PACIFIC NORTHWEST LABORATORY GULFSTREAM I
MEASUREMENTS OF THE KUWAIT OIL-FIRE PLUME
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SUMMARY

In 1991, the Pacific Northwest Laboratory conducted a series of aircraft measurements to determine pollutant and radiative properties of the smoke plume emanating from oil fires in Kuwait. This work was sponsored by the U.S. Department of Energy, in cooperation with several other agencies as part of an extensive effort coordinated by the World Meteorological Organization, to obtain a comprehensive data set to assess the characteristics of the plume and its environmental impact.

Thirteen measurement flights were made with PNL's Gulfstream I (G-1) aircraft during July and August 1991, primarily along the northeast coast of the eastern provinces of Saudi Arabia (over the Persian Gulf) and south of Kuwait. Observations and collections included real-time measurements of gas species (SO_2 , NO_x , O_3 , CO , CO_2) and meteorological parameters, integrated samples of gaseous hydrocarbons, aerosols, SO_4^{2-} , NO_3^- , HNO_3 , SO_2 , and carbon species, particle-size distributions, cloud-condensation nuclei (CCN), aerosol light-scattering, and solar radiation.

This report describes field measurement activities and introduces the various data collected, but provides only limited analyses of these data. Results of further data analyses will be presented in subsequent open-literature publications.

Measurements indicated widely varying concentrations of gas species and particles, depending upon the plume's age and its distance from the fire source. Preliminary observations include the following:

- Observed SO_2 concentrations ranged from a few parts per billion (ppb) to greater than 200 ppb (the upper limit of the range of the instrument used).
- NO_x levels of several parts per billion were observed, but were substantially lower than levels of SO_2 .
- Ozone levels generally were in the range of 50 to 70 ppb.
- Aerosol light-scattering was high, frequently exceeding instrument full scale (10^{-3} m^{-1}).

- Aerosol particle counts frequently exceeded 2000 to 3000 per cm^{-3} .
- A CCN counter indicated similar high counts, suggesting that most particles were capable of forming cloud droplets and consequently being scavenged, and thus were not likely to undergo long-range transport.
- The plume was not observed to rise above about 5000 m, and large-scale atmospheric mixing processes appeared to be the dominant lifting mechanism.
- Filter analyses indicate a high correlation between sulfur dioxide and elemental carbon, a good correlation between sulfate and elemental carbon, a high correlation between chloride and sulfur dioxide, a fair correlation between sulfate and calcium, and high chloride concentrations.
- In-plume sulfur dioxide oxidation rates were of the order of 1% per hour, or less.
- Ozone levels were depleted in the near-source plume. Ozone was generated in the aged plume at levels that were generally consistent with in-plume NO_x levels.
- Based on ratios with plume CO_2 near the source, sulfur and fixed-nitrogen emission rates are consistent with those expected on the basis of oil stoichiometry.

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The study described in this report was one of several conducted in support of an international effort coordinated by the World Meteorological Organization. The Gulf Programs Office of the National Oceanographic and Atmospheric Administration provided invaluable support in accomplishing many diplomatic and logistical activities for our U.S. Department of Energy team. We are indebted to several individuals within the Bahrainian and Saudi Arabian governments; in particular, Dr. Khalid Fakhro and his associates in the Bahrain Environmental Protection Committee, and Mr. A. Majeed Isa and the Bahrain Meteorological Service. We thank the staff at the Saudi ARAMCO Air Marine Science Unit in Dhahran for their meteorological forecasts.

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1.0 INTRODUCTION

During July and August 1991, the Pacific Northwest Laboratory (PNL)^(a) Gulfstream I (G-1) research aircraft performed pollution and solar-radiation measurements in the Kuwait oil-fire plume. This report describes these and ancillary measurements taken during this period and is intended to present the data in a form that is useful for future interpretation by the extended scientific community. This work is part of a comprehensive effort coordinated by the World Meteorological Organization (WMO), and its results are intended to be pooled with the those of the larger undertaking for detailed evaluation of the plume's behavior and environmental impact.

In Geneva, on April 27-30, 1991, the United Nations convened a meeting of experts to advise the WMO on measurement programs and coordination responsibilities regarding the atmospheric impacts of the Kuwaiti oil fires. This meeting resulted in a general planning document for coordinating surface and airborne measurements in the area (WMO 1991), which set forth the concept of coordinated information gathering and sharing by a large number of participating countries and agencies. The document also itemized a number of general recommendations for measurement of both pollution and meteorological variables. Specific objectives for the U.S. Department of Energy (DOE) contribution, described in Section 1.1 below, are consistent with these general recommendations.

One important outcome of the WMO meeting was the recommendation for a staged sequence of aircraft measurements, to provide a seasonal characterization of the plume as it interacted within different meteorological regimes. Table 1.1 summarizes the aircraft measurements that have been performed under this plan. As indicated by this table, the G-1 operations were intended to add to the communal data

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute.

TABLE 1.1. Summary of Participating Aircraft to Date

<u>Dates of Active Operation</u>	<u>Aircraft Type</u>	<u>Responsible Groups</u>
March 23-31	C-130 Hercules (Turboprop)	British Meteorological Office
May 16 - June 15	Convair C-131 (Reciprocating)	University of Washington
May 19 - June 4	Lockheed Electra (Turboprop)	National Center for Atmospheric Research (National Science Foundation)
May 20 - June 6	Piper Navajo (Light Twin Reciprocating)	Umwelt Data
July 30 - August 17	Gulfstream I (Turboprop)	DOE
July 31 - August 8	Helicopter	Saudi Arabian Air Force/ National Aeronautics and Science Administration/ U.S. Environmental Protection Agency

base by providing coverage for late July and early August. The results of this activity are described in the following sections of this report.

1.1 PROJECT OBJECTIVES

The G-1 operations described in this report were funded by the DOE and were conducted with cooperative scientific efforts of the National Oceanographic and Atmospheric Administration (NOAA) and the Bahranian and Saudi Arabian governments. The scientific approach taken by DOE centered on three primary program objectives and a number of secondary objectives. The primary objectives were to

1. measure rates of pollutant transformation or removal in the plume from oil fires in Kuwait
2. characterize the chemical and physical state of the plume over a range of distances from the source
3. quantitatively evaluate global atmospheric chemistry models and associated models of radiant transport through aerosol plumes.

The two DOE global atmospheric chemistry models intended for application within this effort are Lawrence Livermore National Laboratory's (LLNL's) GranTour and PNL's GChM. While these two models differ in fundamental and important ways, both have been used to forecast the Kuwaiti plume's behavior on the basis of climatological meteorology and both are capable of simulating either hemispheric or global domains, with arbitrary spatial resolution. GranTour and GChM are time-resolved (as opposed to time-averaged) models and provide detailed far-field characterizations of chemical and physical processes. As such, they are capable of incorporating, applying, and interpreting field results on a mechanistic basis, thus giving a substantial "first-principles" emphasis to DOE's plume-measurement effort.

Secondary, or collateral objectives were to

- assemble an optimal descriptive observational and modeling data base for assessing the environmental impact caused by pollutant deposition from the plume
- document the solar energy-balance features of the plume
- characterize the radiative absorption properties of the plume and the associated atmospheric motions, for identifying possible plume-induced perturbations of atmospheric dynamics and associated climate-feedback linkages.

1.2 BACKGROUND

Upon retreat from Kuwait during late February and early March of 1991, the Iraqi Army damaged more than 700 wells in the Kuwaiti oil fields and set fire to more than 600. Because of the uncontrolled nature of these fires, significant quantities of organic

and inorganic pollutants were emitted in a smoke plume, which spread throughout the Middle East and was clearly visible from satellite. In addition to particulate matter, the fires emitted large amounts of carbon dioxide, sulfur dioxide, and oxides of nitrogen. Incomplete combustion products were expected to include hydrogen sulfide, carbon monoxide, volatile organic compounds, and heavy metals. It was also anticipated that secondary pollutants such as ozone, as well as acid aerosols such as sulfuric acid, would be formed by reaction as the plume traveled and dispersed through the region. Aside from the obvious potential health effects on the population in the immediate source area, there was concern that the plume would spread beyond the Middle East and cause temporary but significant synoptic-scale contamination and weather modification.

A map of Kuwait showing the geographic distribution of the oil fields is shown in Figure 1.1. The number of well fires and estimated burn rates for the various oil fields are given in Table 1.2. At the peak of the fires it was estimated that approximately 6 million barrels of crude oil per day, plus an unknown quantity of natural gas, were being burned. The Greater Burgan, Magwha, and Ahmadi fields were responsible for between 80 and 90% of the emissions. Because these fields are relatively close to each other, the majority of the emissions from the fires came from a relatively compact area (ca 5000 km²) due south of Kuwait City. The burn rate in the northern oil fields was estimated to be only about 10% of the total.

At the beginning of the DOE flight series in late July, approximately one-third of the well fires set by the Iraqis had been extinguished (cf. Table 1.2). Thus, one distinguishing feature of this study in comparison to others is the altered geographic distribution and reduction in source strength of the fires. During the earlier National Center for Atmospheric Research (NCAR) and University of Washington (UW) flights (Table 1.1) it was estimated that between 4.6 and 5.1×10^6 bbl/day were being burned. In the period between the termination of these flights and the beginning of the DOE flight series, most of the wells in the Magwa field had been extinguished, the number of fires in Burgan field went from 275 to 250, and those in the Ahmadi field

FIGURE 1.1. Map of Kuwait Showing Locations of Major Oil Fields and Numbers of Well Fires, March 1991 (from Hobbs et al. 1992).

TABLE 1.2. Source-Strength of Kuwait Oil Fires (from Robinson 1992).

<u>Field</u>	<u>Number of Well Fires, 3/16/91</u>	<u>Flow (bbl/day)</u>	<u>Well Fires, 7/30/91-8/16/91</u>	<u>Estimated Flow, 7/30/91-8/16/91 (bbl/day)</u>
Ahmadi	60	588,000	7-0	68,600-0
Bahra	3	14,400	3	14,400
Burgan	290	3,480,000	250-220	3,000,000-2,640,000
Magwa	98	970,200	3-0	29,700-0
Minagish	27	75,600	25	70,000
Raudhatian	62	328,600	62	328,600
Sabriyah	38	180,880	38	180,880
Umm Gudair	27	54,000	27	54,000
Wafrah	6	Unknown	Unknown	Unknown
TOTAL (approximate)	611	5,690,000	415-375	3,750,000-3,290,000

went from 34 to 7. All of the Ahmadi fires had been extinguished by the time the DOE measurements were completed. This reduction in the number of well fires lowered the estimated source strength to between 3.3 and 3.8 x 10⁶ bbl/day during the DOE study.

Figures 1.2 and 1.3 show typical examples of the well fires and their associated plumes in the source region. The diversity of sources in these pictures is strongly apparent from the different shades of the plumes. The black plumes were apparently associated with well fires burning crude oil or a combination of oil and natural gas. The white plumes are thought to have resulted primarily from the combustion of natural gas, entraining substantial quantities of sodium chloride (Cofer et al. 1992).

Table 1.3, taken from an article by Browning et al. (1991), provides some idea of the estimated emission magnitudes. Global estimates of anthropogenic sulfur and nitrogen by Finlayson-Pitts and Pitts (1986) are also presented for comparison.

FIGURE 1.2. Kuwait Oil Fires Illustrating Plume Coloration

FIGURE 1.3. Burning Oil Lake in Kuwait Oil Fields

TABLE 1.3. Source-Strength Estimates of Browning et al. (1991)(a)

<u>Type of Pollutant</u>	<u>Estimated Source Strength (Tg/year)</u>	<u>Global Estimates (Tg/year)</u>
Fine particulate black smoke	5	
Sulfur (as sulfur oxides)	2	27
Nitrogen (as nitrogen oxides)	0.5	108
Carbon (ultimately as carbon dioxide)	60	

(a) Based on assumed combustion of 1.5 million barrels of oil with 2.5% sulfur content per day, having 6% conversion into fine-particulate smoke. NO_x source is estimated to be 0.6% of total fuel.

Information derived from helicopter measurements taken in May and June 1991 (Cofer et al. 1992) indicates somewhat different values than those shown in Table 1.3, suggesting that the value cited by Browning and his coworkers may be high by a factor of as much as five. Thus it is apparent that source strength of the oil-fire plumes has been a highly uncertain subject. Later sections of this report will describe findings of the DOE study that are pertinent to this question, as well as a number of additional important issues associated with the plume's behavior.

2.0 SCIENTIFIC AND LOGISTICAL DESIGN

2.1 EXPERIMENT DESIGN

The DOE objectives for the Kuwaiti plume study, which were described in Section 1.1, can be summarized as two project goals. The first of these was to document, inasmuch as it was practical, the movement of the oil-fire plume and its atmospheric impact on Kuwait and other countries within the region. The second goal was to obtain data for future interpretation of other atmospheric behavior, including pollutant transformation, long-range transport, and plume impacts on the solar radiation balance.

The plume behavior that was predicted for the sampling program period, as shown in Figures 2.1 and 2.2, led investigators to develop the design of the study-domain envelope shown in Figure 2.3. Figure 2.1 illustrates a trajectory analysis showing plume positions for the July/August period, based on climatological data. Percentages shown on the figure indicate the expected occurrence of each trajectory for that time of the year. The projected plume tracks are dominated by trajectories moving south to southwest over the Arabian Peninsula. Once in the vicinity of the Arabian Sea, the southerly extent of the tracks exhibits a tendency to proceed in an easterly direction. Monthly averaged soot concentrations projected for July (Figure 2.2) by the GChM global model indicate similar plume paths.

The basic strategy for aircraft deployment was to repeatedly sample the plume as it was transported downwind of the source region, thus allowing observation of progressive changes in chemical, microphysical, and optical properties of the plume as it aged. From the model plume trajectories based on climatological winds (Figure 2.1), it was expected to be necessary to conduct flight operations from bases in both eastern and western parts of Saudi Arabia to effect economical use of aircraft hours. For this reason, initial planning suggested Bahrain (at the Persian Gulf) and Jiddah (at the Red Sea) as principal base locations. However, as a result of actual plume trajectories and

FIGURE 2.1. Predicted Five-Day Trajectories of Plume for July, Based on Climatological 700-mb Winds. Adapted from NOAA ARL trajectory model output.

overflight restrictions in the region, almost all of the sampling missions were conducted along the Saudi Arabian-Persian Gulf coastal area, and the aircraft was continuously based in Bahrain.

It was planned that estimates of plume position and age would be provided daily by the LLNL Atmospheric Release Advisory Capability (ARAC) facility as forecasts for the next day's aircraft sampling strategy. Model forecasts from the NOAA Air Resources Laboratory (ARL) HY-SPLIT transport and dispersion model and images

FIGURE 2.2. GChM Simulation of Predicted Surface-Level Soot Concentrations, Averaged Over a Typical 10-Day Period in July. Contours are normalized to a source strength of 100,000 metric tons carbon per day. Contour levels are 0.1, 0.3, 1, 3, and 10 μg of carbon per cubic meter.

FIGURE 2.3. Design Envelope for Regional Aircraft Sampling Missions

derived from Polar Orbiter satellites also would be provided for this purpose. Frequently, however, the model forecasts were not sufficiently accurate. This inaccuracy appeared to be the result of inadequate wind data rather than model shortcomings; even local wind forecasts provided to the flight crew were inaccurate. Later in the project, flight schedules were altered to take advantage of the most recent satellite images, which proved to be the best indicators of plume movement.

The data required to achieve the project objectives fall into two classes: operational data and comparative/interpretive data. Operational data necessary to drive the models include source magnitudes and meteorology, as well as the plume's initial composition (soot, organic carbon, gas species, other organics, etc.), particle size distribution, optical properties, aerosol cloud-nucleating capability, buoyancy, and associated initial rise. The comparative/interpretive data base is intended primarily for evaluating mechanistic behavior and the proficiencies of models in calculating pollution and radiative properties at various distances from the source. These data include downwind aerosol particle size distributions and chemical/morphological characteristics, ratios of elemental to organic carbon, sulfate and nitrate concentrations, sulfur and nitrogen trace-gas concentrations, ozone, hydrocarbons, cloud-nucleating characteristics, vertical temperature structure, and vertical profiles of plume radiative properties.

Flight segments to characterize the evolution of plume composition consisted of crosswind transects at altitudes that were determined by the vertical structure of the plume. Efforts were made to sample at different altitudes within the plume. Sampling was typically conducted at altitudes near the plume's point of maximum concentration, at its top (to document how entrainment of air aloft affected plume chemical properties), and near its bottom of the plume (to document how the plume's interaction with the surface altered plume properties). Flights were made at various locations downwind of the source region to document how these features changed with plume age. Sampling was conducted over as great a range of plume ages as was possible.

2.2 LOGISTICS: PLANNING AND EXECUTION

When dates for the G-1 research effort in the Middle East became firm, several actions were initiated, including 1) ferrying the aircraft to the region, 2) arranging an operating base in Manama, Bahrain, an island emirate in the Persian Gulf about 300 miles south of Kuwait, and 3) shipping spare equipment and scientific supplies.

Prior to departure, the aircraft was configured with its full complement of research equipment and was sufficiently equipped to be operational without the need for immediate support on arrival at the field site, in anticipation of delays in shipments of support equipment. Configuration of the aircraft and research equipment was a vital part of planning the transition from ferrying mode to operational status. All equipment was installed, calibrated, and rigged for transport to the Gulf region and was operational within a day after arrival in Bahrain.

Once outfitted, the aircraft was made ready for the ferry flight and departed on July 22, 1991, using the northern Atlantic route. This route included stops in Greenland, Iceland, and Europe on the way to the Gulf region. Arrival in Bahrain was synchronized with the arrival of scientific staff via commercial airlines on July 26. The return ferry flight of the aircraft was along the same route, with a departure date of August 19. Because the aircraft was subject to numerous customs inspections in many countries, it carried exactly the same complement of equipment during ferry flights to and from Bahrain.

The operational base in Bahrain was established during the first week in July, when a PNL staff member arrived there and met with an assigned support person from NOAA. This NOAA support was instrumental in providing an easy transition into the country as well as the necessary contacts for conducting business with local authorities. During the week, hotel and banking arrangements were confirmed, security passes to the airport were processed, and other diplomatic contacts were made. It was also decided to base the aircraft at a location on the Bahrain airport with a branch of DHL Worldwide Express, an air cargo business. Contracted support from DHL included ramp space, office use, telephones, storage, and access to ground power equipment 24 hours a day. The combination of NOAA and DHL support helped make the operation run smoothly throughout the project. Space for the research staff was also made available at the Bahrain Meteorological Station located on the airport, for use as a staging area for pre- and post-flight handling of integrated filter samples, and for gathering and studying meteorological information.

Spare equipment and supplies were assembled and packaged in durable containers for shipment by air cargo. This shipment was scheduled to arrive one week after the aircraft and scientific crew and contained a one-for-one replacement of all scientific instrumentation. The supplies included all necessary materials and calibration equipment, enabling the scientific crew to operate independently of the home laboratory for an extended time. Receipt of the shipment of calibration gases was delayed, however, because of difficulties encountered in transporting materials considered to be hazardous, and these were not received until near the conclusion of the project.

Over the period from July 31 to August 17, thirteen flights were conducted at various locations, primarily along the eastern Saudi Arabian coast between Bahrain and Kuwait, but with a few flights made in areas farther south and farther inland. Figure 2.4 illustrates the study area and typical locations of the sampling transects made through the plume. The appendix of this report contains a comprehensive summary for each flight day, including locations, data acquired on each mission, surface meteorological and air quality data, and a synoptic overview.

2.3 AIRCRAFT CONFIGURATION

The PNL G-1, shown in Figure 2.5, is an intermediate-size twin-turboprop aircraft with speed and range capabilities appropriate for a variety of sampling missions in the international domain. It is capable of cruising speeds ranging from 150 to 300 knots, at altitudes up to 30,000 feet. The aircraft is equipped for pressurization, but, for the Kuwait plume study, it was operated in an unpressurized configuration for all flights except for travel between the United States and the study region.

