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SIMULTANEOUS MEASUREMENTS OF OZONE OUTSIDE AND INSIDE CABINS OF TWO B-747 AIRLINERS AND A GATES LEARJET BUSINESS JET

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1. INTRODUCTION

Measurements of ozone concentrations in aircraft cabins are compared with simultaneous measurements of atmospheric ozone concentrations outside the aircraft. These comparisons are to better define the cabin ozone contamination problem. Recently, passengers and crew members on long-distance commercial flights have filed complaints after suffering symptoms of ozone sickness (Carley (1977), Flint (1978), and Carley (1978)). Ozone odors were detected by passengers shortly after commercial jet transports were placed in operation on regular flight schedules. Because the toxicity of ozone was recognized, the FAA sponsored a study conducted by Brabets (1963) to determine the frequency and concentration of ozone in commercial jet transports. Since then a number of authors (Brabets, et al. (1967), Bischof (1973), and Machta and Komhyr (1973)) have published data on ozone concentrations in aircraft cabins.

Ozone is formed predominately in the upper stratosphere near tropical regions and is transported poleward and to lower altitudes. At the cruise altitudes of subsonic jets, ozone concentrations increase with latitude above about 30° and altitude above the tropopause. In the Northern Hemisphere, ozone concentrations are highest during March and April and lowest during September and October.

No regulations are now in effect to limit ozone concentration in aircraft cabins. However, the Environmental Protection Agency's national, primary atmospheric-air-quality standard for photochemical oxidants is 80 parts per billion by volume (ppbv), with the maximum 1-hour concentration not to be exceeded more than once per year (Anon. (July 1977)). The FAA is considering issuing rules to revise aircraft design or operating procedures in order to prevent or reduce aircraft cabin ozone levels during high-altitude flight (Anon. (Oct. 1977)).

NASA instrumentation placed on B-747 airliners to measure constituents of the upper atmosphere, including ozone, helped to identify high atmospheric (outside) ozone concentrations as causing the reported physical discomfort. To better define the ozone problem in the cabin and the effectiveness of corrective actions, measurements of ozone in the cabin were made simultaneously with atmospheric measurements. Since atmospheric ozone concentrations can vary widely and rapidly during flight, these simultaneous measurements provide a better understanding of the variability of ozone concentrations in the cabin. Simultaneous measurements are also necessary to determine the reduction of ozone by the aircraft pressurization-ventilation systems.

The airliner problem with ozone prompted NASA to determine the ozone concentrations that might be encountered in the cabin of a small business jet. Accordingly, the NASA Gates Learjet was instrumented to measure simultaneously both atmospheric and cabin ozone concentrations.

The cabin ozone data presented in this paper were taken during the winter and spring. Measurements were made in cabins of greatly different volumes, the wide-body B-747 aircraft and the Gates Learjet business jet. Data for the B-747 were obtained during routine airline operation; six special flights were made to obtain data in the business jet. First, the B-747 airliner results are described, then the business jet results. Finally, these results are compared with reported measurements from other types of aircraft.

2. OZONE MEASUREMENT INSTRUMENTATION

2.1 Instrument Type

Ozone was measured on both aircraft by using ultraviolet absorption photometers with a range of 3 to 20 ppbv. This instrument works on the principle that ozone in the air passing through a specific length of tubing absorbs some of the ultraviolet light that is passed through the air sample. The instrument is described in more detail by Bowman and Horak (1972). To accurately measure small changes in the ultraviolet light absorbed by the ozone, the instrument compares the measurement with ozone-free or "zero" air that is obtained by passing the air sample through an ozone scrubber every measurement cycle (20 sec). Modifications had to be made to the commercial version of this instrument for airborne use and to meet airline specifications.

2.2 Calibration and Checks

The accuracy of the ozone measurements depends on a number of factors such as a basic calibration conducted periodically with a secondary standard, pressurization to 1 atm at altitude to maintain high sensitivity, in-flight instrument tests to ensure integrity of the measurements, and periodic system checks on the aircraft under simulated flight conditions to detect ozone losses in the air-sample flow lines and the pressurization pump. The secondary standard used for the basic calibration was a photometer similar to that used on the aircraft. It was calibrated against the long-path photometer at the Jet Propulsion Laboratory (De More and Patapoff (1976)). The estimated uncertainty of the instruments used in this flight investigation was ±3 percent, with a long-term repeatability within ±2 percent. In-flight tests include a zero gas reading, span setting of the electronics, and electronic signals that indicate the condition of the ultraviolet source and the presence of excessive contamination in the measurement system. Ozone losses in the aircraft flow system measured 8±5 percent of the indicated ozone concentration.

