of heavy metals in environments surrounding airports. The possibility that wetlands in proximity to airports may be, to some extent, degraded habitats has a variety of implications for airport mitigation planning.

Future Directions

Data indicate that JEPs do have the potential to adversely affect both human health and the environment. Further research designed to give more detailed assessments of the environmental impacts related to JEPs is in order. An important finding is that the number and type of particulates collected varied with different engine types, indicating that engine design can affect particulate emissions. It is also known that different fuel formulations can affect the amount of particulates generated by an engine (*19*). Both findings deserve further study.

Such research is especially vital now, as new emission regulation goals and standards are being set. Limited data are available on the effects of the chemical constituents present in jet engine emissions. Current research such as the MOZAIC project funded by ICAO which is examining NO_x emissions, should help to resolve some of the confusion about the effects of jet engine emissions. Data need to be collected in order to assess the relative risk of various emission components. Revised regulatory guidelines for jet engine emissions seem inevitable, and the data indicate that reduction of some jet engine emissions would likely lead to improvements in human and environmental health. Further research on the environmental effects of emission chemicals will provide the resources necessary to successfully meet the challenge of setting appropriate guidelines. The information obtained would allow regulations and the expenditure of industry resources to be based on scientific data instead of speculation. Such an approach would have a high probability of yielding the maximum possible improvements in environmental and human health in return for the time and resources invested.

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