The G-1 was extensively configured for chemistry, radiation, particle, and meteorological measurements, as indicated in the summary of instrumentation (Table 2.1). Additionally, the aircraft was equipped with specially installed air-conditioning equipment in anticipation of extreme temperatures in the region during mid-summer. Sampling operations would have been impossible without this equipment, as

FIGURE 2.4. Sampling Region with Typical Aircraft Plume Transects

temperatures approaching 50°C, and relative humidities of 80 to 90% were encountered. Even then, a few instruments malfunctioned, apparently as a result of the extreme environmental conditions.

A specially designed electrical power and distribution system, controlling three onboard power conversion systems, provided power for all instruments. Two direct current (DC) to alternating current (AC) solid-state inverter configurations (each

FIGURE 2.5. Pacific Northwest Laboratory's Gulfstream I Aircraft

TABLE 2.1. Aircraft Instrumentation Summary

Parameter	Instrument/Device	Technique
SO ₂	TECO 43S Filter pack	Pulsed fluorescence Wet chemistry
NO/NO _x	M-L 8840 Scintrex Luminox	O ₃ chemiluminescence Luminol chemiluminescence
Ozone	Teco 49 M-L 8410	Ultraviolet absorbance Ethylene chemiluminescence
HNO ₃	Filter pack	Wet chemistry
CO	TECO 48	Infrared absorption
CO ₂	Rosemount Canister grab sample	Infrared absorption ECD/gas chromatography
Gaseous hydrocarbons	Canister grab sample	FID/gas chromatography
Condensed volatile organic compounds	Filter pack	Gas chromatography Mass spectrometer
Carbonaceous aerosol	Filter pack	Pyrolysis/combustion
SO ₄ ⁻ mass	Filter pack	Ion chromatography
NO ₃ ⁻ mass	Filter pack	Ion chromatography
Particle size distribution	PMS ASASP (0.12-3 µm) PMS FSPP (3-47 µm) TSI EAA (0.02-0.4 µm)	Laser light scattering Laser light scattering Particle mobility
Cloud condensation nuclei	DH Associates (Twomey)	Supersaturation/optical
Aerosol light-scattering	MRI integrating nephelometer	Light scattering
Solar radiation short wave long wave	Eppley PSP Eppley PIR	Pyranometer Pyrgometer
Total temperature	Rosemount E102AL/510BF 102U2U/510BF	Platinum resistance Platinum resistance
Dewpoint temperature	EG&G 137C3	Cooled mirror
Absolute pressure/altitude	Rosemount 1201F1	Diaphragm/capacitance
Position	Trimble GPS ONI LORAN	Satellite Surface radio

providing 4000 volt-amps of 60-Hz AC power), a DC-to-AC inverter system providing 1500 volt-amps of 400-Hz AC power, and DC power provided directly from the aircraft's 28-VDC bus supplied all electrical needs for measurement systems, an inertial navigation system, and cabin air conditioning.

Ambient air samples were directed to measurement systems in the cabin by externally mounted probes at the right forward side of the fuselage. Two 1-in. probes provided sample input to the integrated filter collection systems, each probe being monitored by flowmeters connected to the aircraft's data acquisition system. Separate inlets directed air to a sample manifold for gas chemistry instruments and to particle-measuring instruments. Air to the sampling manifold was supplied by a ram-air inlet, with excess flow being vented into the cabin and monitored via rotameter to ensure that flow was sufficient for all instruments served. All sample lines and manifolds were either Teflon or Teflon-lined to minimize contamination or chemical transformation of ambient samples. Air-jet vacuum ejectors installed on each engine, operating on high-pressure air from the engine compressors, created a vacuum for pumping samples through the filter-collection system, as manually operated valves ahead of and behind each filter holder were used to control the flow through each filter pack. Sample flow through the real-time gas chemistry instruments was achieved by means of internal pumps.

Two instruments used to measure size distributions of airborne particles were mounted externally on the aircraft nose. These were laser-based optical sensors (ASASP and FSSP probes manufactured by Particle Measuring Systems, which measure particles in the 0.12- to 3- μm and 3- to 47- μm ranges, respectively). Other external sensors included paired Eppley pyranometers and pyrgeometers that were upward and downward viewing for measurements of broadband solar radiation, and meteorological sensors for temperature and dewpoint temperature measurements. Inside the cabin, in addition to a standard array of real-time gas analyzers (see Table 2.1), an integrating nephelometer measured aerosol light-scattering properties (bscat), a mobility analyzer characterized sub-micron particles, and an optically

sensing quasi-real-time cloud condensation nuclei (CCN) instrument, operated at a 0.6% supersaturation level, counted cloud condensation nuclei.

Spatially integrated collections of ambient gases and particles were acquired by means of filter packs using the sampling system described above. Inorganic element analyses were performed for $\text{SO}_4^{=}$, NO_3^- , NH_4^+ , SO_2 , and HNO_3 . Organic analyses were performed to determine carbon species concentrations (elemental carbon, organic carbon, and $\text{CO}_3^{=}$). Filter packs consisted of tandemly arranged 47-mm-diameter filter materials in Nuclepore polycarbonate and specially constructed aluminum enclosures. The packs were loaded before and unloaded following each flight, after which the filter media were isolated in individual containers and placed in cold storage until their return to the United States via air transport at the conclusion of the project.

In addition to the integrated filter collections, pre-evacuated 6-L stainless steel canisters were used to acquire air samples for laboratory analysis of airborne hydrocarbons and also for carbon dioxide, as a supplement to the real-time CO_2 instrument. Canister samples were acquired simultaneously with filter collections during plume traverses. The samples were transferred into the evacuated canister at a constant rate by means of a pump and electronic flow controller. Results of all laboratory analyses are included in the appendix.

Aircraft position was determined continuously from LORAN (radio-beacon) and GPS (satellite) navigation systems. Aircraft motion and attitude data, necessary to correct radiation sensor position deviations from level, were provided by the onboard inertial navigation system. Outputs from these devices were recorded simultaneously with chemistry and meteorological data.

The aircraft data acquisition system recorded output signals from the navigational, meteorological, chemistry, and particle instruments. The system consists of a 286 processor with multichannel analog-to-digital (A/D) conversion subsystem, digital input/output, serial interfaces, internal hard- and floppy-disk drives, and a magnetic

tape cartridge drive for data recording. The 32-channel A/D subsystem converts to 16 digital bits, providing sub-millivolt data resolution. Data were acquired at 1-s intervals and recorded in blocks on magnetic tape, while the system simultaneously provided real-time displays of operator-selectable parameters on a color monitor, as tabular lists of voltages or engineering unit values, graphic plots of analog instrument and particle instrument data, and flight track progress on a regional map. Several parameters were also recorded on analog strip-chart recorders to provide redundant hard copies of principal measurements, and to serve as aids in processing of the magnetically recorded data.

2.4 ANCILLARY DATA SOURCES

Surface and upper air charts, soundings, and satellite images, as well as weather briefings for each flight were received from the Bahrain Meteorology Services located at the Bahrain International Airport.

The main sources for continuous surface air quality and meteorological data in the area are Saudi ARAMCO, the Meteorology and Environmental Protection Administration (MEPA), and the Royal Commission for Jubail and Yanbu. Daily meteorological data summaries for the mission days in July and August are included in the mission summaries for each flight in the appendix. These data were gathered by Saudi ARAMCO's Air Quality Monitoring and Meteorological Network (AMMNET), which includes two offshore meteorological stations (at Safaniyah GOSP2 and Marjan GOSP1) and four inland air quality and meteorological stations (at Tanajib, Rahimah, Dhahran, and Abqaiq). Figure 2.6 illustrates station locations in eastern Saudi Arabia and the Gulf. The parameters measured at each station vary, as shown in Table 2.2. Surface air quality data gathered at these stations for mission days are included in the appendix.

FIGURE 2.6. Location of AMMNET Stations in the Gulf Region

TABLE 2.2. Parameters Measured at AMMNET Stations

<u>Station</u>	<u>Parameter</u>
Abqaiq	SO ₂ , NO ₂ , PM ₁₀ , wind speed and direction, temperature, dewpoint temperature, pressure
Dhahran	SO ₂ , NO ₂ , PM ₁₀ , O ₃ , wind speed and direction, temperature, dewpoint temperature, pressure, solar radiation
Rahimah	SO ₂ , H ₂ S, PM ₁₀ , wind speed and direction, temperature, dewpoint temperature, pressure, solar radiation
Tanajib	SO ₂ , H ₂ S, NO ₂ , PM ₁₀ , wind speed and direction, temperature, dewpoint temperature, pressure
Marjan GOSP1	wind speed and direction, temperature, pressure
Safaniyah GOSP2	wind speed and direction, temperature

3.0 METEOROLOGICAL OVERVIEW

The Arabian Peninsula has a desert climate with temperature extremes. In the summer, the difference between day and night temperatures can be more than 20°C. Temperatures at the eastern part of the Peninsula, also known as the Eastern Province of Saudi Arabia, are moderated by the effects of the Arabian (Persian) Gulf. Here, the sea and land breezes lower the temperature differentials while raising the humidity. The main climatic features are intense summer heat and frequent strong winds. The Eastern Province has experienced below-freezing temperatures, torrential rains, winter thunderstorms, and extended dust storms.

The information presented in this section was taken from Williams (1979) unless otherwise noted.

The year can be divided into seasons in this region. The summer is longer than in other temperature zones and can be considered to last from May until September, with hottest months being June through August. There is normally no rain during this period, and evaporation rates are high. Relative humidity values are low at inland locations during the summer, although coastal humidities remain quite high.

Beginning in late May and June, an extensive low-pressure area develops over the Asian continent as a result of the early summer heating of this large land mass. The counterclockwise wind circulation around this low is a permanent feature over and adjacent to the continent of Asia during the entire summer. The eastern coast of Arabia lies on the southwest edge of this low-pressure zone and winds blow predominantly from a north-northwest direction. Strong winds, normally accompanied by dust, are known as "shamals." Shamal is an Arabic word that means north, in this case indicating the direction of seasonal strong winds. Sustained winds for two- to three-day periods, with speeds of 40-50 km/h, create blowing dust and limit visibility. Shamals with gusts above 100 km/h lift sand-sized particles a meter or more above

the desert surface and lift dust hundreds of meters. By mid-July, there is no appreciable pressure difference between Asia and Arabia and the still predominantly north-west winds weaken compared to those of early summer. There are two main shamal seasons. The summer shamals begin in May and end in July. Fifty percent of the yearly storms occur during this period. The winter shamals occur mainly in December, January, and February.

The months of October and November are a transitional period, in which temperatures drop and relative humidities begin to rise. The Asian low pressure weakens by November, and the first winter storms may begin to affect the area. These extratropical cyclones move eastward across the Mediterranean and the Middle East. As the centers of these storms approach the Arabian Gulf, the leading boundary of the front frequently creates southeasterly or south winds. These are usually followed by north-westerly winds as the front passes. Wind speeds and directions associated with these storms show wide variations in frequency of occurrence. Severe tropical cyclones from the Arabian Sea weaken as they approach southeast Arabia.

The winter months of December through February are characterized by stormy periods with strong variable winds, some rain, thunderstorms, and blowing dust, interrupted by periods of relatively mild weather. February is usually the windiest month. Though rare, freezing temperatures have been recorded in December and January in the coastal area of Eastern Arabia. The winter storms diminish in frequency and intensity during the spring months of March and April, though local strong thunderstorms may occur during this period.

The temperatures during the months of April through August 1991 were generally lower than normal. However, no historical monthly mean records were broken when compared with more than 40 years of meteorological data collected at Dhahran.

4.0 DATA DESCRIPTION

Daily summaries of the various data collected during each flight day are included in the appendix. Each daily summary contains the following information (when available):

- Meteorological Summary
- Flight Summary
- Satellite Image of Sampling Region
- Vertical Sounding Taken at Dhahran
- Surface Synoptic Chart
- 850-Millibar Chart
- 500-Millibar Chart
- Flight Track
- Selected Real-Time Parameter Plots
- Tables of Integrated Sample Results
- Surface Air Quality Measurements

4.1 CONTINUOUS REAL-TIME DATA

Some of the data presented are still somewhat preliminary. Radiation data, in particular, are not completely processed. Data from the inertial navigation system have not been processed, which, in turn, prevents correcting radiation sensor data to account for changes in aircraft attitude while in flight.

The aircraft's continuous-monitor outputs were sampled and logged each second by the data acquisition system. Position data from LORAN and GPS navigation systems, size distribution data from particle probes, and attitude data from the inertial navigation system were all logged integrally with the continuous instrument data and recorded on 1/4-inch magnetic tape cartridges in binary format. During flight, all parameters were monitored via real-time graphic displays to ensure correct operation

of all systems. Hard-copy prints for selected parameters were also generated between flights at the field site for observation and to aid planning by the scientific staff.

Subsequent to the field measurements, recorded data were processed on a UNIX workstation, using a commercial statistical data software package called S-Plus and specialized PNL-developed data reduction software. The software makes extensive use of on-screen interactive graphics, allowing the scientist to examine, flag, edit, calibrate, and plot the various parameters, and to construct averaged data files that can be distributed and/or used for additional analysis. The processing software implements automatic operator activity logs to document the data reduction process and serve as an important element of the data quality assurance record. The time-series and flight track plots included in the appendix were produced on the workstation.

4.2 INTEGRATED FILTER SAMPLES

Spatially integrated samples of aerosols and trace gases were collected using several filter sampling systems. A triple filter pack system consisted of a quartz filter for aerosol collection, a NaCl-impregnated cellulose filter for collection of HNO_3 , and a K_2CO_3 /glycerol-impregnated filter for collection of SO_2 . These filters were sequentially mounted in 47-mm-diameter polycarbonate filter holders. Packs were loaded prior to each flight and immediately unloaded and stored at the end of each flight. The exposed filters were packaged in individual containers and placed in cold storage prior to transport to the United States at the completion of the project. Procedures for the preparation, collection, and analysis of these filters, and specification of uncertainties are given by Daum and Leahy (1985). Aerosol filters were analyzed for Na^+ , NH_4^+ , Ca^{++} , $\text{SO}_4^{=}$, NO_3^- , and Cl^- . Travel blanks were carried on each flight. Analysis of the blank filters showed analyte concentrations that were never greater than 1% of the quantities observed on the exposed filters.

Aerosol samples to determine organic and elemental carbon concentrations were collected on pre-fired quartz microfiber filters (47 mm) mounted in clean anodized

aluminum holders. Travel blanks were used to monitor the storage and handling conditions that existed for the collected filter samples, and later to assess the total analytical background for possible carbonaceous artifacts. These filters were stored and shipped in annealed aluminum-lined polycarbonate Petri dishes. With the exception of transit time between Bahrain and New York, samples were stored at temperatures below 0°C. Filters were analyzed for elemental, organic, and carbonate carbon using an automated thermal-optical method. The method first pyrolyzes the filter in a helium atmosphere to volatilize organic carbon. The volatilized carbon is oxidized to CO₂ and reduced to methane, which is then measured with a flame ionization detector. After the organic carbon is vaporized (350 to 500°C), inorganic carbonates are decomposed to CO₂ during the pyrolysis step, but at much higher temperatures (500 to 650°C). Elemental carbon is subsequently oxidized to CO₂ in an oxygen atmosphere (at 600 to 700°C), and measured in the same way. Elemental carbon that may be formed during pyrolysis is corrected for by monitoring transmittance through the filter using a He-Ne laser. Details of the method have been reported by Johnson (1981). Residual concentrations of elemental, organic, and carbonate carbon on blank filters that were subjected to all of the handling and storage conditions of the exposed filters were typically only a small fraction (<1%) of the amounts found on the exposed filters.

Results of the filter analyses are reported in each mission daily package included in the appendix.

4.3 CANISTER SAMPLES

At the conclusion of the field project, canister samples were shipped to Battelle's Columbus Laboratory, where analyses were performed for hydrocarbons and CO₂. The C₂ - C₄ hydrocarbons were analyzed with a gas chromatograph using a phenylisocyanate/Proasil C column. After cryogenic collection of the sample, the sample trap was heated and the sample was subjected to a flame ionization detector (FID). The carbon response of the FID was calibrated by analyzing known volumes of

National Institute Standards Technology (NIST) propane-in-air primary standard. The C₄ - C₁₀ hydrocarbons were analyzed after cryogenic preconcentration using a fused silica capillary column gas chromatograph with FID. The carbon response of the FID was calibrated by analyzing samples of a benzene-in-air primary standard prepared by NIST.

Because several unexpected peaks were observed in the chromatograms but not in the blanks, a sample was analyzed by gas chromatography with mass selective detection (MSD). The peaks were identified as acetaldehyde, propanal, butanal, pentanal, hexanal, and heptanal. Excessive concentrations of n-hexane and i-hexane were also observed in many of the samples. Some of the aldehydes coeluted with hydrocarbon species and thereby interfered with the hydrocarbon analysis. Because these chemicals were present at excessive levels, well above normal ambient concentrations in all samples, including test samples acquired on the return trip over the North Atlantic, and since blank canister samples did not exhibit these peaks, the values reported do not include the suspected contaminants. These data will be studied further to attempt to establish the source(s) of the contamination.

Carbon dioxide was determined via gas chromatography/electron capture detector using a carrier gas that was N₂-doped with 10 ppm N₂O to improve sensitivity for CO₂. Calibration employed dilutions of CO₂-in-N₂ from an NIST primary standard and pure CO₂ gas.

Only summaries of canister analyses of total non-methane hydrocarbons are reported in the integrated sample results for each mission, although speciated data are available.

4.4 SUB-MICRON GRAB SAMPLES

Grab samples, over intervals typically 30 to 60 s long, were collected and processed with an onboard Thermo Systems Incorporated (TSI) mobility analyzer to determine sub-micron particle quantity and size distribution. The algorithm used to

process these data was compared to examples suggested by Liu et al. (1976) and was found to agree very favorably when applied to test data sets. Channels at the higher end of the instrument range were deemed unreliable and were discarded, so that results indicate particles in six size ranges with midpoint values ranging from 0.013 to 0.237 μm . Example plots are shown in mission data sets in the appendix.

5.0 DATA OVERVIEW AND INITIAL DATA ANALYSIS

The primary intent of this report is to present the G-1 data set in a form that makes it easily accessible for future analysis by the extended research community, and thus extensive analyses of these data will not be provided here. Because early analyses of these data have led to some important initial findings, however, it is worthwhile to mention some of these at this point. These results are presented in the context of several overview examples, which appear immediately below.

5.1 VERTICAL AND HORIZONTAL PLUME DISPERSION

Conditions during a majority of the flights involved southward plume movement, and sampling was conducted along E-W transects at a fixed latitude at various altitudes. Vertical and horizontal distributions of the plume during these missions when the main body of the plume was sampled are illustrated in Figures 5.1 through 5.5. In these plots, the measured aerosol particle number densities are represented by vertical lines, which are superimposed on longitude/altitude plots of the aircraft's flight track. These data are derived from the Axially Scattering Aerosol Spectrometer Probe (ASASP) and represent particles with nominal diameters between 0.2 and 3 μm . While the choice of particle number density to represent plume structure is somewhat arbitrary, this parameter is well correlated with the concentrations of other plume constituents, such as CO_2 , NO_x , and SO_2 , and provides a good visual representation of crosswind plume structure.

Figures 5.6 through 5.9 show selected vertical profiles of aerosol properties [ASASP, Forward-Scattering Spectrometer Probe (FSSP) and cloud condensation nucleus (CCN) counter number densities] and the mixing ratios of selected trace gases (NO_x , O_3 , and SO_2) through the central section of the plume for several representative missions. Individual points on these profiles correspond to median concentrations calculated for the central section of the plume using data collected on constant-altitude tracks over about 0.5 degrees of longitude.