The cabin air sample was not separately pressurized before measurement since cabin pressure is only about 20 percent below atmospheric pressure. However, a positive correction was applied to the ozone reading for the cabin air density. Cabin pressure was measured along with the ozone concentration.

3. B-747 AIRLINERS

3.1 Equipment Installation

Ozone was measured on two B-747 airliners by equipment installed for the NASA Global Atmospheric Sampling Program (GASP). GASP was undertaken to measure atmospheric constituents related to aircraft engine exhaust emissions, including ozone (Perkins and Papathakos (1977)). The air sampling system is completely automated. Unattended operation provides continuous data acquisition during normal passenger service along established airline routes. Similar equipment was added to the GASP system to measure ozone in the cabin simultaneously with the normally acquired atmospheric measurements.

3.2 Location of Sample Air Inlets

The points where ozone was measured outside and inside the B-747 cabin are shown in figure 1. Air from outside the aircraft was sampled by a special external probe extending beyond the boundary layer near the nose of the aircraft. Air flowed in a 2.54-cm-diameter tube from the probe to the ozone instrument and associated equipment mounted on a special rack below the passenger deck at about station 360. Air from inside the aircraft was sampled at only one point in the cabin. Air was drawn from a 0.62-cm-diameter port about 1.5 m above the floor in the right outside wall of the staircase to the upper deck (left side of the right isle). A tetrafluorethylene (TFE) ring attached to the wall extended the inlet to the port about 0.62 cm from the wall surface (detail in fig. 1). This minimized drawing air from along the wall surface into the sample since ozone can be destroyed by contact with surfaces. About 6 m of 0.62-cm-diameter TFE-coated tubing was used between this port and the ozone analyzer on the GASP rack. The tubing was cleaned and found to cause negligible loss of ozone.

3.3 Data Acquisition

Ozone data were acquired on two airliners: a B-747-100, operated by United Airlines, that flies over the United States (coast to coast) and to Hawaii; and a B-747-SP (Special Performance), operated by Pan American World Airways, that frequently flies long nonstop routes such as that between New York and Tokyo.

During flight above 6 km (20000 ft) a data set is recorded every 5 min, or about every 72 km (45 miles). The time; the position of the aircraft; and its altitude, speed, and direction pinpoint each ozone measurement. Air temperature, horizontal wind direction and velocity, and turbulence as measured by vertical acceleration are also recorded.

Sample air from outside the aircraft is pressurized to 1 atmosphere before it enters the ozone instrument. This pressure and the cabin pressure are measured at the time of ozone measurement.

3.4 B-747 Airliners - Results and Discussion

Simultaneous measurements of atmospheric and cabin ozone were obtained from both B-747's at irregular intervals from March 1977 to the present and are expected to continue until March 1979.

A typical plot of simultaneous measurements of cabin and atmospheric ozone data taken during a B-747-100 flight is shown in figure 2. Some points to note from this plot are

(1) Atmospheric ozone concentrations vary widely during a flight.

(2) A constant difference, or ratio, between ozone concentrations outside and inside the cabin does not exist.

(3) The percentage of ozone retention in the cabin, that is, the percentage of atmospheric ozone that is measured in the cabin at any given time, increases as the flight progresses. A possible cause is passivation of ducting and cabin surface materials with ozone with time during a flight in high ozone concentrations. Toward the end of the flight the retention of ozone in the cabin air was about 43 percent of the atmospheric concentration; earlier in the flight the retention was about 32 percent. The percentage of retention was obtained by averaging simultaneous readings taken over a 1/2-hour period.

Comparisons of cabin ozone levels with atmospheric ozone mixing ratios.- Simultaneous measurements of ozone inside and outside the cabin show that an appreciable fraction of atmospheric ozone was not destroyed by the pressure-ventilation system. In the B-747-100 aircraft, when averaged over an entire flight, 38 percent of the atmospheric ozone was not destroyed before it entered the cabin and moved to the cabin sample air inlet. When the B-747-SP was first introduced into airline service, data showed that, on the average, 80 percent of the atmospheric ozone was not destroyed before it reached the cabin sample air inlet.

This high retention of atmospheric ozone in the cabin of the B-747-SP on the Pan Am routes prompted corrective actions to be taken to destroy ozone in air entering the cabin. One method of destroying ozone is to heat the inlet air to a higher temperature. This could be accomplished on the B-747-SP by taking bleed air for the cabin from the 15th stage of the engine compressor instead of from the lower temperature eighth compressor stage normally used. When this action was taken, ozone retention dropped to 19 percent, on the average, of the atmospheric ozone levels.

Since compressor bleed from high-pressure engine stages imposes a fuel penalty, other methods of ozone destruction were implemented. Providing greater recirculation in the cabin reduced ozone retention to 58 percent of atmospheric, on the average, without any other corrective actions to reduce ozone. Providing charcoal filters in the inlet air ducts reduced ozone retention to only 5 percent of atmospheric. The long-term life and effectiveness of these filters was not evaluated. These results are given in table I and shown graphically in figure 3.

Atmospheric encounter statistics.- Atmospheric ozone measurements from GASP-equipped airliners can establish the susceptibility of these aircraft to high cabin ozone concentrations. In GASP, atmospheric ozone measurements are much more extensive than cabin measurements. A full year of data showed ozone levels to be highest in the spring in northern latitudes (Belmont, et al. (1978)). Measurements from the North American ozonesonde network (Hering and Borden (1965)) show similar results. Comparing ozone encounters for the two B-747 aircraft during the 1-year period revealed that the B-747-SP encountered higher atmospheric ozone levels than did the B-747-100 aircraft. This can be explained by the combined higher altitude operations and higher latitude routes of the SP during this period.

4. GATES LEARJET BUSINESS JET

4.1 Equipment Installation

The experimental equipment was installed in the Gates Learjet Model 23 based at NASA Ames Research Center, Moffett Field, California.

Atmospheric air entered a 2.5-cm-diameter sampling probe and was pressurized with a single-stage diaphragm pump. A pressure regulator system described by Reck, et al. (1974) was used to maintain a pressure of 1 atm at the inlet to the atmospheric ozone measuring instrument. Downstream of each instrument, a needle valve was used to set the instrument flow rate. The inlet sample pressure to the ozone instruments was independent of aircraft altitude and cabin pressure. The instrument sample flow was not required to pass directly through the regulator upstream of the instrument in order to minimize ozone destruction. The discharge flow was exhausted overboard through a static exhaust probe.

Cabin sample air was ducted to the cabin ozone measuring instrument through 3 m of 0.95-cm-diameter TFE tubing. During flight, this tubing was used to sample ozone at various locations in the cabin. The difference between cabin pressure and atmospheric static pressure was used to drive a sample through the cabin ozone measuring instrument. A 0.079-cm-diameter orifice and a 0.066-cm-diameter venturi were used downstream of the instrument to establish a sample flow rate. Pressure transducers were located near the inlets of both instruments so that the output data could be corrected to 1-atm pressure. A zero check on both instruments could be made by activating two three-way solenoid valves that would direct a pressurized air sample scrubbed of ozone through both instruments.

TFE tubing was used to interconnect the sample probe, the pressure regulators, and the ozone measuring instruments. Because of the compatibility of TFE with ozone, all components contacting the sample flow upstream of the instruments were either fabricated from TFE or coated with TFE whenever possible. The synthetic-rubber sample pump diaphragm was covered with a sheet of TFE-coated fiberglass mesh, and the internal flow surfaces were TFE coated. The inlet system and the pump were tested for ozone losses in the laboratory. Ozone concentration data reported herein have been corrected for these losses, which were 8.6 percent of the incoming ozone concentration. Output signals from the two ozone instruments were connected to a dual-channel strip-chart recorder.

The pump, the regulators, and the two ozone measuring instruments were mounted in the luggage compartment of the aircraft. The pressure transducers, the zero gas scrubbers, the strip-chart recorder, the pressure transducer readouts, and the three-way solenoid valves were mounted on a special equipment rack, behind the copilot's seat, designed for experiments on the Gates Learjet. The gas sample probe was mounted in the emergency hatch on the left side of the airplane.