FIGURE 5.1. Plots of Number Density of Aerosol Particles ($0.2 < d < 3 \mu\text{m}$) Measured by the ASAP on Crosswind Transects: a) Between 0315 and 0730 GMT at $28^{\circ}09'N$ Latitude on 8/2/91; and b) Between 0700 and 1100 GMT at $27^{\circ}04'N$ Latitude on 8/4/91

FIGURE 5.2. Plots of Number Density of Aerosol Particles ($0.2 < d < 3 \mu\text{m}$) Measured by the ASAP on Crosswind Transects: a) Between 0450 and 0930 GMT at $27^{\circ}40'N$ Latitude on 8/6/91; and b) Between 0500 and 0930 GMT at $27^{\circ}00'N$ Latitude on 8/7/91

FIGURE 5.3. Plots of Number Density of Aerosol Particles (0.2 < d < 3 μm) Measured by the ASAP on Crosswind Transects: a) Between 0500 and 0700 GMT at 26°55'N Latitude on 8/11/91; and b) Between 0500 and 0920 GMT at 28°00'N Latitude on 8/13/91

FIGURE 5.4. Plots of Number Density of Aerosol Particles ($0.2 < d < 3 \mu\text{m}$) Measured by the ASAP on Crosswind Transects: a) Between 0510 and 0910 GMT at $28^{\circ}00'N$ Latitude on 8/14/91; and b) Between 0700 and 1400 GMT at $28^{\circ}0'N$ Latitude on 8/15/91

FIGURE 5.5. Plots of Number Density of Aerosol Particles (0.2<d<3 μm) Measured by the ASAP on Crosswind Transects: a) Between 0730 and 1140 GMT at 25°00'N Latitude on 8/16/91 ; and b) Between 0730 and 1100 GMT at 26°15'N Latitude on 8/17/91

FIGURE 5.6. Vertical Profiles of SO₂, O₃, NO_x, ASASP, FSSP, and CCN Through Central Section of Plume on 8/6/91, Between 0450 and 0930 GMT at 27°40'N Latitude

FIGURE 5.7. Vertical Profiles of SO₂, O₃, NO_x, ASASP, FSSP, and CCN Through Central Section of Plume on 8/7/91, Between 0500 and 0930 GMT at 27°00'N Latitude

FIGURE 5.8. Vertical Profiles of SO_2 , O_3 , NO_x , ASASP, FSSP, and CCN Through Central Section of Plume on 8/14/91, Between 0510 and 0910 GMT at $28^\circ 00' \text{N}$ Latitude

FIGURE 5.9. Vertical Profiles of SO₂, O₃, NO_x, ASASP, FSSP, and CCN Through Central Section of Plume on 8/16/91, Between 0730 and 1140 GMT at 25°00'N Latitude

Figures 5.1 through 5.5 indicate that plume structure varied considerably with distance from the source, with plume width ranging roughly from 40 km on August 2 (Figure 5.1a) to >200 km on August 16 (Figure 5.5a). On many of the flights, the plume appeared to be bifurcated vertically or horizontally, or both. In Figures 5.6 and 5.7, it is apparent that the plume had separated vertically into two components. On the mission of August 6 (Figure 5.6) a concentration peak was observed just above plume base between 1200 and 1400 m. This appeared to be well separated from a much more intense concentration peak at 2500 m. As indicated in Figure 5.4a, similar behavior was noted on the flight of August 14.

Bifurcation of the plume was observed in the horizontal direction as well. Figures 5.1b and 5.3a exhibit an intense concentration peak in the eastern part of the transects and a much less intense peak towards the western edge. Similar horizontal bifurcation was noted on the flight of August 15 (Figure 5.4b), except that concentrations were highest at the western edge of the plume instead of on the east. This horizontal bifurcation probably resulted from the effect of the geographic distribution of the fires (cf. Figure 1.1).

On several flights (e.g., August 6, 14, 16, and 17), extensive vertical sampling, including above-plume transects, allowed determination of the plume's vertical extent. From the vertical cross-section plots for these days (Figures 5.2a, 5.4a, 5.5a, and 5.5b, respectively), it is apparent that elevated aerosol concentrations were not encountered above about 5000 m msl (ca. 16,500 ft), and while not apparent from the figures, aircraft observers reported several instances when plume top was limited to altitudes of 3000 m or less. Plume top was generally observed to be highest in regions directly above the most concentrated portions of the plume. This observation is consistent with the expectation of more extensive absorption of solar energy in the densest portions of the plume, and consequent enhancement of plume rise due to heating. These observations of the maximum extent of plume rise are consistent with previous observations (Hobbs and Radke 1992) and have a strong bearing on the distance over which the plume was likely to have been transported.

In several instances it was possible to fly at a sufficiently low elevation to define the base of the plume. On the August 2 flight, plume base was observed to be above 800 m; on August 6, it was found to be at ca. 1100 m, and on August 14, about 1400 m (Figures 5.2a and 5.4a, respectively). The highest plume base (ca. 2400 m) was observed well downwind of the source region on August 16 (Figure 5.5a). During some flights (e.g., August 4 and 7, Figures 5.1b and 5.3b), plume base appeared to be considerably lower (<400 m and 900 m, respectively). In general, however, it appeared that plumes were elevated considerably above the surface, as far north as the the Kuwait/Saudi Arabia border. Thus, it can be inferred that there was little if any direct impact of the plume on the populated areas along the east coast of Saudi Arabia during the G-1 missions. This is consistent with observations at surface sites in the northeast Provinces of Saudi Arabia during the measurement period of only minimally elevated concentrations of substances that could be associated with the plume (Al-Sunaid 1992).

5.2 TRACE-GAS CONCENTRATIONS

Figure 5.10, parts a-d, depicts cross-sectional trace-gas observations for the early morning of August 6. The plume was particularly well defined on this mission, and its vertical structure was characterized extensively by repeated plume traverses at different altitudes. These plots are generally representative of observations during crosswind transects on other missions, although the plume became progressively more diffuse with increasing distance from the source.

As indicated by Figure 5.10a, substantial concentrations of sulfur dioxide were measured in the plume, with peak concentrations on the order of >300 ppbv. Comparison of SO₂ concentrations shown in Figure 5.10a with the corresponding aerosol concentrations in Figure 5.2a shows a high correlation, indicating a common source. A similar correlation between SO₂ and aerosol concentrations is exhibited in the vertical profiles shown in Figures 5.6 through 5.9. In this context, it is important to note that substantial surface-level emissions of SO₂ were observed on several of the

FIGURE 5.10. Plume Cross Sections on 8/6/91 Between 0450 and 0930 GMT at 27°40'N Latitude:
a) SO₂; b) NO_x; c) CO₂; and d) FSSP

FIGURE 5.10. (cont'd)

flights, particularly at low altitudes along the northeast coast of Saudi Arabia, where industrial activity is concentrated; thus the absolute commonality of the aerosol/SO₂ source should be viewed with some caution in the interpretation of these data.

A plume cross section of the NO_x concentration for August 6 is shown in Figure 5.10b. Of particular note is the fact that observed NO_x concentrations were about 20 times lower than corresponding SO₂ concentrations. This 20:1 ratio was characteristic of all of the plume-sampling missions, although there was a discernible increase with increasing distance from the source. The highest plume NO_x concentrations that were observed were on the order of 40 ppbv during the mission of August 2 in a plume that was spatially very compact. In dilute plumes, NO_x concentrations of about 1 ppbv were observed (cf. Figure 5.8). Out-of-plume NO_x concentrations were typically less than 1 ppbv.

The low NO_x concentrations in comparison to those observed in urban plumes in the United States and other locations appears to be a consequence of relatively low combustion temperatures of the oil and gas fires in Kuwait. Under such conditions, the predominant source of nitrogen oxides is expected to be nitrogen-bearing compounds in the fuel, as opposed to formation by nitrogen fixation that would occur under high temperature conditions. The low concentrations of NO_x observed outside the plume are consistent with the low density of vehicular use on the Arabian Peninsula.

Figure 5.10c shows a cross section of excess CO₂ concentrations, defined as total measured CO₂ concentrations minus those from background, on August 6. As expected from a source of this nature, excess CO₂ concentrations were well correlated with the concentrations of SO₂, NO_x, and aerosol. Unfortunately, limitations of the instrumentation used during the program precluded accurate measurement of excess CO₂ concentrations in the plume well downwind. However, as will be shown below, several of the missions close to Kuwait gave CO₂ concentrations of sufficient quality to allow calculation of emission ratios of plume constituents. Excess CO₂ concentrations

in the plume were only a small fraction (1% or less) of the excess CO_2 concentrations, indicating that the combustion process was relatively efficient.

It is of considerable interest to determine whether the plume was sufficiently active photochemically to generate measurable quantities of O_3 . Presumably high concentrations of reactive hydrocarbons were being emitted from the fires but there is some question whether sufficient NO_x was present to act as a catalyst for rapid generation of O_3 . Out-of-plume O_3 concentrations typically ranged between 30 and 60 ppb, with higher concentrations observed along the more industrialized regions on the northeast coast of Saudi Arabia, indicating some photochemical production of O_3 outside the plume. Concentrations in the lower portion of the range were observed during flights over sparsely populated regions in south-central Saudi Arabia.

Ozone depletion was observed in some of the near-field plume measurements (Figure 5.11), as expected from oil-fire NO production and subsequent reaction with ambient O_3 . In some instances (e.g., Figure 5.6), in-plume O_3 was indistinguishable from background. In other cases, O_3 production was evident around the plume's edges and as the plume aged and became more dilute. An example of such production is shown in Figure 5.12, in which the aerosol concentration is plotted as a marker of plume position. Comparison of the particle number density and the O_3 concentration indicates out-of-plume O_3 concentrations of about 40 ppbv. In-plume O_3 concentrations increased to a peak value of about 60 ppbv, which is about 20 ppbv peak excess. Ozone production is also evident in Figures 5.10b-d. The low rate of O_3 production is not surprising, considering the strong light-absorption properties of the plume, which greatly decrease the rates of the photochemically driven reactions necessary to produce O_3 . Around the edges of the plume, and in plumes that had been significantly diluted, light intensity was higher and O_3 was obviously being produced.

FIGURE 5.11. Cross-Plume Transect at 28°09'N Latitude on 8/2/91 at an Altitude of 800 m msl of NO_x and O₃, Illustrating O₃ Depletion in the Plume

FIGURE 5.12. Plot of O₃ and Particle Concentration During a Cross-Plume Transect on 8/11/91 at 26°54'N, Showing O₃ Production

5.3 MICROPHYSICAL FEATURES

Aerosol number densities and size distributions were measured optically using two sensors, the PMS FSSP (range: $2 < d < 47 \mu\text{m}$) and ASASP (range: $0.2 < d < 3 \mu\text{m}$). These optical instruments were complemented by a Thermo Systems Incorporated electrostatic aerosol analyzer (EAA), which measured particle sizes in the nominal size range $0.01 < d < 0.5 \mu\text{m}$. The EAA was included with the instrument ensemble to obtain measurements in the lower portion of the particle size spectrum and to provide a check on ASASP performance, which was in some doubt because of the poor light-scattering properties expected for the carbonaceous fraction of the plume aerosol.

As indicated in Figures 5.1 through 5.5, particle number densities in the nominal size range $0.2 < d < 3 \mu\text{m}$ varied greatly during the various missions. In compact plumes close to the source (e.g., the August 2 mission, Figure 5.1a), number concentrations exceeding $30,000/\text{cm}^3$ were observed. Even in more dilute plumes, sampled well downwind of the source region, number concentrations of $2\text{-}4,000/\text{cm}^3$ were common. Concentrations of aerosol particles in this size range appeared to be roughly conserved as the plume diluted and moved downwind. This is consistent with the low expected dry deposition velocities for such particles, with the absence of wet deposition as a loss mechanism, and with the observation that plumes were mostly lofted substantially above the surface, further minimizing losses by dry deposition.

Number densities of particles in the size range $2\text{-}47 \mu\text{m}$ were typically less than number densities of accumulation-mode particles by a factor of 1000 and never exceeded $100/\text{cm}^3$ even in very concentrated plumes. A typical plume cross section is given in Figure 5.10d. In contrast to concentrations of other species, shown in Figures 5.10a-d, large-particle aerosol concentrations were not negligible outside the plume. It should be noted in particular that the highest concentrations of particles exhibited in Figure 5.10d occurred below the plume, in the flight segment between 48.2 and 48.6 degrees longitude at an altitude of about 750 m . The source of these particles was undoubtedly desert dust, which had been entrained to this altitude. It is

also noteworthy that, particularly at the east end of the flight segment at 1100 m, significant amounts of dust appeared to be mixed into the bottom portion of the plume. Such mixing of dust from below was frequently observed during many of the G-1's sampling missions. The rather poor correlation ($r^2 = 0.29$) between the ASASP and the FSSP plume measurements is also noteworthy. It reinforces our expectation that the large aerosol particles in the plume originated from multiple sources, including both the oil fires and soil entrainment.

Representative measurements of number, surface-area, and volume distributions for the plume aerosol, based on merged data from the EAA, ASASP, and FSSP, are shown in Figures 5.13a-c, where best fits of log-normal distributions to the total data ensembles are indicated by the superimposed curves. The number distribution shown in Figure 5.13a contains large numbers of relatively fine particles with little indication of multimodality, although a coarse-particle mode emerges with the surface distribution (Figure 5.13b) and becomes strongly apparent with the volume distribution (Figure 5.13c).

An instrument mismatch between the EAA and the ASASP is apparent in the overlap range near $0.5\ \mu\text{m}$. This mismatch was a rather consistent feature in all of the aerosol data acquired during the flights, and it is reflected by the poor visual fit of the log-normal curves (dashed lines) to the total data set. Based on EAA operating theory, which indicates that aerosol-charging ambiguities degrade measurements for particle sizes much above $0.1\ \mu\text{m}$, it is common to discard results from the top two EAA channels. Doing this to the data of Figure 5.13 results in the solid curves, which give a much more visually appealing fit to the remaining points.

The capability of plume aerosol particles to act as cloud condensation nuclei was evaluated using a CCN counter operating at a fixed supersaturation of 0.6%. To provide a context for interpretation of the CCN data, it is referenced to the concurrently measured ASASP particle concentration. Shown in Figure 5.14 is a plot of the ratio

FIGURE 5.13. Example of Merged, In-Plume Particle Size Measurements from the Electrical Aerosol Analyzer (EAA), the ASASP, and the FSSP. One-minute sample at 6:41 a.m. local time on 8/6/91, at an altitude of 1536 m. a) Particle number spectrum, b) particle surface-area spectrum (area in square micrometers), c) particle volume spectrum (volume in cubic micrometers). Logarithm on ordinates is base-e.

FIGURE 5.14. Plot of the Ratio CCN:ASASP Number Densities Averaged Over the Collection Time of the Filter Samples Listed in Table 5.1. CCN concentrations measured at a supersaturation of 0.6%. ASASP particle number densities include particles over the nominal size range $0.2 < d < 3 \mu\text{m}$.

CCN:ASASP number densities averaged over times coinciding with collection times of filter samples listed in Table 5.1. Table 5.1 indicates that these samples were collected under a variety of circumstances and include samples collected in plumes of various ages, as well as some out-of-plume samples. It may be inferred from Figure 5.14 that samples exhibiting the highest aerosol concentrations were measured in the plume near the source, and that samples exhibiting the lowest concentrations were measured in background air.

The general shape of the plot in Figure 5.14 suggests that a large fraction (by number) of the plume aerosol particles in the size range measured by the ASASP are activatable at relatively low supersaturation. The reason for the general shape of the

curve is not clear. Toward the left-hand side of the plot, particles with diameters below the cutoff size for the ASASP probe (nominally $0.2\ \mu\text{m}$) were activated. In contrast, in concentrated plumes on the right-hand side of the plot, large numbers of particles less than the minimum detectable size for the ASASP appear not to have been activated. This result arose partially from an inherent limitation of the CCN counter at high particle number densities, but current analyses indicate that the aerosol's cloud-nucleating efficiency increased with plume age. Further insights on this point are expected upon further analysis of the data.

5.4 MACROSCOPIC OPTICAL FEATURES

Optical properties of the plume discussed here are based on measurements of solar radiation with upward- and downward-facing short-wave radiometers. Plots of plume transmittance, defined as the ratio of the downwelling solar radiation at a given altitude within the plume to the downwelling solar radiation measured at plume top, are shown in Figure 5.15a for two of the missions. Data for this figure were selected from cross-plume transects at various altitudes in the central section of the plume. The plot for August 6, when the plume was quite concentrated, indicates that only about 15% of the incident solar radiation reached the surface. The plot for August 17, when plume aerosol concentrations were considerably lower than those for August 6, shows a situation in which approximately 60% of the downwelling solar radiation reached the surface. As expected, this inverse relationship between aerosol column burden and plume transmittance was observed on all mission flights.

Figure 5.15b shows a plot of downwelling and upwelling solar radiation and albedo, calculated from the ratio of the upwelling to downwelling radiation, for the flight of August 6, where a cross-plume transect was made approximately 500 m above plume top. Albedo was found to minimize at about 48° longitude, in the region where plume aerosol-particle concentrations are at a maximum (see Figure 5.2a). Albedo rose to about 0.16 on the edges of the plume. While the latter value may seem low for an area where the underlying surface is a desert, a widespread haze layer pervaded

FIGURE 5.15. Plume Optical Properties. a) Plot of plume transmittance as a function of altitude for cross-plume transects made on flights made on 8/6 and 8/17/91. b) Plot of downwelling, upwelling solar radiation, and albedo, for a transect across plume top on 8/6/91.

the area and thus the albedo measured outside the main body of the plume was not that of the underlying surface, but rather a combination of the properties of the surface and the haze layer.

The combination of low transmittance and low albedo suggests that the plume was absorbing a significant fraction of the incident solar radiation. Two effects are expected to result from this absorption. First, significant radiative heating of the plume should cause increased mixing and plume loft. Second, radiative absorption should decrease the intensity of solar radiation reaching the surface and result in surface temperatures cooler than normal.

An example of plume heating, presumably caused by absorption of solar radiation, is given in Figure 5.16, which shows vertical profiles of temperature and aerosol

FIGURE 5.16. Plot of Temperature and ASASP Particle Concentration ($0.2 < d < 3 \mu\text{m}$) for a Vertical Profile Through the Plume on 8/15/91. Note temperature inversion at the altitude of highest particle concentration.

concentration observed through the central section of the plume on August 15 (see Figure 5.4b for reference). Here the temperature inversion at 3000 m coincides with a maximum in the aerosol concentration--a situation that is entirely consistent with heating of the plume caused by absorption of solar radiation.

5.5 AEROSOL COMPOSITION

Two types of aerosol samples were collected for subsequent laboratory analysis; samples for inorganic analysis and samples for organic analysis. For various technical reasons, including sample-loading requirements for the filters, samples from the two filter types were not always collected coincidentally in time. For the inorganic filter samples, the general procedure was to expose a filter for the duration of a single pass through the plume at a specific altitude. For the organic filters, loading requirements dictated shorter exposure times, so several filters were usually collected during a single pass through the plume. Results of the analyses are given in Tables 5.1 and 5.2 for the inorganic and organic filters, respectively. These tables include data specifying the location of the sample (average altitude, latitude, and longitude), and in the last column, an indication of the conditions under which the filter was collected.