4.2 Gates Learjet - Results and Discussion

The installation was flown on six test flights, for a total of approximately 15 flight hours. Results of a typical data flight are shown in figure 4, where ozone concentrations are plotted against universal time. Because the data are plotted at 2.5-min intervals even though the ozone measuring instruments update every 20 sec, fine variations in ozone concentration do not appear on the figure.

Table II gives the percentage of retention for the flights. The percentage of retention was computed for each flight from a linear regression analysis forced through zero of all the data points. Also given in table II is the standard deviation of the ozone retention for each flight. Note that two configurations are referred to in table II. In the first configuration, no equipment unnecessary to the experiment was carried in the cabin. The cabin contained only the pilot, the copilot, the experimental equipment, and one experimenter. The average ozone retention for this configuration was 63 percent. In the second configuration, the cabin also contained numerous pieces of luggage, aircraft spare parts, ground support equipment, and a passenger. The average ozone retention for this configuration was 42 percent.

In all flights, cabin ozone concentration generally followed the trend in atmospheric ozone concentration. However, the changes in cabin ozone concentration lagged the changes in atmospheric ozone concentration. This lag is related to the cabin pressurization-ventilation system's air exchange rate, which is estimated to be 2.5 min. If the cabin ventilation system is considered as a first-order system from a time-response point of view, the 2.5 min can be taken as the time constant for this system. Thus, 2.5 min would be required for the cabin to reach 63 percent of its final concentration level when responding to a step change in atmospheric ozone concentration.

The lag in cabin ozone concentration relative to atmospheric ozone concentration can be seen in figure 4. For example, at 16:15 the atmospheric ozone concentration began to decrease and at 16:25 reached a minimum of 96 ppbv. During the same period the cabin ozone concentration decreased from 340 ppbv to 105 ppbv. The rate of decrease in cabin concentration was considerably less than the rate of decrease in atmospheric concentration. At 16:25, the cabin concentration was greater than the atmospheric concentration. When the atmospheric concentration changed slowly, the cabin concentration followed reasonably well; but the cabin concentration did not respond as well when the atmospheric concentration fluctuated rapidly. It is therefore difficult to exactly define ozone retention in the cabin when the atmospheric concentration is changing rapidly. Ozone retention in the cabin computed for all the data taken during one flight was 75 percent. Peak concentrations were 474 ppbv of atmospheric ozone and 340 ppbv of cabin ozone. Cruising altitude for the flight was 13.1 km.

During two other flights, data were taken adjacent to the conditioned-air outlet in the cabin. It quickly became apparent that only a relatively small percentage of the ozone going into the cabin pressurization-ventilation systems was destroyed before reaching the cabin. Most of the atmospheric ozone destruction occurred within the cabin and not within the pressurization-ventilation systems.

An analysis of the data from the strip-chart recorder for flight 2 indicated that it took an average of 54 seconds for a step change in atmospheric ozone concentration to become apparent in the cabin. In all cases the rate of change in cabin ozone concentration was considerably less than the rate of change in atmospheric ozone concentration.

5. COMPARISON WITH OTHER AIRCRAFT

5.1 Air Exchange Rates

According to data from the aircraft manufacturer, the time for a complete air exchange in the Gates Learjet cabin is 2.5 min. For the B-747-100 and the B-747-SP the times for a complete air exchange are 3.4 and 2.3 min, respectively. These rates are roughly comparable to air exchange rates of 2 to 3 min for large narrow-body aircraft in the commercial fleet studied by Brabets, et al. (1967). One method suggested to reduce cabin ozone concentration is to reduce the ventilation and circulation rates. There are no regulatory standards for ventilation rates in aircraft passenger cabins.

5.2 Ozone Measurements

Reck, et al. (1974) give a limited amount of cabin and atmospheric ozone concentration data for a Convair 990 aircraft. For 23 data points, the ozone retention varied from 41 percent to 59 percent, with an average of 50 percent. These rates must be adjusted downward somewhat because the atmospheric ozone concentration data were not corrected for losses in the pressurization system. When these losses were taken into account, the ozone retention was 44 percent. The average atmospheric ozone concentration was rather low (85 ppbv).

The same aircraft was investigated by Machta and Komhyr (1973), who found that there was a 10-percent reduction in atmospheric ozone concentration when a sample was measured near a conditioned-air outlet. No direct comparison was made between atmospheric and cabin ozone concentrations.

Bischof (1973) found that cabin air at some distance from the conditioned-air outlets showed an ozone concentration about half that of the entering air. He made no direct measurements of atmospheric ozone concentration but concluded that very little ozone was destroyed in the pressurization system. Aircraft tested were DC-8's, DC-9's, and a B-747.

The aircraft investigated by Brabets, et al. (1967) were not identified but are assumed to be B-707's, B-720's, B-727's, and DC-8's. In that investigation there were no direct measurements of atmospheric ozone concentration. It was concluded that there was no significant difference in the ozone destruction efficiency of the various types of aircraft. The authors made no estimate of what the ozone destruction rates were for the various aircraft.

6. SUMMARY OF RESULTS

Simultaneous measurements of atmospheric ozone levels and ozone levels in the cabins of jet aircraft were necessary because of the wide and rapid variability of atmospheric ozone in flight. Such measurements provide a better understanding of the variability of ozone in the cabin and the attenuation of ozone in the aircraft pressurization-ventilation systems.

6.1 B-747 Airliner

Boeing 747 aircraft equipped with two ozone measuring instruments provided the following results:

1. Cabin ozone measurements expressed as an average percentage of the atmospheric

concentrations were

a. B-747-100 - 38 percent

b. B-747-SP, with no corrective actions, 80 percent

c. B-747-SP, with changes in cabin ventilation system, 58 percent

d. B-747-SP, with high-temperature 15th-stage compressor bleed, 19 percent

e. B-747-SP, with cabin air filtered through charcoal, 5 percent (long-term life of filter not evaluated)

2. The charcoal filter was the most effective way of removing ozone from the cabin.

3. Atmospheric ozone measurements taken for 1 year to establish the probability of these airliners encountering high levels of cabin ozone showed the following results:

a. The probability of high ozone encounters varied substantially with the season. The highest ozone levels were encountered in the spring in the Northern Hemisphere.

b. The B-747-SP encountered higher ozone levels than did the B-747-100, most likely because of the higher operating altitudes of the SP. Routing may be a significant factor also since, during ozone data taking from the SP, the aircraft was operated predominately on long flights at northern latitudes.

6.2 Gates Learjet

A Gates Learjet business jet equipped with ozone measuring instrumentation provided the following results:

1. The average amount of atmospheric ozone retained in the Gates Learjet cabin when the surface area was relatively low (one passenger, two crew members, and ozone measuring equipment) was 60 percent.

2. When the surface area in the cabin was relatively high (two passengers, two crew members, and additional equipment and baggage), the average amount of atmospheric ozone retained in the cabin was 47 percent.

3. Ozone measured near the conditioned-air inlet to the cabin was reduced only slightly from the atmospheric ozone concentration.

4. The amount of atmospheric ozone retained within the Gates Learjet cabin in this study was consistent with results obtained by other investigators in other aircraft types.

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TABLE I. - CORRELATION BETWEEN ATMOSPHERIC AND CABIN OZONE LEVELS FOR B-747 AIRLINERS
(Selective sample flights with and without ozone destruction techniques used in cabin air system)

Aircraft type	Added technique for reducing ozone	Ozone retention in cabin, percent of atmospheric level	Standard deviation, percent
B-747-100	None	38	1.06
B-747-SP	None	80	1.32
	Modified cabin air circulation	58	2.22
	15th-stage compressor bleed	19	0.93
	Charcoal filter	5	0.52

TABLE II. - CORRELATION BETWEEN ATMOSPHERIC AND CABIN OZONE LEVELS FOR GATES LEARJET

Flight	Aircraft cabin configuration	Ozone retention in cabin, percent of atmospheric level	Standard deviation, percent
1	Relatively empty	75	3.34
2		65	3.50
3		61	3.97
4		52	4.06
	Average	63	
5	Relatively full	43	5.42
6	Relatively full	41	3.34
	Average	42	