To understand the concentrations of various species that were collected in the plume, it is important to have a context with which plume composition can be compared. Thus, we initially focus attention on samples collected outside the plume (see notes in Tables 5.1 and 5.2). Out-of-plume aerosol composition is interesting from several perspectives. First, concentrations of aerosol calcium, sulfate, and nitrate were quite high. Although the sources of these components are not known, it is evident that the oil-fire plume was not emitted into a pristine aerosol-free environment. As noted previously, substantial industrial activity exists along the northeast Saudi Coast between Bahrain and Kuwait, and some of these activities (e.g., gas desulfurization) emit substantial quantities of SO_2 , which were ultimately converted to sulfate aerosol. Furthermore, the observed high concentrations of calcium indicate that the out-of-plume aerosol may have had an important soil-derived component. This is consistent

TABLE 5.1. Results of Inorganic Filter Analyses

<u>Date</u>	<u>Time</u> <u>(UT)</u>	<u>Alt.</u> <u>(m)</u>	<u>Location</u> <u>(lat/lon)</u>	<u>Ca⁺⁺</u> <u>(ppbv)</u>	<u>Na⁺</u> <u>(ppbv)</u>	<u>NH₄⁺</u> <u>(ppbv)</u>	<u>SO₄⁻</u> <u>(ppbv)</u>	<u>NO₃⁻</u> <u>(ppbv)</u>	<u>Cl⁻</u> <u>(ppbv)</u>	<u>HNO₃</u> <u>(ppbv)</u>	<u>SO₂</u> <u>(ppbv)</u>	<u>Remarks</u>
8/6-1	0500-0520	766	27.1/50.0	22.6	4.8	2.0	6.0	3.4	1.4	1.2	9.5	1
8/6-2	0546-0606	1158	27.7/48.1	57.4	47.5	5.5	14.3	7.2	47.7	1.0	60.1	2
8/6-3	0619-0644	1536	27.7/48.1	39.9	32.5	3.5	9.7	5.5	33.5	0.8	44.3	2
8/6-4	0656-0722	1843	27.7/48.1	27.09	26.4		7.2	4.3	21.9	0.7	27.8	2
8/6-5	0725-0756	2463	27.7/48.2	31.3	49.0	4.2	10.2	5.2	41.7	1.0	60.5	2
8/6-6	0806-0819	2856	27.7/48.0	36.5	37.8	5.4	9.3	5.5	28.2	0.7	38.2	2
8/7-1	0603-0621	1465	27.1/48.0	26.5	27.6	4.8	6.9	4.4	20.4	0.5	27.9	2
8/7-2	0659-0728	950	27.1/47.9	104.8	75.2	25.1	17.2	11.8	60.3	2.0	87.6	2
8/7-3	0753-0816	2366	27.1/47.9	28.9	43.7	4.7	7.6	4.9	29.4	1.0	47.9	2
8/9-1	0536-0600	1422	24.4/50.4	20.7	8.5	1.9	4.8	4.5	4.4	0.3	4.5	3
8/9-2	0651-0738	1415	22.0/47.6	29.0	18.3	2.2	8.7	5.6	8.5	0.1	1.7	1
8/9-3	0802-0911	2951	22.4/48.8	10.5	6.2	0.28	3.5	2.5	3.7	0.0	0.4	1
8/9-4	0919-0943	2478	24.8/50.1	26.5	12.0	4.7	4.2	4.6	5.1	0.0	2.8	3
8/11-1	0537-0550	1433	26.9/48.9	56.5	43.3	27.6	12.4	8.9	17.8	0.2	28.1	2
8/11-2	0602-0629	847	26.9/49.1	47.2	16.4	2.4	9.2	4.5	10.6	0.2	9.1	2
8/12-1	1212-1312	893	26.9/49.7	26.4	8.3	1.2	5.5	4.5	4.5	0.5	6.3	2
8/13-1	0518-0541	960	27.4/49.9	48.4	15.5	7.7	7.2	7.5	10.4	0.05	4.4	5
8/13-2	0554-0614	1650	48.4/28.0	38.1	15.2	4.5	5.3	4.3	7.3	0.1	10.9	4
8/13-3	0623-0653	949	28.0/48.4	45.8	12.3	5.8	6.7	7.0	7.9	0.4	9.5	4
8/13-4	0813-0904	514	28.0/48.5	27.3	12.0	1.8	5.2	5.3	7.5	0.05	5.4	4
8/14-1	0536-0558	1131	27.6/50.0	46.1	9.3	2.8	6.0	4.7	5.6	0.2	3.2	?
8/14-2	0615-0633	1482	28.0/48.9	41.7	11.8	1.98	4.4	3.2	5.8	0.2	8.2	7
8/14-3	0643-0709	2070	28.0/48.9	26.5	11.7	2.3	4.7	4.0	6.0	0.2	7.1	7
8/14-4	0718-0740	2691	28.0/48.9	68.9	29.0	7.2	11.1	5.8	28.2	0.4	38.0	2
8/15-1	0722-0745	1263	27.4/50.2	39.3	10.6	2.3	4.9	3.7	2.2	0.3	1.0	1
8/15-2	0754-0822	1251	28.0/48.8	71.3	27.0	8.23	10.6	6.7	10.7	0.4	17.2	7
8/15-3	0828-0847	1595	28.0/48.9	60.1	23.8	4.43	9.3	5.1	13.5	0.0	20.4	7
8/15-4	0935-0959	2623	27.0/49.1	36.1	17.7	2.0	6.4	4.4	7.9	0.2	9.3	7
8/15-5	1026-1056	2031	27.2/50.5	29.2	8.7	0.98	3.3	3.1	3.0	0.05	0.7	1
8/16-1	0855-0929	2546	25.0/49.4	42.3	17.2	3.6	7.1	5.9	10.0	0.3	10.2	2
8/16-2	0941-1027	3165	25.0/49.2	20.1	8.1	0.71	3.8	3.1	4.5	0.2	6.0	2
8/17-1	0754-0829	1453	26.2/49.1	68.7	28.6	9.2	9.1	9.0	20.4	0.7	22.7	2
8/17-2	1019-1053	934	26.3/49.2	42.6	11.1	2.3	6.3	4.7	4.6	0.2	3.3	6

Remarks: 1 = Out of plume; 2 = In plume; 3 = Aged recirculated; 4 = Plume edge close to source; 5 = In and out of plume;
6 = Below plume; 7 = In plume below main body.

TABLE 5.2. Results of Organic Filter Analyses

Date	Time (UT)	Location (lat/lon)	Altitude (m msl)	Elemental Carbon ($\mu\text{g}/\text{m}^3$)	Organic Carbon ($\mu\text{g}/\text{m}^3$)	Carbonate Carbon ($\mu\text{g}/\text{m}^3$)	EC/OC	Remarks
8/6-1	0500-0520	27.0/50.1	764	1.3	23.7	18.5	0.055	1
8/6-2	0546-0554	27.7/48.1	1160	178.4	114	9.8	1.56	2
8/6-6	0656-0708	27.7/48.0	2954	87.7	53.0	12.1	1.65	5
8/7-1	0628-0639	27.1/48.0	1462	103.6	61.8	6.2	1.68	2
8/7-4	0753-0804	27.1/48.0	2367	87.8	70.6	5.5	1.24	2
8/7-5	0845-0905	27.2/49.2	3950	0.69	15.4	11.5	0.045	1
8/9-1	0604-0623	22.7/50.5	1420	0.88	15.5	12.3	0.057	1
8/9-4	0919-0943	24.8/50.1	2479	6.42	19.0	2.29	0.34	3
8/13-1	0518-0541	27.5/49.8	1058	13.8	28.9	15.8	0.48	5
8/13-3	0623-0653	28.0/48.4	949	26.8	33.8	19.0	0.79	4
8/14-1	0536-0558	27.6/50.0	1131	9.25	21.8	23.7	0.42	4
8/14-2	0615-0633	28.0/48.9	1483	35.1	39.4	32.3	0.89	7
8/14-7	0821-0837	28.0/48.6	4100-4900	102.3	89.6	20.9	1.14	2
8/14-8	0838-0900	27.4/49.8	4860-2000	0	7.6	0	0	1
8/15-1	0722-0745	27.4/50.2	1270	1.0	19.6	16.9	0.051	1
8/15-2	0754-0822	28.0/48.8	1250	29.7	35.2	45.2	0.84	7
8/15-3	0828-0847	28.0/48.9	1595	52.0	61.6	77.0	0.84	7
8/15-4	0935-0959	27.0/49.1	2642	30.5	44.6	49.9	0.68	2
8/15-5	1026-1056	27.2/50.5	2364-1937	4.01	20.4	36.7	0.20	1
8/16-1	0855-0927	25.0/49.3	2546	23.8	25.08	8.04	0.95	2
8/17-3	0904-0916	26.3/49.5	2049	77.3	77.1	37.7	1.0	2
8/17-5	1019-1053	26.3/49.2	934	14.3	21.9	113.2	0.65	6

Remarks: 1 = Out of plume; 2 = In plume; 3 = Aged recirculated; 4 = Plume edge close to source; 5 = In and out of plume; 6 = Below plume; 7 = In plume below main body.

with frequent visual observations of desert dust suspended to altitudes of several thousand meters. Measured Na^+ and Cl^- in the out-of-plume aerosol were reasonably low--a feature having an important bearing on the interpretation of in-plume samples in the following discussion. Elemental, organic, and carbonate carbon concentrations in the out-of-plume samples are also illustrative. From the perspective of carbon concentrations, the out-of-plume samples can be characterized as having low concentrations of elemental and organic carbon and low elemental-to-organic carbon ratios. Carbonate carbon concentrations were high and variable, at least for the samples collected within the boundary layer. This probably reflects the resuspension of soil-derived constituents into the atmosphere.

In some respects, the compositions of in-plume samples were similar to those of the background samples, but substantial differences were observed as well. Near-source and compact, well-defined plumes contained sulfate and nitrate concentrations that were considerably elevated in comparison to out-of-plume values, indicating formation of these species during combustion. It should be noted, however, that even the highest in-plume sulfate concentrations were only a factor of two to three higher than the out-of-plume concentrations. Similar comments can be made with respect to nitrate. In-plume sulfate and nitrate concentrations measured well downwind of the source region were similar to those observed in the background. Indeed, it would not be possible to distinguish dilute plume from background on the basis of measured sulfate and nitrate aerosol concentrations alone. Similar arguments apply to calcium. It is clear that some calcium was emitted from the source region, but calcium concentrations became indistinguishable from background levels with progressive plume dilution.

High concentrations of NaCl were observed in the in-plume aerosol, particularly near the oil-fire source region, where NaCl concentrations exceeded those of all other major inorganic constituents (with the exception of calcium) by a factor of three to five. As the plume aged and diluted, these ratios decreased because of the dilution of the plume by air that contained much higher sulfate- and nitrate-to-chloride ratios. The oil-fire source of NaCl and, to a somewhat lesser extent, Ca^{++} was apparently the so-called white plumes, which have been hypothesized to result from the aspiration of substantial quantities of brine (Cofer et al. 1992). Measurements in the source region (Cofer et al. 1992) show that most of the Na^+ and Cl^- and a fair fraction of the Ca^{++} came from such fires. In contrast, fires producing black plumes were found to contain little Na^+ and Cl^- .

Plume aerosol samples also exhibited high concentrations of elemental, organic, and carbonate carbon. Elemental carbon, organic carbon, and elemental-to-organic carbon ratios (EC/OC) were all higher than observed in the out-of-plume samples.

The EC/OC for the in-plume samples averaged 0.95 ± 0.42 , whereas in the out-of-plume samples, EC/OC was only 0.07 ± 0.07 . Most of this difference was caused by changes in the elemental carbon concentration, which varied by as much as a factor of 100 between in- and out-of-plume samples. The difference between in- and out-of-plume organic carbon concentrations was much less. In- and out-of-plume carbonate carbon concentrations were indistinguishable. This is probably because substantial quantities of soil-derived carbonate mixed into the plume from the surrounding atmosphere.

5.6 EMISSION FACTORS

Sulfur and nitrogen-oxide emission factors were calculated on the basis of data collected during flights that were either close to the source region or in compact plumes where CO_2 concentrations were significantly above background. Calibration standards for the CO_2 instrument were unavailable during the field program due to shipping and customs delays, necessitating calculation of excess CO_2 concentrations as follows: During each transect of the plume at each altitude, the CO_2 instrument response was normalized to an atmospheric mixing ratio for CO_2 of 356 ppm. The excess CO_2 was then computed using a response factor (ppm/V) measured just outside the plume. Instrument response to ambient air from which the CO_2 had been removed was measured at least once (and usually twice) during each plume transect. The CO_2 mixing-ratio measurements made during rapid altitude changes were not used in these calculations because the instrument exhibited a significant altitude response, probably as a result of changes in instrument temperature with altitude.

Emission factors were calculated as grams of pollutant per 100 grams of excess CO_2 carbon. For SO_2 and aerosol constituents, the factors were computed from concentrations derived from filter measurements and the excess CO_2 measured during the time of filter collection. Emission factors for NO_x were computed from response of the continuous instrument in the central section of the plume. Concentrations were corrected for background levels. The results of these calculations are given in Table 5.3.

TABLE 5.3. Emission Factors for Plume Constituents

	<u>Emission Factor</u> <u>(g/100 g CO₂ C)</u>	<u>Variation</u> <u>(Standard</u> <u>Deviation)</u>	<u>Number of</u> <u>Samples</u>
SO ₂ S	1.5	±0.2	7
Total S	2.1	±0.2	7
NaCl	2.2	±0.03	7
NO ₃ ⁻ N	0.08	±0.02	7
NO _x N	0.06	±0.01	6
EC	2.62	±0.2	4
OC	2.11	±0.5	4

Some discussion of these emission factors is warranted. Two emission factors are reported for sulfur. The first pertains to gaseous SO₂ only, while the second includes sulfate as well. Neither of these sulfur emission factors has been corrected for sulfur originating from mixing of ambient air into the plume. For SO₂, this contribution should be negligible since SO₂ concentrations outside the plume during the selected sampling missions were typically several orders of magnitude lower than peak in-plume concentrations. For sulfate, ambient concentrations were lower than sulfate concentrations measured in the plume by a factor of only 2 or 3; thus estimated total sulfur emission factors are somewhat more uncertain than the emission factor for SO₂. However, since plume sulfate constituted less than 20% of the total sulfur in the chosen samples and background contributions represent a sulfate uncertainty of 50% or less, the effective uncertainty should be only about 10%.

These estimates of the sulfur emission factors are considerably higher than those reported by other investigators. Cofer et al. (1992) estimated emission factors for sulfur in the source region to be lower than those reported here by a factor of 2 to 5, and lower than that which would be predicted on the basis of oil stoichiometry by a similar factor (a crude oil containing 2% sulfur by weight corresponds to a sulfur

emission ratio of roughly 2.4 grams of sulfur per 100 grams of CO₂ carbon). However, Cofer and his coworkers report measurements from only a small number of the 400 wells burning at the time of their study, and thus there is some question about the representativeness of their emission estimates. Hobbs and Radke (1992) estimated emission factors that were about a factor of 3 lower than those reported here, results that are again inconsistent with oil stoichiometry. Hobbs and his coworkers have attempted to resolve this discrepancy by suggesting oxidation of SO₂ to sulfate in the near-source plume, followed by fast deposition of the sulfate reaction product. Sulfur emission ratios derived from the G-1 measurements are stoichiometrically consistent with the estimated fuel sulfur content, and there is no need to invoke the suggested rapid oxidation and loss mechanism to account for the results. With regard to this point, it will be shown subsequently that oxidation of sulfur dioxide appears to have occurred only very slowly in the plume.

The emission factor for NaCl underscores the importance of the so-called white-plume fires to the aerosol burden in the plume. Measurements in the source region (Cofer et al. 1992) show that NaCl appears to result almost solely from such fires. The NaCl concentrations from black plumes, which presumably resulted from burning crude oil, were very low by comparison, as were the NaCl concentrations in plumes from burning oil pools.

We have divided estimates of nitrogen emissions into aerosol and gaseous components. The emission factor for aerosol nitrate is uncertain to at least a factor of 2 because of the high background concentrations of this species. The emission factor for nitrogen in the form of NO_x is somewhat lower than the stoichiometric estimate, based on a fuel nitrogen content of 0.2%. The sum of the two emission factors is approximately 0.16, close to the fuel N content estimate, but it is somewhat uncertain. The measured emission factor for N reinforces the perception that plume NO_x originated principally from fuel nitrogen, rather than from atmospheric nitrogen fixation during the combustion process. This is consistent with the relatively low combustion temperatures presumed for these fires.

Aerosol elemental carbon and organic carbon each represented about 2% of the total carbon emissions in the plume. The elemental carbon emission factors were similar in magnitude to the factors reported elsewhere for measurements of black plumes in the source region (Cofer et al. 1992), but they are significantly higher than those reported by Hobbs and Radke (1992). Organic carbon emission factors are considerably higher, and the reason for this is not clear. We note, however, that background aerosol organic carbon concentrations can be a substantial fraction of the in-plume concentrations, and that absorption of gas-phase organic species by carbonaceous aerosol can occur as the plume ages and is transported downwind from the source region. Both of these would cause our estimates of source emissions ratios of aerosol organic carbon to be high.

5.7 IN-PLUME SO₂ OXIDATION

Figure 5.17 shows the fraction of total sulfur present in the plume as sulfate as a function of the SO₂ concentration for filter samples that were identified as being collected only in the plume. This fraction is high at low SO₂ concentrations, decreases monotonically with increasing values, and asymptotically approaches a value of about 0.1 at high SO₂ concentrations. In general, the lower SO₂ concentrations were measured at greater downwind distances from the source, where the plume became more dilute. Accordingly the behavior shown in Figure 5.17 is consistent with about 10% of the fuel sulfur occurring as sulfate in the source region, and 1) oxidation of the SO₂ to sulfate as the emissions were transported downwind, 2) dilution of the plume with background air containing significant quantities of sulfate, or 3) some combination of these two processes. Our analysis strongly indicates that the relationship shown in Figure 5.17 was dominated by the second of these processes, and that the rate of SO₂ oxidation was quite low.

This analysis is based upon the assumption that aerosol Cl⁻ can be employed as a conservative tracer of the plume. It can be argued that this should be the case on several bases. First, chloride in the lower troposphere is fairly inert chemically, so

FIGURE 5.17. Plot of the Fraction of Plume Sulfur in the Form of Sulfate for Filter Samples Identified as Having Been Collected Solely in the Plume

losses by chemical conversion to other species should be minimal. Second, most of the Cl⁻ mass in the near-source plume appears in particles that are less than 0.5 μm in diameter (Cofer et al. 1992). This fact, coupled with the observation that the plumes are typically elevated from the surface downwind of the source region, implies that Cl⁻ losses by gravitational settling and by dry deposition to the surface should be slow. Third, while Cl⁻ particles are good CCN and thus expected to be easily removed from the atmosphere by wet deposition, the absence of rain in the project area precluded any loss of aerosol constituents by this mechanism. Fourth, Cl⁻ concentrations measured in this study are highly correlated ($r^2 = 0.93$) with those for elemental carbon, another aerosol constituent having characteristics that should make it a rather conservative plume constituent.

The conservative properties of the Cl^- plume can be applied to address two points: 1) the reactivity of plume SO_2 and 2) the origin of plume sulfate. Figure 5.18 shows a plot of aerosol Cl^- versus SO_2 (on a log-log plot to de-emphasize points at high concentration) for the same measurements shown in Figure 5.17. Obviously, SO_2 and Cl^- are closely related ($r^2 = 0.98$). The regression slope of the log-log plot, 1.06, is close to that expected (1.0) if the SO_2/Cl^- ratio were constant for all of the samples. Since we have argued above that Cl^- is an inert tracer of the plume because the loss processes for Cl^- are low under conditions of our measurements, the high degree of association of Cl^- and SO_2 suggests that SO_2 is also a relatively inert tracer of the plume. This in turn implies that SO_2 was not rapidly oxidized to sulfate over the transport distances that were sampled during this study.

Further evidence toward this point is shown in Figure 5.19, which is a plot of the SO_2/Cl^- ratio as a function of the transport distance downwind of the source region. In

FIGURE 5.18. Plot of Concurrently Measured SO_2 and Aerosol Chloride for Samples Collected in the Plume. Data are for same samples as Figure 5.17.

FIGURE 5.19. Plot of the Ratio SO_2/Cl^- for Plume Samples as a Function of Distance Downwind of Kuwait City. Data are for same samples as Figure 5.17.

this instance, transport distance is used as a rough surrogate for transport time to illustrate time-dependent behavior. Values of SO_2/Cl^- are scattered about a line that has a non-zero slope, suggesting some conversion (or loss of SO_2 relative to Cl^-) occurred as the plume parcels moved downwind. However, it is also clear that the rate of conversion (or loss) of SO_2 was slow, corresponding, if a mean windspeed of 10 km/h is assumed, to a rate of less than 0.5% per hour. Such low oxidation rates are consistent with the conditions under which the measurements were conducted, namely O_3 concentrations of about 50 ppbv, low relative humidities, and reduced solar intensity because of plume absorption. Furthermore, no clouds were present for aqueous phase conversion of SO_2 by H_2O_2 or O_3 .

Table 5.1 shows measured sulfate concentrations obtained in both in-plume and out-of-plume environments and thus provides some insight regarding the origin of in-plume aerosol sulfur, particularly in the downwind samples. These data indicate that ambient sulfate concentrations in air adjacent to the plume were comparable to those

observed directly within the plume, suggesting a substantial background contribution as the plume ingested background air. Further insight is provided by Figure 5.20a, which presents the molar ratio of aerosol calcium:chloride ratio ($\text{Ca}:\text{Cl}$) as a function of Cl^- . Here $\text{Ca}:\text{Cl}$ increases with decreasing Cl^- concentration, suggesting that as the plume dilutes, Ca from the ambient atmosphere is being mixed into the plume. Figure 5.20b indicates that the sulfate-to-chloride ratio ($\text{SO}_4^{2-}:\text{Cl}^-$) increases as $\text{Ca}:\text{Cl}$ increases. Again, this suggests that much of the sulfate observed in the plume at high dilutions is contributed by background air, as opposed to primary sulfate from the oil-well fires or SO_2 oxidation. These observations are consistent with those relating to the dependence shown in Figure 5.17 and lead to the conclusion that the oxidation rates of plume SO_2 were quite low.

A major reason for choosing Cl^- as a quasi-conservative plume tracer was the fact that the on-board CO_2 instrument did not produce results that were sufficiently sensitive for CO_2 to be used successfully as a tracer at extended downwind distances. Recent evaluations of SO_2/CO_2 ratios in near-source samples, however, indicate maximum conversion rates of the order of one percent per hour or less, a finding that is consistent with the Cl^- -based results described above. It should be noted that this finding is in strong disagreement with earlier interpretations by Hobbs and his co-workers (Hobbs and Radke 1992; Ferek et al. 1991) who suggested that SO_2 oxidation occurred extremely rapidly, having e-folding times of the order of one-half hour. In a more recent publication (Ferek et al. 1992), this group has indicated that these earlier reports were in error, and that SO_2 conversion rates were actually of the order of 6% per hour, with corresponding NO_x conversion rates in the range of 22% per hour. They note further that these rates exceed those attributable to photochemical oxidation and suggest that heterogeneous reactions with soil dust may have been a contributing factor.

FIGURE 5.20. Relationship Between Concentrations of Aerosol Constituents: a) $\text{Ca}^{++}:\text{Cl}^-$ Versus Cl^- , b) $\text{SO}_4^{--}:\text{Cl}^-$ Versus $\text{Ca}^{++}:\text{Cl}^-$ for Samples Collected in Plume. Same samples are represented as in Figures 5.17, 5.18, and 5.19.

These authors' revised estimates of in-plume SO₂ oxidation rates, however, are still an order of magnitude larger than those observed in the present study. Accordingly, and although some heterogeneous chemical conversion certainly must have occurred (Al-Sunaid 1992), our measured oxidation rates are within the bounds of those expected based on conventional homogeneous photochemistry. Furthermore, our results (not detailed here) suggest NO_x oxidation rates of roughly 5% per hour--again within the expected range, based on conventional photochemical knowledge. Although we feel confident with the interpretation of reaction rates described here, the reason for this large discrepancy remains uncertain at the present time.

6.0 CONCLUDING REMARKS

This report is intended as an aid to the extended scientific community for future interpretive analysis of the Kuwait oil-fire data. The following are some of the more important observations acquired from this data set to date:

- SO₂ concentrations ranged from a few to >200 ppb (the upper range of the instrument used).
- NO_x levels of several parts per billion were observed, but these were substantially lower than levels of SO₂.
- Ozone levels were generally in the range of about 50 to 70 ppb. Ozone depletion occurred in the near-source plume, and limited ozone production occurred in more dilute regions of the plume downwind.
- Aerosol light scattering, b_{scat} , readings were high, frequently exceeding instrument full scale, 10^{-3} m^{-1} .
- Particle counts, as observed by PMS optical counting probes, frequently exceeded 2000 to 3000 per cm^{-3} .
- A CCN counter, operating at 0.6% supersaturation, indicated similar high particle counts, and, as was suggested by previous measurement teams, also indicated that most particles were hygroscopic and thus, likely to be scavenged by precipitation rather than undergoing long-range transport.
- Ratios of measured in-plume SO_x and NO_x concentrations to those of CO₂ were consistent with those expected on the basis of oil stoichiometry. These ratios are significantly higher than those measured by previous authors.
- In-plume conversion rates for both SO₂ and NO_x are consistent with those expected on the basis of current understanding of oxidation in polluted atmospheres. The maximum conversion rates observed from this study are substantially lower than those estimated by some previous authors.
- Plume height was observed to be limited to about 5000 m, and it appears that, except at near-source distances where some self-lifting may have occurred, large-scale atmospheric mixing processes were the dominant factors in elevating

the plume. This conclusion agrees with findings reported by other groups (Browning et al. 1991; Johnson et al. 1991) and reinforces speculation that long-range transport of the plume did not occur, limiting climate modification to the near-source region.

7.0 REFERENCES

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APPENDIX

MISSION DATA SUMMARIES

FLIGHT 01: 31 JULY 1991

METEOROLOGICAL SUMMARY

The 0300 GMT surface chart shows a 994-mb low centered near the southern Iran-Pakistan border. Cyclonic flow around this low was producing west northwest winds of 3 to 5 m/s at Kuwait, and northwest to north northwest winds of 5 to 8 m/s at Dhahran. The pressure patterns and winds were similar at 0600 and 0900 GMT. No clouds or weather, other than smoke, were reported in the region of interest. Surface winds at regional air quality sites were as follows:

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0300	0400	0500	0600	0700	0800
Abqaiq	WNW06	WNW06	WNW07	NW 08	NW 10	NNW11
Dhahran	NW 03	NW 04	NW 05	NNW06	NW 07	NW 07
Marjan GOSP1	NW 06	NW 06	NW 05	NW 05	NW 05	NW 05
Rahima Town	NW 07	NW 08	NW 08	NW 10	NNW10	NNW10
Safaniyah GOSP2	W 08	W 08	WNW06	WNW08	WNW08	WNW07
Tanajib	WNW06	WNW05	WNW05	WNW06	NW 06	NW08

The 1200 GMT 850-mb chart shows that a low was centered over Oman, with a lobe extending northwestward to the Black Sea. The gradient was light over the Persian Gulf, but the rawinsondes at Dhahran and Riyadh (or near there) indicated north and north northwest wind of 13 to 14 m/s. Temperatures of 30°C at 850 mb were indicated south and east of Dhahran, but less than 30°C to the north. The 1200 GMT 500-mb chart shows a weak low over Saudi Arabia, and a weak high to the north, over Iraq and Iran. At this level, wind speeds of only <2 m/s were indicated over Dhahran. The wind maxima (18 to 26 m/s) were observed well to the north, at the east end of the Mediterranean and over the Black and Caspian Seas. The soundings at Dhahran show that at 0000 GMT the surface inversion extended to about 800 m msl. Above that

there was an isothermal layer between 2150 and 2450 m. At 1200 GMT the surface inversion had been wiped out, but there were two shallow inversions, at ~1500 and 2100 m. The persistent inversion or isothermal layer at 5400 to 5700 m is shown on both sounding plots. The soundings are dry throughout.

There were no satellite images collected for this day. Flight notes about the plume are sketchy. The mission was flown from 0305 to 0742 GMT. Flight notes report that the smoke was more dense near the western coast as the aircraft approached from out over the Persian Gulf. The top of the haze layer was observed to be near 4500 m msl. A plume forecast by the Bahrain Meteorological Service (BMS) predicted the main plume would be along the western shore of the Persian Gulf, from the source at Kuwait, extending south-southeastward along the coast line and out over the Great Sandy Desert.

FLIGHT SUMMARY

The flight commenced at 0730 GMT. Temperature at the surface was circa 36°C with light winds from the north. The aircraft headed almost due west of Bahrain to the Saudi coast at an altitude of 1450 m msl. The eastern edge of the plume was encountered at 26°17'N, 050°01'E. As the flight proceeded to the west, we were clearly in the region of the plume, but it appeared that most of the plume was above our flight altitude. The western edge of the plume was determined to be at 26°15'N, 048°38'E. The plume was sampled on subsequent passes at 2000 and 2650 m, and during a final pass at 900 m, we were clearly below the main body of the plume. The height of the plume was observed to vary approximately with the plume optical density. Plume top was near 3500 m at the western edge of the plume where the optical density was lowest and was observed to increase to about 4500 m where the plume was most optically dense. Filter samples for inorganic analysis were collected at 1450 and 900 m. Samples for aerosol organic analysis were collected at 900, 1450, 2000, and 2650 m. Canister samples for VOC analysis were collected at 1450 and 2000 m.

Temperature, deg. C
1200Z SOUNDING DHAHRAN 31 JULY 91

Surface Chart
31 July 91 1200Z

850 Millibar Chart
31 July 91 1200Z

500 Millibar Chart
31 July 91 1200Z

Aircraft Flight Track
7/31/91 03:05:28 - 07:42:41

7 / 31 / 1991

Kuwait Mission 01

7 / 31 / 1991

Kuwait Mission 01

A.9

7 / 31 / 1991

Kuwait Mission 01

Kuwait Mission 01

7 / 31 / 1991

A.11

Integrated Samples

a. Inorganic Filter Analysis

None collected

b. Organic Filter Analysis

None collected

c. Canister Sample Analysis

None collected

Surface Air Quality Measurements - 31 July 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	29 (10) 60 (21) 1700,1800				370 590 0400
Dhahran	58 (20) 113 (60) 2100		56 (30) 130 (69) 2100	41 (21) 84 (43) 1300	454 926 1500
Rahimah	39 (14) 110 (38) 0800	6 (4) 7 (5) 0500			439 622 0500
Tanajib	34 (12) 86 (30) 0200	4 (3) 7 (5) 0400	11 (6) 24 (13) 0800		276 850 0100

FLIGHT 02: 02 AUGUST 1991

METEOROLOGICAL SUMMARY

The 1200 GMT surface chart shows a 994-mb low over eastern Iraq, and a 993-mb low over the eastern Persian Gulf. The northern end of the Gulf was in the col between these two low-pressure centers. Surface winds over the region from Kuwait to Dhahran were from the northwest at 5 to 10 m/s. Other than smoke being reported at sites under the oil-fires plume, there were no reports of clouds or weather in the region. Satellite imagery shows the plume to be located along the western Persian Gulf shoreline, spreading to the east over the water, and extending southward from Dhahran out over the Great Sandy Desert. Surface winds at the Air Quality sites are tabled below:

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0300	0400	0500	0600	0700	0800
Abqaiq	WNW04	WNW05	WNW05	WNW04	NW 04	NW 05
Dhahran	NNW03	NW 02	NW 03	NW 03	NW 04	NNW04
Marjan GOSP1	WNW05	WNW05	WNW05	NW 04	NW 04	NNW03
Rahima Town	NW 03	WNW03	WNW04	NW 04	NW 06	NNW06
Safaniyah GOSP2	W 06	W 06	W 05	WNW05	W 07	W 05
Tanajib	W 03	W 03	WNW03	W 03	NW 04	NW 04

The 850-mb chart for 1200 GMT also shows two warm (~30°C) low centers spatially coincident with those at the surface. Wind flow at this level was also from the northwest at 20 to 25 knots (10 to 13 m/s) at both 0000 and 1200 GMT. At 500 mb (5890 m), the Dhahran soundings show 345° 5 m/s at 0000 GMT and 290° 4 m/s at 1200 GMT. However, between ~750 and 550 mb, those soundings indicate winds from 150 to 200° at 2 to 4 m/s. During the aircraft mission, the scientists on board reported the plume height to be from 1830 to 2440 m (6000 to 8000 ft). Take-off time was at

0300 GMT. At 0000 GMT there was a strong temperature inversion shown on the Dhahran sounding to about 500 m msl, an unstable layer to about 1650 m, and an isothermal layer from there to about 2250 m. A high-level inversion was present at both 0000 and 1200 GMT at about 6000 m msl. By 1200 GMT, the low-level inversions were wiped out by heating, although there was a shallow (~300 m) near-isothermal layer with base at about 1480 m msl.

FLIGHT SUMMARY

This flight departed Bahrain at 0300 GMT and headed northeast at an altitude of circa 800 m msl to the Hotel intersection at 28°09'N, 050°06'E. During this portion of the flight, pollutant concentrations were quite low, except for a few pockets of SO₂, and except for the observation that the b_{scat} was quite high (circa $2.6 \times 10^{-4}/\text{m}$). Stratified layers were observed to the west and a haze layer was observed close to the surface (water). At the Hotel intersection, the aircraft headed west at an altitude of 800 m msl. An apparent cloud, which proved to be the oil-fire plume, was observed at the Saudi coast. In the plume, concentrations were very high, with SO₂ > 200 ppbv, b_{scat} > $10 \times 10^{-4}/\text{m}$, NO_x > 40 ppbv, etc. Both CO and CO₂ concentrations increased by about 50% relative to their out-of-plume values. We broke out of the plume heading westbound after about 30 km. After a few additional kilometers, we entered another plume, which was less dense and much narrower than the first. These plumes were sampled at altitudes of 800, 1300, 1800, 2350, 3050, and 4000 m msl. Plume top appeared to rise with time due to solar heating. Some turbulence was encountered towards the top of the plume, which reinforced this perception. Plume top was at 2000 to 2500 m. During our flight across the top of the plume at 3050 m and during the 4000-m leg between the Hotel intersection and Bahrain, regions of high SO₂ were encountered. It is hypothesized that these came from segments of the plume that had been lofted several days previously and had been recirculated into the area. The plane landed at Bahrain at 1103 GMT.

SATELLITE IMAGES OF SAMPLING REGION

Temperature, deg. C
1200Z SOUNDING DHAHRAN 02 AUG 91

Surface Chart
02 Aug 91 1200Z

500 Millibar Chart
02 Aug 91 1200Z

Aircraft Flight Track
8/2/91 02:49:24 - 07:33:01

8 / 2 / 1991

Kuwait Mission 02

8 / 2 / 1991

Kuwait Mission 02

8 / 2 / 1991

Kuwait Mission 02

Kuwait Mission 02

8 / 2 / 1991

52.A

Submicron Size Distribution 02 Aug 91 04:47 - 04:48

Submicron Size Distribution 02 Aug 91 05:35 - 05:36

Integrated Samples

a. Inorganic Filter Analysis

None collected

b. Organic Filter Analysis

None collected

c. Canister Sample Analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
1	0358 0416	0416 0440	800	248	417

Surface Air Quality Measurements - 02 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	37(13) 110(38) 1700				154 230 0700
Dhahran	76(27) 115(40) 1100		55(29) 113(60) 2300	33(17) 69(36) 1600	218 540 0200
Rahimah	21(7) 100(35) 1300	3(2) 6(4) 0700,0800 2200,2300			192 317 0900
Tanajib	24(8) 60(21) 1400,1500	6(4) 6(4) most hours	11(6) 26(14) 2200		146 319 0200,0300

FLIGHT 03: 04 AUGUST 1991

METEOROLOGICAL SUMMARY

At 0000 GMT, a surface trough of low pressure was over the Persian Gulf area, extending from a 996-mb low over Baghdad in the north, to two 995-mb lows, one over the mountains of southern Iran, and the other over the Great Sandy Desert. Surface winds were generally less than 5 m/s throughout the Gulf Area. Meteorological observations reported no clouds, but did indicate the presence of smoke and haze along the western Gulf shoreline. Surface winds at regional Air Quality Sites were as follows:

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0700	0800	0900	1000	1100	1200
Abqaiq	WNW05	NW 06	NW 06	N 08	NNE07	N 08
Dhahran	NW 04	NW 04	NNW05	N 06	N 06	N 06
Marjan GOSP1	NW 03	WNW05	NW 05	NW 03	NNW03	NW 03
Rahima Town	NW 04	NNW05	N 05	N 05	NNW05	N 04
Safaniyah GOSP2	WNW07	NNW07	NNW06	NNW05	N 05	NNE05
Tanajib	WNW06	WNW05	N 05	NNE06	NE 06	NE 06

The 1200 GMT 850-mb chart shows a contour pattern very similar to that of the surface chart, with a crescent-shaped low center directly over the Persian Gulf with other low centers to the north and southwest. At Dhahran the 850-mb wind was 355° at 12 m/s. A 30°C warm zone was over southern Saudi Arabia. At 500 mb, at 1200 GMT, west to northwest winds of 2 to 7 m/s were occurring over Saudi Arabia. The gradients were light over the region; the height contours depicted three small high cells. These cells were located just southwest of the Caspian Sea, over the northern Red Sea, and over western Saudi Arabia. In the lower atmosphere, to about 800 mb, the 0000 and 1200 GMT Dhahran soundings are quite similar, both showing strong surface inversions to 960 and 987 mb, respectively. Above the inversions, near-lapse

conditions existed to above 800 mb. At 0000 GMT, there was a high inversion from 500 to 485 mb, and an isothermal layer from 410 to 400 mb. At 1200 GMT, there was an isothermal layer from 740 to 720 mb, and increases in stability above 500 mb and again above 400 mb. The satellite imagery for 1100 GMT shows the western boundary of the smoke plume to have been very close to the western shore of the Persian Gulf for about 300 km south of Kuwait; farther south it appears as a narrow band, slightly inland from the western shore. Beyond the southern shore of the Gulf, the plume appears as a 300- to 400-km-wide dark area over southeastern Saudi Arabia. It appears, based on the width of the plume at this location, that much of the northern portion of the plume on this day was out over the Gulf, and not visible against the dark of the water.

The G-1 flight was from about 0700 to 1100 GMT. The flight scientists noted light winds and a surface temperature of 31°C. A low-level haze layer was present, and layering was noted as the aircraft gained altitude. Over the sampling area, the plume was higher than the aircraft flight levels of 1200 and 1500 m msl. The orientation of the plume was toward the south southeast.

FLIGHT SUMMARY

The purpose of this flight was to sample the plume at two different distances downwind of the source region to characterize plume composition changes as a function of time or downwind distance. The aircraft took off at 0700 GMT. Skies were hazy, temperature was 31°C, and winds were light. After takeoff, the aircraft headed north-northwest (342°) toward a turning point of 27°04'N, 050°20'E. On takeoff, a low-level haze layer was observed that decreased in density as we approached our en route altitude of 800 m msl. En route to the turning point, general haziness was observed with some layering. As we headed due east at the turning point and as we approached the Saudi coast, concentrations of trace species increased. These elevated concentrations persisted for about 100 to 120 km as we traveled east. We broke out of the western edge of the plume at 27°05'N, 048°55'E. We repeated

transects of the plume at 500 and 1350 m. The plume seemed to be reasonably well mixed vertically. We made no effort to determine the top of the plume at this location, but it was well above 1350 m.

During the first set of transects, we noted the presence of a chemical manufacturing complex along the flight track. A Saudi scientist on board for this flight said that the complex was a significant source of SO₂ and hydrocarbons.

After completion of the first set of transects, the aircraft headed south in an attempt to sample the plume over the Saudi Arabian desert west of Qatar by flying an east-west transect at 24°N. During the transit south we were mostly in clear air, except for a few spikes of SO₂ that were probably from oil-well facilities scattered about the region. We saw no evidence of the plume during the west-east transect at 24°N and did not again see evidence of the plume until we were inbound to Bahrain. Review of the satellite image taken at 1130 GMT confirmed our observations regarding plume location. From the satellite image, it could be seen that the plume was being advected on a south-southeast track, which took it directly over Bahrain and Qatar rather than over the Saudi desert east of Qatar.