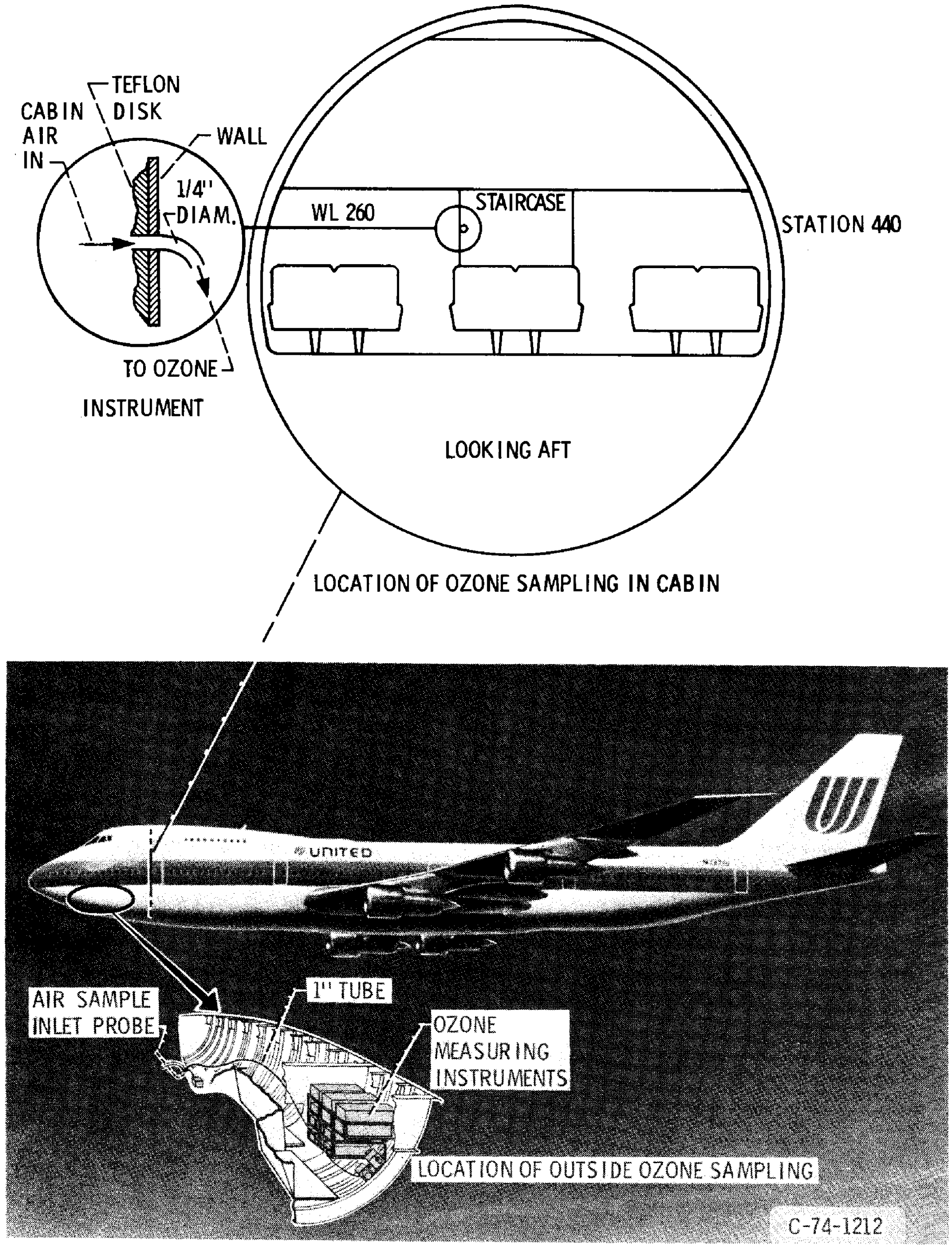

Figure 1. - Ozone measurement locations on B747 airliner.

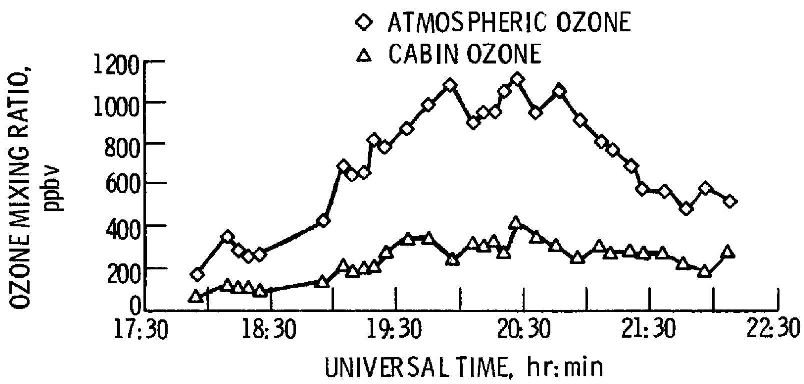

Figure 2. Time history of ambient and cabin ozone levels for B747-100 airliner flying from New York to San Francisco on April 3, 1977