SATELLITE IMAGES OF SAMPLING REGION

Temperature, deg. C

1200Z SOUNDING DHAHRAN 04 AUG 91

Aircraft Flight Track
8/4/91 06:50:07 - 11:03:18

8 / 4 / 1991

Kuwait Mission 03

8 / 4 / 1991

Kuwait Mission 03

Kuwait Mission 03

8 / 4 / 1991

8 / 4 / 1991

Kuwait Mission 03

Submicron Size Distribution 04 Aug 91 08:59 - 09:00

Submicron Size Dostribution 04 Aug 91 08:16

Integrated Samples

a. Inorganic Filter Analysis

None collected

b. Organic Filter Analysis

None collected

c. Canister Sample Analysis

None collected

Surface Air Quality Measurements - 04 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	34 (12) 81 (28) 1800				134 209 1600
Dhahran	47 (16) 139 (49) 1200		56 (30) 102 (54) 1800	35 (18) 82 (42) 1400	149 194 1900
Rahimah	24 (8) 58 (20) 1000	6 (4) 8 (6) 2400			139 178 1300
Tanajib	21 (7) 118 (41) 1300	6 (4) 7 (5) 1400, 1500	17 (9) 38 (20) 2100		120 197 0200

FLIGHT 04: 06 AUGUST 1991

METEOROLOGICAL SUMMARY

At the surface, a two-lobed low pressure trough was present; the northern lobe at 996 mb was centered near Baghdad in eastern Iraq, and the southern lobe, with a pressure center of about 998 mb, was over central Saudi Arabia. The pressure field over the Persian Gulf and adjacent Kuwait and eastern Saudi Arabia was rather flat, resulting in light easterly surface winds at Dhahran of about 4 m/s at 0500 GMT. There was some local ground fog at Bahrain at takeoff time of 0448 GMT. Surface air quality stations along the western shore of the Persian Gulf reported hourly winds for the flight period, as follows:

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0400	0500	0600	0700	0800	0900
Abqaiq	N 02	N 02	NE 02	ENE02	ENE01	E 02
Dhahran	ENE03	E 04	E 04	E 04	E 03	MISG.
Marjan GOSP1	SSW02	SSW02	SSW01	SSE<1	ESE<1	ENE01
Rahima Town	N 01	ENE02	ENE03	ENE03	ENE04	ENE03
Safaniyah GOSP2	ESE04	ESE04	SSE02	SW 01	SW 02	SSW<1
Tanajib	E 02	SSE03	SSE03	SE 04	E 03	SE 03

The two low centers were also evident at 850 mb. A weak upper trough extended south-southeastward to the Red Sea from the northern low center. Temperature analysis for the 850-mb surface shows a 36°C hot area immediately north of the Persian Gulf. A cooler tongue of air (<30°C) was present over the western half of the Gulf and adjacent land mass, to about 150 km inland.

The 0000 GMT sounding taken at Dhahran shows the top of the surface temperature inversion was at 870 mb (~1250 m msl). Winds measured in this layer were

northerly at 3 to 4 m/s. There was also a shallow isothermal layer at 535 mb (~5100 m msl), with winds 120° 3 to 4 m/s below the layer, and 065° 3 to 4 m/s above. The aircraft determined the top of the smoke plume to be circa 5000 m msl. The 1200 GMT sounding indicates a low-level inversion from 860 to 820 mb (~1350 to 750 m msl), and a higher one between 444 and 425 mb (~6500 to 6750 m msl). The 1200 GMT 500-mb chart, showing conditions at roughly 5900 m msl, indicates east to east southeasterly flow of 3 to 8 m/s along the western Persian Gulf between Bahrain and Kuwait. It is apparent from the 1242 GMT satellite photo, however, that the plume is being carried parallel to the western shoreline of the Gulf by winds having a northwest component. Neither the 0000 GMT nor the 1200 GMT rawinsondes measured any northwesterly winds at any level between the surface and 70 mb (~18500 m msl).

FLIGHT SUMMARY

The purpose of this flight was to sample the plume in northern Saudi Arabia near the source region. Takeoff was at 0448 GMT, in calm surface winds with some local ground fog and a temperature of 31°C. After takeoff, the aircraft flew north-northwest over the Persian Gulf toward Kuwait. During transit to the sampling location, we were in a layer of brown haze with modestly high concentrations of SO₂ (10 to 50 ppb) and other trace pollutants. On reaching 27°40'N, 049°30'E, we turned west to intercept the plume. The eastern edge of the plume was penetrated at 27°41'N, 048°21'E; the western edge at 27°41'N, 047°55'E. Transects across the plume were sequentially made at 800, 1100, 1450, 1850, 2550, and 3000 m msl. High concentrations of both trace gases and aerosols were found at all altitudes during these transects with SO₂ > 200 ppbv, particle concentrations > 5,000 cm⁻³, and b_{scat} offscale (>10 x10⁻⁴). Upon completion of the crosswind transects, we climbed to 5300 m to locate the upper boundary of the plume, which was determined to be at about 5000 m. We returned to Bahrain, landing at 0925 GMT.

SATELLITE IMAGES OF SAMPLING REGION

Temperature, deg. C

1200Z SOUNDING DHAHRAN 06 AUG 91

Surface Chart
06 Aug 91 1200Z

850 Millibar Chart
06 Aug 91 1200Z

500 Millibar Chart
06 Aug 91 1200Z

Aircraft Flight Track
8/6/91 04:26:23 - 09:42:09

Real Time Measurements

Kuwait Mission 04

8 / 6 / 1991

15.A

8 / 6 / 1991

Kuwait Mission 04

8 / 6 / 1991

Kuwait Mission 04

Kuwait Mission 04

8 / 6 / 1991

A.54

Submicron Size Distribution 06 Aug 91 05:49 - 05:50

Submicron Size Distribution 06 Aug 91 07:53 - 07:54

Integrated Samples

a. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/6-1*	0500	0520	800	22.6	4.8	1.4	2.0	6.0	3.4	9.5	1.2
8/6-2*	0546	0606	1100	57.4	47.5	47.7	5.5	14.3	7.2	60.1	1.0
8/6-3*	0619	0644	1450	39.9	32.5	33.5	3.5	9.7	5.5	44.3	0.83
8/6-4*	0656	0722	1850	27.0	26.4	21.9		7.2	4.3	27.8	0.74
8/6-5	0725	0756	2550	31.3	49.0	41.7	4.2	10.1	5.2	60.5	1.0
8/6-6*	0806	0819	3000	36.5	37.8	28.2	5.4	9.3	5.45	38.2	0.67

b. Organic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Remarks	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/6-1	0500	0520	800	lightly loaded, background, light tan	23.7	1.3	9.12	18.57
8/6-2	0546	0554	1100	In plume near Kuwait, dark grey	113.5	178.4	9.80	0.64
8/6-4	0619	0626	1,450	In plume near Kuwait, med. grey	53.0	87.7	12.12	0.60

c. Canister Sample Analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
2	0601	0611	1100	113	420
3	0638	0647	1450	84.4	372

Surface Air Quality Measurements - 06 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	18(6) 50(18) 0300		- - -		274 624 0300
Dhahran	10(4) 37((13) 1500		19(10) 32(17) 1500	39(20) 84(43) 1300	- - -
Rahimah	5(2) 13(5) 1500	4(3) 6(4) 0200,0300 0700,1000			163 415 2300
Tanajib	5(2) 13(5) 1300	4(3) 8(6) 0100	11(6) 56(30) 0600		242 574 0400

FLIGHT 05: 07 AUGUST 1991

METEOROLOGICAL SUMMARY

The surface chart for 0900 GMT (1200 LST) shows the Persian Gulf area within a 1000-mb low pressure trough, oriented generally north and south. Reported winds were less than 5 m/s, northwesterly at the beginning of the flight, shifting to northeast by the end of the mission. Surface temperature at Dhahran at the start of the mission was ~30°C, and the surface layer was more moist than on previous missions. Wind velocities at the air quality monitoring sites are shown below:

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0500	0600	0700	0800	0900	1000
Abqaiq	N 03	NNE03	NNE03	NNE03	NE 03	NE 03
Dhahran	NW 02	NW 02	NE 02	NNE03	NE 03	NE 04
Marjan GOSP1	W 03	W 02	W 02	W 02	W 01	WNW01
Rahima Town	NW 02	N 03	N 03	N 04	N 04	NNE04
Safaniyah GOSP2	SSW02	SW 01	SSW01	S 01	E <01	ENE01
Tanajib	SSW02	S 02	SSE02	SE 03	E 04	ENE04

At 850 mb (1200 GMT), a small elongated cell made up of low centers (1440 m) was positioned at the northern end of the Persian Gulf, oriented west-northwest to east-southeast. Winds over Kuwait and the west shoreline of the Gulf were light at the 850-mb level. Wind reports from the soundings at 0000 GMT indicate speeds of less than 1 m/s above Dhahran, and 285° winds of 4 m/s at Qaisomah. By 1200 GMT, the Dhahran sounding showed easterly winds at about 4 m/s from the surface to 700 mb, and easterly winds with speeds of 12 to 17 m/s at 500 mb (~5500 m msl), with a decrease in speeds above that level. Warm areas of >30°C were identified north of and over the Gulf. At 500 mb, a lobe of a >5880-m ridge covered the region from the Caspian Sea to the northern half of Saudi Arabia, from west of the Red Sea to east of

Iran. A pronounced anticyclonic flow was occurring in the outer margins of this lobe, with westerly winds 20 to 23 m/s over the southern Caspian Sea, and winds of 15 to 23 m/s from the east southeast of the southern Persian Gulf area. Easterly winds of 10 m/s were over central Saudi Arabia.

The 0000 and 1200 GMT rawinsondes at Dhahran show lapse conditions to about 950 mb, then an inversion to about 850 mb. The layer below 950 mb was somewhat more moist than had been shown on soundings from previous mission days. At 1200 GMT, there was also a moist layer at 500 mb. Lapse conditions existed between 850 and 500 mb at both 0000 and 1200 GMT, then near-isothermal conditions to 450 mb. For the most part, the soundings were quite similar. The air was very dry above 450 mb.

In apparent defiance of the easterly winds measured by the 1200 GMT upper air soundings, the smoke plume shown on the 1242 GMT satellite photo was being carried nearly due south from its source in Kuwait. The G-1 flight scientists intercepted the plume west of Dhahran and observed that the maximum height of the plume in their mission area was 4000 m msl.

FLIGHT SUMMARY

The purpose of the mission was to sample modestly aged plume over northern Saudi Arabia. Humidity was very high (>90%) and surface temperature was 35°C. The aircraft took off at 0457 GMT and headed northwest over the Persian Gulf to about 27°N. East-west transects were flown at 27°N between about 047°30'E and 050°E at altitudes of 900, 1650, 2500, and 3200 m msl. High concentrations of SO₂ (>200 ppb), particles, and b_{scat} were observed during these transects. The top of the plume was found to be between 3800 and 4200 m. Scattered clouds, and at some locations almost overcast skies, were observed above the plume. We returned to Bahrain at 0925 GMT.

SATELLITE IMAGES OF SAMPLING REGION

Surface Chart
07 Aug 91 0900Z

850 Millibar Chart
07 Aug 91 1200Z

500 Millibar Chart
07 Aug 91 1200Z

Aircraft Flight Track
8/7/91 04:47:52 - 09:25:52

Kuwait Mission 05

8 / 7 / 1991

A.66

8 / 7 / 1991

Kuwait Mission 05

8 / 7 / 1991

Kuwait Mission 05

8 / 7 / 1991

Kuwait Mission 05

Submicron Size distribution 07 Aug 91 06:37 - 06:38

Submicron Size Distribution 07 Aug 91 07:35 - 07:36

Integrated Samples

a. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/7-1	0603	0621	1650	26.5	27.6	20.5	4.8	6.9	4.4	27.9	0.54
8/7-2	0659	0728	900	104.8	75.2	60.3	25.1	17.2	11.8	87.6	2.0
8/7-3	0753	0816	2500	28.9	43.7	29.4	4.7	7.6	4.9	47.9	1.0

b. Organic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Remarks	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/7-1	0628	0639	1650	In plume near Kuwait, dark grey	61.8	103.6	6.24	0.60
8/7-4	0753	0804	900	In plume near Kuwait, med. grey	70.58	87.81	5.47	0.80
8/7-5	0845	0905	4200	Out of plume, white	15.35	0.69	11.54	22.71

c. Canister Sample Analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
4	0607	0618	1650	104	369

Surface Air Quality Measurements - 07 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	3 (1) 8 (3) 1600 -1800				185 252 1800
Dhahran	8 (3) 10 (4) 0900		19 (10) 38 (20) 0700,0800	20 (10) 41 (21) 1400,1500	170 216 0600
Rahimah	0 (0) 3 (1) 0500-1300	4 (3) 6 (4) 0700			137 170 0200
Tanajib	10 (4) 26 (9) 1200,1400	6 (4) 21 (15) 2000	4 (2) 11 (6) 0700,0800		146 192 1300

FLIGHT 06: 09 AUGUST 1991

METEOROLOGICAL SUMMARY

A surface low-pressure area was positioned over the Persian Gulf at 1200 GMT. There was one 994-mb center east of Baghdad, and another over the mountains of southern Iran. Most stations in the region reported clear skies; however, some high cirrus was reported at Riyadh. It was very hot. The Dhahran air quality site record showed temperatures above 40°C by 1100 LST, and the mean maximum temperature in the afternoon was 43.9°C. Surface winds in the western Gulf region were generally from the west, northwest, or north at 3 to 8 m/s during the 0500 to 1000 GMT flight period. Most regional air quality sites experienced an increase in wind speed toward the end of this period (table below).

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0500	0600	0700	0800	0900	1000
Abqaiq	WNW04	WNW05	WNW06	NW 06	N 08	N 07
Dhahran	NW 03	NW 03	NW 04	NNW05	NNW07	N 08
Marjan GOSP1	NW 04	WNW04	NW 03	NW 03	NW 03	NW 02
Rahima Town	WNW03	WNW04	NNW06	NNW07	NNW06	NNW07
Safaniyah GOSP2	WSW05	W 05	WNW06	WNW06	NW 06	NW 04
Tanajib	WNW04	WNW05	NW 05	NNW08	NNW08	N 08

The 850-mb chart for 1200 GMT shows a broad upper trough extending westward from India over the Persian Gulf area. Temperatures were above 30°C over Iraq, Iran, and most of Saudi Arabia. Streamline analyses show the flow at the 850-mb level to be north-northwesterly at about 12 m/s near Qaisomah, the same direction but at 6 m/s above Dhahran, and north-northeast at 9 m/s over Riyadh. The 500-mb chart for 1200 GMT shows a high centered just north of the Persian Gulf and a low over Greece. Clockwise flow around this high had an easterly wind speed maximum over the

southern half of the Gulf. At Dhahran, the speed was 20 m/s at 0000 GMT, but by 1200 GMT the wind speed had decreased to 10 m/s. Lighter wind speeds were observed above Kuwait, nearer to the center of the high. The rawinsondes taken at Dhahran show the air to be very dry to above 700 mb; then there was a gradual increase in moisture with height to a maximum relative humidity of about 60% at 500 mb at both 0000 and 1200 GMT. At 0000 GMT, there was a strong surface temperature inversion to 980 mb, but only a very shallow one to 990 mb at 1200 GMT. However, the latter sounding showed a stable layer from about 900 to 1500 m msl. The customary inversion at about 500 mb was evident on both soundings; above that, to about 415 mb, there were layers of varying degrees of stability. There was a layer of light wind speeds (<4 m/s) above Dhahran at both 0000 and 1200 GMT. The satellite photo for 1230 GMT shows the plume being carried southward parallel to, and inland from, the western Persian Gulf shoreline to about 27.5°N. Lat.; then it was carried more to the west and became more spread out.

FLIGHT SUMMARY

The purpose of the mission was to sample aged plume in southcentral Saudi Arabia. The flight path was direct south-southwest from Bahrain to 050°E, 22°N, then due west to 046°E, 22°N. The flight commenced at 0500 GMT and ended at 1000 GMT. The first half of the flight was made at an altitude of about 1650 m msl; the second half at 2800 m. On departure from Bahrain, we encountered modest concentrations of pollutants and aerosol particles (SO₂, 1 to 4 ppb; O₃, 30 to 50 ppb; particle concentrations of 100 to 200 cm⁻³) that decreased as we flew south. Concentrations on the east-west portion of the flight were uniform and low until we reached the end of the transect, where they increased. On the return portion of the flight (flown at 2900 m), concentrations were uniformly low until we were about 200 km south-southwest of Bahrain, where they rose to modest levels. At this location we started to observe a well-defined haze layer, with a top at 2500 to 3000 m.

Review of the afternoon visible satellite photograph indicated that the plume had not traveled as far south or east as our flight track. As a result, the main body of the plume was never encountered during this flight.

SATELLITE IMAGES OF SAMPLING REGION

1200Z SOUNDING DHAHRAN 09 AUG 91

Surface Chart
09 Aug 91 1200Z

850 Millibar Chart
09 Aug 91 1200Z

500 Millibar Chart
09 Aug 91 1200Z

Aircraft Flight Track
8/9/91 04:48:20 - 10:04:03

Kuwait Mission 06

8 / 9 / 1991

A.82

Kuwait Mission 06

8 / 9 / 1991

A.83

8 / 9 / 1991

Kuwait Mission 06

8 / 9 / 1991

Kuwait Mission 06

Submicron Size distribution 09 Aug 91 05:38 - 05:39

Submicron Size Distribution 09 Aug 91 09:23 - 09:24

Integrated Samples

a. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/9-1	0536	0600	1650	20.7	8.5	4.4	1.9	4.8	4.5	4.47	0.27
8/9-2*	0651	1738	1650	29.0	18.3	8.5	2.2	8.7	5.6	1.65	0.09
8/9-3*	0802	0911	3000	10.5	6.2	3.7	0.3	3.5	2.5	0.38	0.0
8/9-4*	0919	0943	3000-2200	26.5	12.0	5.1	4.7	4.2	4.6	2.81	0.0

b. Organic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Remarks	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/9-1*	0604	0623	1650	Background, very pale tan	15.46	0.88	12.37	17.50
8/9-4*	0919	0944	3000-2200	Plume edge, light grey	19.02	6.42	2.29	2.96

c. Canister Sample Analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
5	0834	0845	3000-2200	17.4	384

Surface Air Quality Measurements - 09 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	21 (7) 42 (15) 1000				156 257 1300
Dhahran	39 (14) 68 (24) 1100		53 (28) 143 (76) 0200	41 (21) 96 (50) 1200	144 293 2400
Rahimah	13 (5) 52 (18) 1000	4 (3) 6 (4) 0100-0500			
Tanajib	29 (10) 89 (31) 1000	4 (3) 10 (7) 2100	9 (5) 17 (9) 2200,2300		245 552 1900

FLIGHT 07: 11 AUGUST 1991

METEOROLOGICAL SUMMARY

At 1200 GMT, the surface chart showed a 989-mb low-pressure center over the mountains of southern Iran. Cyclonic flow around this low was producing north-westerly winds over and to the west of the Persian Gulf. The air quality monitoring stations reported wind speeds of 3 to 7 m/s during the G-1 flight period of 0454 to 0628 GMT. By midday, local time, the surface winds were becoming more northerly to northeasterly. Some blowing dust/sand was reported inland from Dhahran at 1200 GMT. The G-1 flight scientists reported hazy conditions and a surface temperature of 33°C at takeoff.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0500	0600	0700	0800	0900	1000
Abqaiq	WNW04	WNW05	NW 06	N 07	NNW07	N 08
Dhahran	NNW03	NW 03	NNW06	N 07	NNE06	N 05
Marjan GOSP1	WNW04	WNW04	NW 03	NW 03	NNW04	NW 03
Rahima Town	NW 05	NNW07	NNW07	N 06	NNE03	N 05
Safaniyah GOSP2	WNW07	WNW06	WNW06	WNW08	WNW10	NW 08
Tanajib	WNW03	WNW03	NW 04	NNW07	N 08	NNE07

The 1200 GMT 850-mb height contours reveal a small upper ridge located over western Saudi Arabia, and a small upper low to the east, over Iran. Air flow between these features was from the northwest, along the western shoreline of the Gulf (Dhahran reported 350° at 16 m/s). The air was very hot and dry at this level; a closed 35°C isotherm is shown over southern Saudi Arabia.

At 500 mb (1200 GMT), an upper trough extended southward from an upper low between the Black and Caspian Seas, to near the northern end of the Red Sea. A

wind maximum of 15 to 18 m/s was occurring over Syria and Iraq, but the gradient eased southward over Saudi Arabia, where winds of only 5 to 10 m/s were measured in the anticyclonic flow around an upper ridge that was over Saudi Arabia and Iran.

The Dhahran sounding for 0000 GMT shows a strong surface temperature inversion of about 5°C to 960 mb, then lapse conditions to about 470 mb. This inversion had been destroyed by surface heating by 1200 GMT, and surface temperatures at that time were 41.5°C. The persistent upper inversion was at about 470 to 430 mb. There was a gradual increase in moisture, starting at about 800 mb, that reached a maximum at 470 mb. Above 470 mb and below 800 mb, the air was very dry.

The satellite photo for 1200 GMT indicates that the plume was probably over water at the northern end of the Persian Gulf. It became visible as it crossed over the western shoreline at about 27°N, and was carried south-southwest from there. The G-1 observers reported being above the plume at 1500 m msl as they flew west at 27°N.

FLIGHT SUMMARY

The flight commenced at 0500 GMT. Skies were hazy, winds were light, and surface temperature was 33°C. The initial segment of the flight was made at an altitude of 1600 m and a heading of 340° from Bahrain. Concentrations were at background values during this segment of the flight. The aircraft turned to a heading of 270° at 26°55'N, 050°11'E. As we proceeded west, we encountered the eastern edge of the plume. For the most part, the plume was below our altitude (<1600 m). The western edge of the plume was found to be at 26°54'N, 048°34'E. On exiting the plume to the west, the altitude was decreased to 900 m and we proceeded to sample on an east-west track at 26°54'N for approximately half an hour. A generator failed on the left engine at 0630 GMT, and we returned to Bahrain.

SATELLITE IMAGES OF SAMPLING REGION

Temperature, deg. C
1200Z SOUNDING DHAHRAN 11 AUG 91

Surface Chart 11 Aug 91 1200Z

850 Millibar Chart
11 Aug 91 1200Z

500 Millibar Chart
11 Aug 91 1200Z

Aircraft Flight Track
8/11/91 04:54:28 - 06:28:12

Kuwait Mission 07

8 / 11 / 1991

A.97

8 / 11 / 1991

Kuwait Mission 07

86.V

Kuwait Mission 07

8 / 11 / 1991

66A

8 / 11 / 1991

Kuwait Mission 07

Submicron Size Distribution 11 Aug 91 05:43 - 05:44

Submicron Size Distribution 11 Aug 91 06:26 - 06:27

Integrated Samples

a. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/11-1	0537	0550	1650	56.5	43.3	17.8	27.5	12.4	8.9	28.1	0.20
8/11-2	0602	0629	900	47.2	16.4	10.6	2.3	9.2	4.5	9.05	0.16

b. Organic Filter Analysis

none

c. Cannister Sample Analysis

none

Surface Air Quality Measurements - 11 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	34 (12) 94 (33) 0800				444 785 0300
Dhahran	55 (19) 147 (51) 0900		47 (25) 88 (47) 2200	37 (19) 84 (43) 1400	461 694 0600,0700
Rahimah	24 (8) 55 (19) 0700	4 (3) 7 (5) 2200			
Tanajib	34 (12) 165 (58) 1200	4 (3) 7 (5) 1900	13 (7) 30 (16) 2100		235 535 0200

FLIGHT 08: 12 AUGUST 1991

METEOROLOGICAL SUMMARY

The surface chart for 1200 GMT shows a 992-mb low over the Salt Desert of Iran. A trough extended southward to link with low centers across the Great Sandy Desert (Ar Rub' al Khali) in southern Saudi Arabia. There is an indication of a dry, cool front just crossing the northern end of the Persian Gulf at 1200 GMT. Surface winds measured at the air quality sites were mostly from a northerly direction, with speeds of 3 to 6 m/s at the beginning of the flight, becoming more northeasterly at 3 to 5 m/s by 1400 GMT.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0900	1000	1100	1200	1300	1400
Abqaiq	N 06	N 06	N 06	N 06	N 06	NNE06
Dhahran	N 08	N 07	N 06	N 06	N 06	NNE05
Marjan GOSP1	W 05	WNW04	WNW04	NW 02	NW 01	NNW02
Rahima Town	NNW06	N 06	N 05	NNW05	N 05	N 03
Safaniyah GOSP2	NW 04	NNW05	NNW05	NNW04	N 04	NE 02
Tanajib	NNE05	NE 06	NE 05	NE 05	ENE04	ENE04

No 850-mb chart was collected for this day. The soundings at Dhahran showed the 850-mb temperatures to be about 31°C. Winds at 850 mb were northwesterly 13 m/s at both 0000 and 1200 GMT. A 500-mb trough at 1200 GMT extended southwest from eastern Turkey, across Syria, to the northern tip of the Red Sea. Over Saudi Arabia and Kuwait, winds at 500 mb were westerly 8 to 10 m/s; at 400 mb, winds were from the east and northeast at 4 to 5 m/s. As on August 11, the Dhahran sounding showed a strong surface inversion at 0000 GMT, but by 1200 GMT it had been replaced by a very hot, unstable layer to about 920 mb. Above that, a layer of increased stability was present to 750 mb, then lapse conditions prevailed up to the

seasonally permanent inversion between 490 and 450 mb. The air was dry throughout; the layer of least dryness was at about 500 mb. Meteorological resources did not include a satellite image for this day.

FLIGHT SUMMARY

Takeoff was at 1200 GMT. This mission started out as a test flight to check operation of aircraft systems following generator repair. Aircraft systems checked out and the flight became a sampling mission when we headed west just north of Bahrain, crossing the Saudi coastline at 26°55'N, 049°50'E. Westbound at about 1000 m altitude, we intercepted what appeared to be an extensive area of aged plume. Sampling continued in this area in a series of east-west transects for about an hour before returning to Bahrain where we landed at 1325 GMT.

Surface Chart
12 Aug 91 1200Z

500 Millibar Chart
12 Aug 91 1200Z

Aircraft Flight Track
8/12/91 12:01:12 - 13:24:32

8 / 12 / 1991

Kuwait Mission 08

8 / 12 / 1991

Kuwait Mission 08

8 / 12 / 1991

Kuwait Mission 08

Kuwait Mission 08

8 / 12 / 1991

A.113

Submicron Size Distribution 12 Aug 91 12:22 - 12:23

Submicron Size Distribution 12 Aug 91 12:38 - 12:39

Integrated Samples

a. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/12-1	1212	1312	1,300-600	26.4	8.3	4.5	1.21	5.5	4.5	6.32	0.52

b. Organic Filter Analysis

none

c. Canister Sample Analysis

none

Surface Air Quality Measurements - 12 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	24 (8) 63 (22) 0800,0900				206 350 0900
Dhahran	34 (12) 81 (28) 0700,2400		43 (23) 103 (55) 2300	37 (19) 75 (39) 1100,1500	226 326 2400
Rahimah	8 (3) 31 (11) 0700	3 (2) 7 (5) 2200			
Tanajib	45 (16) 134 (47) 1000,1100	4 (3) 7 (5) 1000	15 (8) 41 (22) 0700		250 307 2000

FLIGHT 09: 13 AUGUST 1991

METEOROLOGICAL SUMMARY

No surface chart was collected for this day. Surface winds at the four land-based air quality sites, which had been westerly 3 to 4 m/s from 0500 to 0700 GMT, shifted to a more northerly direction at 3 to 5 m/s for the 0800 to 1000 GMT period. No such shift occurred at the two sites located well out into the northern Persian Gulf (GOSP1 and GOSP2); there the winds remained west-northwest or west throughout the period. It is possible that some sort of surface trough feature was responsible for the wind shift, but the records of temperature, dew point, and pressure for 0500 to 1000 GMT show no interruption in trends of these parameters at any of the sites.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0500	0600	0700	0800	0900	1000
Abqaiq	W 04	WNW04	WNW03	N 03	NNW02	N 04
Dhahran	NW 02	NW 02	WNW02	NNW03	N 04	N 05
Marjan GOSP1	WNW03	WNW03	WNW02	WNW03	W 04	WNW04
Rahima Town	W 03	W 03	WNW03	NNW04	N 04	N 04
Safaniyah GOSP2	WSW05	W 05	W 04	W 04	W 4	WNW04
Tanajib	WNW03	WNW03	WNW02	NNW02	NNE04	NNE05

At 850 mb, the 0000 GMT chart portrays an upper trough extending west over Saudi Arabia and Iraq from a low over Pakistan and India. Cyclonic flow around this extension was producing northwest winds of 10 to 15 m/s over the Persian Gulf. Temperatures at 850 mb were slightly less than 30°C from the center of the Gulf westward, and >30°C to the east. The 0000 GMT 500-mb chart indicates a wind maximum of northwest 10 to 13 m/s over the Gulf region. However, in contrast to the 850-mb cyclonic flow, this was related to anticyclonic flow around a 500-mb high-pressure area that was located over Saudi Arabia.

The copies of the plots of the 0000 and 1200 GMT rawinsondes for this day were of very poor quality, and no coded reports are currently available to assist in interpreting the plots. Surface inversions to about 930 and 980 mb are evident for 0000 and 1200 GMT, respectively. The persistent stable layer between 500 and 450 mb was present. The air was dry throughout all layers.

The satellite images indicate that the smoke plume was being carried south-eastward over the Persian Gulf waters. The plume cannot be seen on the normal contrast image until it appears over land beyond the southern shore of the Gulf (over the United Arab Emirates and Oman). Reverse contrast photos of the satellite image, which show some shading over the water, confirm the over-water trajectory, as do the flight scientist's notes, which indicate that the aircraft was not in the main plume when it flew transverses west of the Gulf.

FLIGHT SUMMARY

The aircraft took off at 0500 GMT and headed northwest from Bahrain to a sampling location just south of Kuwait. In transit, multiple layers of what was apparently old plume were noted. When the Seleg intersection (28°N, 049°22'E) was reached, the aircraft turned west and continued at an altitude of 1350 m. Measurements were made during transects at 28°N between 048° and 048°50'E at altitudes of 450, 900, and 1350 m. Concentrations during this set of transects indicated that the main body of the plume was not being sampled. Upon completion of these transects, the aircraft flew south and sampled on an east-west track at 26°35'N between 048°25'E and 050°15'E. Again, it did not seem that the main body of the plume was being sampled. The aircraft landed at Bahrain at 0920 GMT. Review of the satellite imagery for this day revealed that the plume had been transported considerably east of our sampling location.

SATELLITE IMAGES OF SAMPLING REGION

Temperature, deg. C
1200Z SOUNDING DHAHRAN 13 AUG 91

850 Millibar Chart
13 Aug 91 0000Z

500 Millibar Chart
13 Aug 91 0000Z

Aircraft Flight Track
8/13/91 04:48:53 - 09:20:42

Kuwait Mission 09

8 / 13 / 1991

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Kuwait Mission 09

8 / 13 / 1991

Kuwait Mission 09

Kuwait Mission 09

8 / 13 / 1991

Submicron Size Distribution 13 Aug 91 06:03 - 06:04

Submicron Size Distribution 13 Aug 91 07:04 - 07:05

Surface Air Quality Measurements - 13 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	21 (7) 34 (12) 1800		21 (11) 64 (34) 0100		134 192 0100
Dhahran	45 (16) 68 (24) 2300		68 (36) 117 (62) 2300	27 (14) 100 (52) 1500	137 245 0100
Rahimah	5 (2) 26 (9) 1800, 1900	3 (2) 4 (3) 0100, 0200 2300			132 206 0200
Tanajib	21 (7) 63 (22) 1100	3 (2) 4 (3) 1900-2200	13 (7) 41 (22) 2100		134 180 2000

Integrated Samples

a. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/13-1*	0518	0541	900-1600	48.4	15.5	10.4	7.7	7.2	7.5	4.41	0.05
8/13-2*	0554	0614	1800-1600	38.1	15.2	7.3	4.5	5.3	4.3	10.9	0.13
8/13-3*	0623	0653	900	45.8	12.3	7.9	5.8	6.7	7.0	9.5	0.36
8/13-4*	0813	0904	1400	27.3	12.0	7.5	1.8	5.2	5.3	5.44	0.48

b. Organic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Remarks	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/13-1*	0518	0541	900-1600	Plume edge, med. grey	28.89	13.80	15.81	2.09
8/13-3	0623	0653	900	Dilute plume, med grey	33.78	26.77	18.97	1.26

c. Canister sample analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
7	0626	0637	900	45.2	339
8	0854	0904	1400	21.3	408

FLIGHT 10: 14 AUGUST 1991

METEOROLOGICAL SUMMARY

There is no surface chart in the meteorological data base for this day. The winds reported at the ARAMCO air quality sites show west to northwest winds 2 to 6 m/s from 0500 to 0700 GMT, then becoming generally more northwesterly or northerly, and increasing to 3 to 7 m/s from 0800 to 1000 GMT. At the Abqaiq site, winds were up to 8 to 9 m/s during the latter period.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0500	0600	0700	0800	0900	1000
Abqaiq	WNW04	W 05	WNW06	NW 08	NW 08	NNW09
Dhahran	NW 02	NW 02	NW 03	NW 04	N 05	N 06
Marjan GOSP1	WNW03	WNW02	NW 02	WNW03	WNW04	WNW04
Rahima Town	WNW03	WNW04	WNW04	NNW05	MISG	NNW06
Safaniyah GOSP2	W 06	W 05	WNW04	NNW04	N 04	NNW04
Tanajib	WNW03	NW 04	NW 05	NNW07	NNW07	N 05

The 0000 GMT chart for 850 mb shows an upper trough still extending westward over the Persian Gulf from a low center somewhere to the east of Iran. Cyclonic flow was producing north-northwesterly winds of 13 to 15 m/s over the western Gulf region. In this vicinity, the 850-mb temperature was 28°C.

At 700 mb (0000 GMT), similar winds were observed, but at 500 mb, though the direction was north-northwest, the speed was only 6 m/s. At 400 mb, the winds had shifted to a northeast direction and speeds were up to 10 m/s. An elliptical low dome of higher pressure at 500 mb was oriented east-west over the northern half of the Red Sea; winds at that level were a measure of the anti-cyclonic flow around that feature.

The plot for the 0000 GMT rawinsonde at Dhahran shows a strong but shallow surface inversion below 970 mb. By 1200 GMT, strong heating had wiped out the surface inversion and created a shallow superadiabatic layer at the surface, with lapse conditions above to 770 mb. The 0000 GMT sounding shows the customary stable layer above 500 mb, but by 1200 GMT the temperature structure showed less stability in this region than had been noted on previous mission days.

The satellite photo for 1230 GMT indicates that the smoke plume was streaming along the western shoreline of the Persian Gulf southward to the Gulf of Bahrain and Qatar, then continuing southward over Saudi Arabia from there to about 28°N, where it appeared to come under a more westerly flow. The flight scientists measured the top of the plume at 16,000 ft (4880 m) as the G-1 made east-west transects near 28°N at 1100, 1500, 2100, 2700, and 3700 m. They also reported that some plume flow to the east occurred over the northern Persian Gulf.

FLIGHT SUMMARY

Takeoff occurred at 0509 GMT under fairly clear skies. The aircraft headed northeast to the Ratun intersection just northeast of Bahrain over the Persian Gulf. Flight then proceeded north-northwest to the Seleg intersection (28°N, 049°24'E) at an altitude of 1000 m msl. Low levels of trace pollutants were found throughout the entire Ratun-Seleg flight. The aircraft headed westbound at the Seleg intersection and shortly thereafter encountered the plume. Filters were collected at an altitude of 1000 m from just west of the Seleg intersection to approximately 28°N, 048°28'E. Another filter set was collected at an altitude of 1450 m. It was apparent visually that the plume was moving south from Kuwait, then turning east over the northern part of the Gulf and heading toward Iran. Radio contact with Kuwait controllers revealed that winds in Kuwait were westerly; thus our sampling transects were probably on the southern edge of the east-moving plume. Additional transects were flown at altitudes of 2000, 2650, and 3600 m. Canister samples for VOC analysis were taken at 2000 and 3600 m.

Concentrations of trace species were higher at higher altitudes. There also appeared to be higher concentrations of NO_x than on previous flights. Plume top was found to be near 5100 m. We returned to Bahrain directly from Seleg and observed that the plume was moving more southerly over the Gulf, and closer to the Saudi Arabian coastline. The aircraft landed at Bahrain at 0913 GMT.

SATELLITE IMAGES OF SAMPLING REGION

1200Z SOUNDING DHAHRAN 14 AUG 91

850 Millibar Chart
14 Aug 91 0000Z

500 Millibar Chart
14 Aug 91 0000Z

Aircraft Flight Track
8/14/91 04:51:12 - 09:12:57

Kuwait Mission 10

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Kuwait Mission 10

Kuwait Mission 10

8 / 14 / 1991

8 / 14 / 1991

Kuwait Mission 10

Submicron Size Distribution 14 Aug 91 06:12 - 06:13

Submicron Size Distribution 14 Aug 91 07:24 - 07:25

Integrated samples

a. Organic filter analysis

Filter ID	Time On	Time Off	Alt. m	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/14-1	0536	0558	1000	21.80	9.25	23.67	2.36
8/14-2	0615	0633	1300	39.44	35.13	32.31	1.12
8/14-7	0821	0837	4100	89.64	102.34	20.85	0.88
8/14-8	0838	0900	5000	7.64	-0.72	0.00	-10.67

b. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/14-1*	0536	0558	1000	46.1	9.3	5.6	2.8	6.0	4.7	3.22	0.21
8/14-2*	0615	0633	1300	41.7	11.8	5.8	1.9	4.4	3.2	8.15	0.17
8/14-3*	0643	0709	2100	26.5	11.7	6.0	2.3	4.7	4.0	7.08	0.22
8/14-4*	0728	0740	2500	68.9	29.0	28.2	7.2	11.1	5.8	38.0	0.44

c. Canister analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
9	0643	0654	2100	48.2	482
10	0802	0813	3600	119	411

Surface Air Quality Measurements - 14 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	31(11) 86(30) 1900		28(15) 66(35) 0700,0800		178 336 1600
Dhahran	45(16) 84(29) 2400		58(31) 117(62) 2300	45(23) 106(55) 1300	166 350 0800
Rahimah	10(4) 47(16) 1100	1(1) 4(3) 0200			144 281 1300
Tanajib	18(6) 50(18) 1000,1500	3(2) 6(4) 1400	11(6) 40(21) 2100		113 216 0500

FLIGHT 11: 15 AUGUST 1991

METEOROLOGICAL SUMMARY

The surface chart for 1200 GMT shows that there was a 994-mb low covering the Great Sandy Desert of Saudi Arabia. A low-pressure trough from this low extended northwestward along the eastern shore of the Red Sea. A narrow ridge of higher pressure pushed east and southeast from Jordan into northern Saudi Arabia. At the ARAMCO air quality sites, the surface wind flow at the beginning of the mission (0654 GMT) was <5 m/s, mostly from the northwest quadrant. During the mission, slight increases in wind speeds to 5 to 7 m/s were measured at these sites, and wind directions at most sites veered with time to become more northerly or northeasterly. There were no reports at 1200 GMT of clouds or weather in the plume vicinity.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0600	0700	0800	0900	1000	1100
Abqaiq	NE 02	NNE03	N 04	NNE04	NNE06	NNE07
Dhahran	W 02	WNW02	NNW01	E 04	E 03	NE 02
Marjan GOSP1	NW 02	NW 02	NNW03	NNW02	NW 02	WNW03
Rahima Town	WSW01	N 01	NNE02	NNE03	ENE03	NE 03
Safaniyah GOSP2	W 05	W 05	W 05	WNW07	WNW06	NW 05
Tanajib	WNW03	NW 03	WNW03	NW 03	NNW04	N 05

At 1200 GMT, the 850-mb chart indicated a low centered over the Gulf of Oman and southern Persian Gulf. A low-pressure trough from the low extended west, then north to the Black Sea. The flow on the west side of this trough was producing west to northwest winds over Kuwait and the northern Persian Gulf. Farther south, toward Dhahran, the winds at 850 mb veered to the north and north-northeast at about 7 to 10 m/s. Temperatures at 850 mb (1200 GMT) were 28°C over the flight area, but >30°C over the Great Sandy Desert.