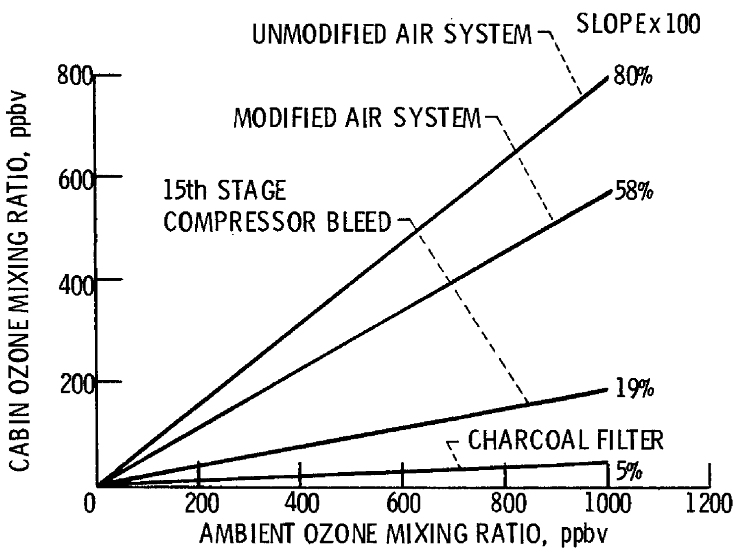

Figure 3. Comparison of cabin and ambient ozone mixing ratios for the B747 SP aircraft showing the results of three techniques for reducing ozone in the cabin

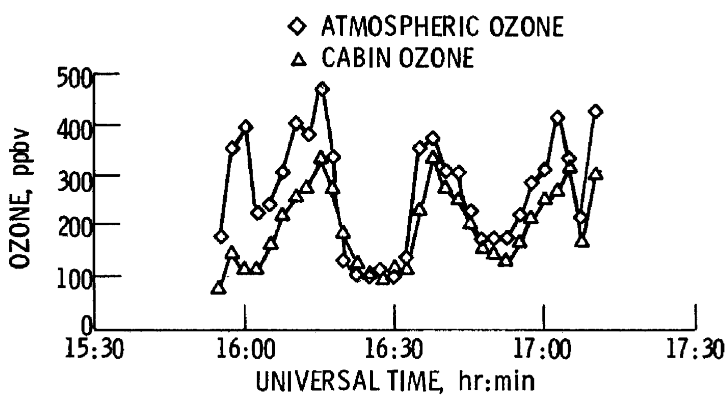

Figure 4. Comparison of ambient and cabin ozone for Flight 1, flight level 430 (13.1 km)

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15. Supplementary Notes

16. Abstract

This paper compares cabin ozone concentration measurements with simultaneous measurements of atmospheric ozone concentrations outside the aircraft. Since atmospheric ozone concentrations can vary widely and rapidly during flight, these simultaneous measurements provide a better understanding of the variability of ozone in the cabin. A constant difference, or ratio, between ozone concentrations inside and outside the cabin does not exist. The average amount of ozone measured in the cabins of two B-747 airliners varied from 40 percent to 80 percent of the atmospheric concentrations without special ozone destruction systems. A charcoal filter in the cabin air inlet system of one B-747 reduced the ozone to about 5 percent of the atmospheric concentration. A Gates Learjet Model 23 was also instrumented with monitors to measure simultaneously the atmospheric and ozone concentrations. Results indicate that a significant portion of the atmospheric ozone is not destroyed in the pressurization system and remains in the aircraft cabin of the Learjet. For the two cabin configurations tested, the ozone retentions were 63 and 41 percent of the atmospheric ozone concentrations. Ozone concentrations measured in the cabin near the conditioned-air outlets were reduced only slightly from the atmospheric ozone concentrations.

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