At 500 mb, the 1200 GMT chart shows that a ridge, elongated east-west, reached from eastern Africa nearly to India. To the north, an upper trough was approaching Kuwait and Dhahran from the west; however, both the 0000 and 1200 GMT rawinsondes from Dhahran show the atmosphere to be so dry at all levels that it is doubtful that any clouds or weather were associated with the trough during its passage in this region. The elongated ridge produced westerly flow of ~3 to 5 m/s over Kuwait, and east or northeast winds over Dhahran and southward.

The 0000 GMT sounding for Dhahran shows that there was a strong surface inversion to 970 mb. Above that, lapse conditions generally prevailed, except for a layer of increased stability between 500 and 470 mb. By 1200 GMT, the surface inversion had been destroyed by heating, but an upper-level inversion was present between 700 and 670 mb. The inversion or stable layer that had frequently been observed near 500 mb was present at 470 to 425 mb.

Satellite imagery for 1230 GMT shows the smoke plume from the Kuwait oil fields being carried right along the west coast of the upper Gulf to about Tanajib, then being borne more to the south-southwest to as far as ~28°N. Lat. Beyond there, it appears to have been carried more toward the southeast.

FLIGHT SUMMARY

Skies were basically clear with a light haze, winds were light from the east; surface temperature was 37°C. After takeoff at 0659 GMT, the aircraft headed northeast to the Ratun intersection at an altitude of 1000 m msl. Upon reaching Ratun (which is approximately 50 nm northeast of Bahrain), we proceeded on a northwest heading toward the Seleg intersection (28°N, 049°24'E) at an altitude of 1000 m. Concentrations of trace atmospheric constituents were all low between Ratun and Seleg. Upon reaching Seleg, we turned due west. Increasing trace concentrations were encountered as we approached the Saudi coast. The flight continued west to about 048°30'E, where we reversed course and headed back to the Seleg intersection. We flew east-west transects between Seleg and 048°30'E at altitudes of

1000 and 1450 m. On the last west-east transect, we climbed through the plume and determined that the top was at about 3900 m. Trace species concentrations were found to be higher at the higher altitudes, indicating occurrence of substantial plume lofting, probably from a previous day's emissions. After completing the transects close to the Kuwait border, we moved south and conducted east-west transects at 27°N and an altitude of 2300 m. We reversed course at 049°10'E and continued east to 049°37', where we then flew north to the Seleg intersection at 2000 m. We proceeded from the Seleg intersection to the Ratun intersection, and on to an 1113 GMT landing at Bahrain. It was later determined that the major portion of the plume had turned west about 500 km downwind of Kuwait, and that at least the second set of transects on this flight was not flown in the main body of the plume.

SATELLITE IMAGES OF SAMPLING REGION

Surface Chart
15 Aug 91 1200Z

850 Millibar Chart
15 Aug 91 1200Z

500 Millibar Chart
15 Aug 91 1200Z

Aircraft Flight Track
8/15/91 06:53:58 - 11:13:23

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Kuwait Mission 11

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Kuwait Mission 11

Submicron Size Distribution 15 Aug 91 07:25 - 07:26

Submicron Size Distribution 15 Aug 91 09:39 - 09:40

Integrated samples

a. Organic filter analysis

Filter ID	Time On	Time Off	Alt. m	Remarks	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/15-1	0722	0745	1000	Out of plume in haze, light tan	19.63	1.01	8.30	19.36
8/15-2	0754	0822	1000	In plume, medium grey	35.18	29.70	22.22	1.18
8/15-3	0828	0847	1450	In plume, medium grey	61.63	52.03	37.84	1.18
8/15-4	0935	0959	3000-2150	At upper extremity of plume, dark grey	44.58	30.45	24.53	1.46
8/15-5	1026	1056	2150	Probably in dilute plume, light grey	20.35	4.01	17.98	5.08

b. Inorganic filter analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/15-1*	0722	0745	1000	39.3	10.6	2.2	2.3	4.9	3.7	0.98	0.27
8/15-2*	0754	0822	1000	71.3	27.0	10.7	8.2	10.6	6.7	17.2	0.38
8/15-3*	0828	0847	1450	60.1	23.8	13.5	4.4	9.3	5.1	20.4	0.0
8/15-4*	0935	0959	3000 - 2150	36.1	17.7	7.9	2.0	6.4	4.4	9.33	0.24
8/15-5*	1026	1056	2150	29.2	8.7	3.0	1.0	3.3	3.1	0.65	0.05

c. Canister samples

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
11	0830	0841	1450	68.4	359

Surface Air Quality Measurements - 15 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	29(10) 71(25) 1000		17(9) 79(42) 2400		127 161 1100
Dhahran	47(16) 81(28) 1100		56(30) 109(58) 2400	65(34) 169(87) 1300	115 166 1200
Rahimah	8(3) 47(16) 1200	1(1) 4(3) 0700,0900			113 146 1300
Tanajib	39(14) 144(50) 1400	3(2) 4(3) 0800-1100 2000-2200	21(11) 56(30) 0700		185 240 0700

FLIGHT 12: 16 AUGUST 1991

METEOROLOGICAL SUMMARY

At the surface, at 1200 GMT, low pressure of 996 to 998 mb dominated the area from Iran to the Great Sandy Desert of Saudi Arabia. Surface winds from Kuwait to southern Saudi Arabia were northwest to north at about 5 m/s during the sampling mission. The ARAMCO air quality sites had winds generally from the northwest at 2 to 5 m/s. There was some veering of the wind to a more northerly or northeasterly direction at the three southern sites (Abqaiq, Dhahran, and Rahima Town). The 1200 GMT sounding at Dhahran measured winds east 5 m/s at the surface. Except for smoke reported near Kuwait, surface stations did not report any clouds or weather. On traverses west from Bahrain, the G-1 flight scientists reported sand and dust from the ground being lifted to the plume height of 4300 m.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0700	0800	0900	1000	1100	1200
Abqaiq	WNW04	NW 05	NW 04	NNW03	N 03	N 04
Dhahran	NW 04	NNW03	NNE02	NE 03	NE 04	NE 03
Marjan GOSP1	NNW02	NNW03	NW 02	NW 02	NW 02	NW 02
Rahima Town	NNW03	NNE03	NNE03	NNE03	NNE04	N 04
Safaniyah GOSP2	WNW06	WNW05	NW 05	NW 04	WNW05	WNW04
Tanajib	NNW04	NNW04	NNW05	NNW04	NNW04	NNW04

At 850 mb (1200 GMT), a long tongue of low pressure extended from a center somewhere over India all the way west to the Mediterranean Sea. The lowest heights, 1440 m, and the highest temperatures, 30°C, were over Iraq. The 850-mb winds over Kuwait and Saudi Arabia were northwesterly about 4 m/s, but farther to the north, over Iran and eastern Iraq, winds were southerly.

Wind flow at 700 mb was less well defined, but the major flow pattern over Kuwait and the western Gulf shoreline appears to have been from the west and southwest at about 5 m/s.

At 500 mb, there was a ridge of higher pressure extending northeast from Egypt to northern Saudi Arabia and Iraq, and into Iran. Over Kuwait and the northern Gulf there was a wind speed minimum. To the south there was considerable directional shear. Dhahran measured 070° at 7 m/s, while Qaisomah, to the northwest, had southwest winds of 5 m/s. Still farther south, over the Great Sandy Desert, there was a wind speed maximum with northeasterly winds to ~18 m/s.

The customary strong but shallow surface temperature inversion reached to about 955 mb at 0000 GMT at Dhahran; there was another shallow inversion from 720 to 700 mb, and a stable layer at 470 to 430 mb. By 1200 GMT, the surface layer to 970 mb was superadiabatic. Above, there were inversions at 760 to 740 and 500 to 490 mb. The wind profile at Dhahran showed considerable directional shear to 400 mb. Surface wind was 080°; at 850 mb, 340°; at 700 mb, 195°; and at 500 mb, 070°. Above 400 mb, the direction was from 100 to 120° with speeds 8 to 21 m/s.

The satellite photo for 1110 GMT shows a somewhat tattered-looking smoke plume from Kuwait, southward to about 23°N. Lat. In addition, the photo shows a dark, plume-like feature extending almost due north from Kuwait. Is it possible that a wind shift, or wind shear, of ~180° occurred near Kuwait on this day to carry the smoke as two plumes with different directions? At the surface, no directional shift of anything like that magnitude is shown at the northernmost air quality sites of Marjan GOSP1 and Tanajib. However, the 500-mb data, though sparse, do show southerly winds at Qaisomah, Saudi Arabia, and Kermanshah, Iran, while farther south at Dhahran the winds were northeast.

FLIGHT SUMMARY

The mission started at 0734 GMT in a sky that was cloud-free, but hazy at takeoff. Temperature was circa 38°C at the surface; winds were light from the north-northwest.

After taking off, the aircraft headed west-southwest toward Riyadh at an altitude of 1300 m msl. Upon reaching 48°E, 25°N, we climbed to about 2200 m and turned east. At this location, there appeared to be plume above and a sand-dust mix below. We intersected the plume, and then climbed to 2500 m, where concentrations of plume constituents seemed to be higher than below (e.g., SO₂, 4 to 20 ppb). We turned back to the west at 50°E, 25°N and climbed to 3100 m. The position of the turn did not represent the eastern boundary of the plume, but rather was made to avoid penetrating Qatar airspace. Upon reaching the western boundary of this transect (48°E, 25°N), we again turned eastbound and climbed to determine the upper boundary of the plume, which was at 4300 m. After locating the top of the plume, we descended to 2800 m and continued eastbound to 50°E, 25°N, then turned northeast to Bahrain where we landed at 1137 GMT. The plume during this flight appeared to be aged and elevated considerably above the surface. It was also obvious during the flight that sand/dirt from below was being advected up into the plume and being mixed with plume constituents. Filter samples were collected at altitudes of 2350 and 3000 m msl.

SATELLITE IMAGES OF SAMPLING REGION

1200Z SOUNDING DHAHRAN 16 AUG 91

Surface Chart
16 Aug 91 1200Z

850 Millibar Chart
16 Aug 91 1200Z

500 Millibar Chart
16 Aug 91 1200Z

Aircraft Flight Track
8/16/91 07:24:25 - 11:37:43

8 / 16 / 1991

Kuwait Mission 12

8 / 16 / 1991

Kuwait Mission 12

Kuwait Mission 12

8 / 16 / 1991

A.173

Kuwait Mission 12

8 / 16 / 1991

Submicron Size Distribution 16 Aug 91 09:00 - 09:01

Submicron Size Distribution 16 Aug 91 10:25 - 10:26

Integrated Sample Results.

a. Organic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Remarks	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	CO ₃ ⁼ $\mu\text{g}/\text{m}^3$	OC:EC
8/16-1	0855	0929	2350	In aged plume, dark grey	25.08	23.76	8.04	1.06

b. Inorganic Filter analysis

Filter ID	Time On	Time Off	Alt. m	Ca ⁺⁺ $\mu\text{g}/\text{m}^3$	Na ⁺ $\mu\text{g}/\text{m}^3$	Cl ⁻ $\mu\text{g}/\text{m}^3$	NH ₄ ⁺ ppbv	SO ₄ ⁼ ppbv	NO ₃ ⁻ ppbv	SO ₂ ppbv	HNO ₃ ppbv
8/16-1*	0855	0929	2350	42.3	17.2	10.0	3.6	7.1	5.9	10.2	0.33
8/16-2*	0941	1027	3000	20.1	8.1	4.5	0.7	3.8	3.1	5.95	0.20

c. Canister analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO ₂ ppm
12	0908	0915	2350	50.6	407
13	0942	0952	3000	40.5	397
14	1104	1114	9500	59.9	369

Surface Air Quality Measurements - 16 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	21 (7) 42 (15) 1900		15 (8) 38 (20) 2000		151 295 2300
Dhahran	50 (18) 81 (28) 1100,1200		47 (25) 92 (49) 0100	55 (28) 124 (64) 1400	166 324 2300
Rahimah	8 (3) 71 (25) 1200	1 (1) 3 (2) 0100,0200			187 324 2400
Tanajib	16 (6) 50 (18) 1000	4 (3) 6 (4) 1100,1800	15 (8) 49 (26) 2000		218 326 2100

FLIGHT 13: 17 AUGUST 1991

METEOROLOGICAL SUMMARY

There were no surface, 850-mb, or 500-mb charts available for this mission. The table below indicates that during the G-1 mission from 0718 to 1107 GMT, the surface winds at the ARAMCO air quality sites were from the west-northwest to north with speeds of 3 to 8 m/s. At the Tanajib site there were 2 hours of north-northeast winds, 6 to 7 m/s, but the mean direction was again north by 1100 GMT.

AMMNET MEAN HOURLY WINDS (m/s)

Station	GMT					
	0700	0800	0900	1000	1100	1200
Abqaiq	NW 06	NW 08	NNW08	N 07	N 06	N 07
Dhahran	NW 05	NNW06	NNW08	NNW08	N 08	N 08
Marjan GC SP1	NNW05	NNW04	NW 03	NW 03	NNW03	NW 04
Rahima Town	NW 08	NNW08	NNW08	NNW07	NNW07	N 06
Safaniyah GOSP2	WNW06	NW 06	NNW06	WNW06	NW 06	NNW06
Tanajib	NNW04	N 06	NNE06	NNE07	N 08	NNE07

At 0000 GMT, the Dhahran sounding indicates a strong, but shallow temperature inversion from the surface to 970 mb. The persistent high-level inversion was between 510 and 490 mb. At that level, an increase in moisture to 49% relative humidity was measured, but below that level the air was quite dry, with humidities of about 15%. Above 500 mb, the humidity was less than 10%. At 1200 GMT, all significant level rawinsonde data are missing from the data base. The mandatory levels do show that the surface inversion had been destroyed by heating, and that the heights of the constant-pressure surfaces had increased during the 12-hour period, some by as much as 20 to 30 m. The wind profiles at Dhahran for both 0000 and 1200 GMT show northwest to north-northwest winds up to 850 mb. Speeds increased with height from 4 to 10 m/s at 0000 GMT, and from 9 to 16 m/s at 1200 GMT. At 700 mb on both

soundings, however, the winds had come around to south and south-southeast, and speeds had decreased to 5 m/s or less. At 1200 GMT, this southerly flow was also present at 500 mb (195° at 5 m/s).

The G-1 flew west from Bahrain nearly along the 26° parallel. The flight scientist noted that most of the plume was above 1500 m. The top of the plume in that region varied from 3200 to 4500 m.

The satellite photo for 1100 GMT shows a dark plume streak from Kuwait southward. Near Kuwait, the plume appears to be over the waters of the northern Gulf. Southward from about 28°N., the plume appears as a dark shadow against the lighter-colored terrain. As noted on 16 August, there is also a dark feature directed toward the Caspian Sea from the northern tip of the Persian Gulf. One can speculate that portions of the plume at higher altitudes were being transported northward by a southerly flow at some height above 850 mb (~1500 m). Without additional data, though, it is not known whether the southerly winds observed at Dhahran above 850 mb were representative of the upper flow farther to the north.

FLIGHT SUMMARY

The flight commenced at 0730 GMT. Temperature at the surface was circa 36°C with light winds from the north. The aircraft headed almost due west of Bahrain to the Saudi coast at an altitude of 1450 m msl. The eastern edge of the plume was encountered at 26°17'N, 050°01'E. As the flight proceeded to the west, we were clearly in the region of the plume, but it appeared that most of the plume was above our flight altitude. The western edge of the plume was determined to be at 26°15'N, 048°38'E. The plume was sampled on subsequent passes at 2000 and 2650 m; during a final pass at 900 m, we were clearly below the main body of the plume. The height of the plume was observed to vary approximately with the plume optical density. Plume top was near 3500 m at the western edge of the plume, where the optical density was lowest, but was observed to increase to about 4500 m where the plume was most optically dense. Filter samples for inorganic analysis were collected at 1450

and 900 m. Samples for aerosol organic analysis were collected at 900, 1450, 2000, and 2650 m. Canister samples for VOC analysis were collected at 1450 and 2000 m.

SATELLITE IMAGES OF SAMPLING REGION

Temperature, deg. C

1200Z SOUNDING DHAHRAN 17 AUG 91

Aircraft Flight Track
8/17/91 07:18:00 - 11:06:40

8 / 17 / 1991

Kuwait Mission 13

Kuwait Mission 13

8 / 17 / 1991

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Kuwait Mission 13

Kuwait Mission 13

8 / 17 / 1991

Submicron Size Distribution 17 Aug 91 08:40 - 08:41

Submicron Size Distribution 17 Aug 91 09:33 - 0934

Integrated Samples

a. Organic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Remarks,	EC $\mu\text{g}/\text{m}^3$	OC $\mu\text{g}/\text{m}^3$	$\text{CO}_3^{=}$ $\mu\text{g}/\text{m}^3$	OC:EC
8/17-3	0904	0916	2000	In aged plume, light grey	77.08	77.27	37.69	1.00
8/17-5	1019	1053	900	Below plume, light grey/tan	21.91	14.28	55.62	1.53

b. Inorganic Filter Analysis

Filter ID	Time On	Time Off	Alt. m	Ca^{++} $\mu\text{g}/\text{m}^3$	Na^+ $\mu\text{g}/\text{m}^3$	Cl^- $\mu\text{g}/\text{m}^3$	NH_4^+ ppbv	$\text{SO}_4^{=}$ ppbv	NO_3^- ppbv	SO_2 ppbv	HNO_3 ppbv
8/17-1*	0754	0829	1450	68.7	28.6	20.4	9.2	9.1	9.0	22.7	0.72
8/17-2*	1019	1053	900	42.6	11.1	4.6	2.3	6.3	4.7	3.34	0.24

c. Canister Sample Analysis

Canister ID	Time On	Time Off	Alt. m	NMHC ppbC	CO_2 ppm
15	0753	0804	1450	34.3	382
16	0906	0916	2000	45.6	494

Surface Air Quality Measurements - 17 August 1991

Station	Concentration, ug/m ³ (ppbv)				
	SO ₂	H ₂ S	NO ₂	O ₃	PM ₁₀
	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	Daily mean Max. hour Time	daily mean Max. hour Time
Abqaiq	13 (5) 37 (13) 1400		13 (7) 32 (17) 2200		194 398 0300
Dhahran	34 (12) 84 (29) 1100		43 (23) 102 (54) 2200	49 (25) 98 (51) 1300	192 378 0300,0400
Rahimah	5 (2) 50 (18) 0900	3 (2) 7 (5) 0800			192 398 0300
Tanajib	29 (10) 181 (63) 1000	4 (3) 6 (4) 0900,1000	15 (8) 41 (22) 1900		132 317 1100

END

**DATE
FILMED**

5 / 12 / 93