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and Space Administration

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SUMMARY

A Gates Learjet Model 23 was instrumented with monitors to measure simultaneously the atmospheric and cabin concentrations of ozone at altitudes up to 13 kilometers. Six data flights were flown in February 1978.

Four flights were made with the cabin relatively empty except for the pilot, copilot, experimental equipment, and one experimenter. Cabin ozone concentrations varied from 52 to 75 percent of the atmospheric ozone level at various areas around the cabin. It took 54 seconds for a step change in atmospheric ozone concentration to begin to be reflected in the cabin ozone concentration.

Two data flights were made with the aircraft loaded to a greater extent than on the other four flights: It carried an additional passenger, numerous pieces of luggage, and some aircraft spare parts and ground-support equipment. In this configuration the measured cabin ozone concentration varied from 41 to 43 percent of the atmospheric ozone level. The probable reason for the increased ozone destruction was the larger amount of surface area in the cabin. Because ozone is an unstable gas, it tends to be destroyed on surfaces with which it becomes in contact.

The ozone concentration measured near the cabin ventilation system outlets was only slightly reduced from the atmospheric ozone concentration. Peak ozone concentration measured in the cabin was 410 ppbv.

INTRODUCTION

Recently, passengers and crew members on long distance commercial flights have filed complaints after suffering symptoms of ozone sickness (refs. 1 to 4). No regulations are now in effect to limit ozone concentration in aircraft cabins. However, the Environmental Protection Agency's national primary ambient air quality standard for photochemical oxidants has been set at 80 ppbv, which is the maximum 1-hour average concentration which is not to be exceeded more than once per year (ref. 5). The FAA has issued an advanced notice of proposed rules indicating the possibility of revising aircraft design or operating procedures to reduce aircraft cabin ozone levels during high altitude flight (ref. 6). There is considerable interest, therefore, in what ozone concentration might be encountered in the cabin of a small business jet since there has been no published information on cabin ozone concentration in this type of aircraft. Accordingly the NASA Ames Research Center Gates Learjet was instrumented with two ozone

monitors, one to measure atmospheric ozone concentration and one to measure cabin ozone concentration.

Ozone odors were detected by passengers shortly after commercial jets transports were placed in operation on regular flight schedules. Because the toxicity of ozone was recognized, the FAA in 1961 sponsored a study (ref. 7) to determine the frequency and the concentration of ozone in commercial jet transports. Since, then, a number of reports have been published on ozone concentration in aircraft cabins (refs. 8 to 10).

Ozone is formed in the stratosphere (between 20 and 40 kms) as a result of photochemical processes due to ultraviolet radiation from the sun. Above the tropopause the concentration rapidly increases with a maximum usually found at altitudes between 15 and 30 kilometers, depending on the season and latitude. In the Northern Hemisphere a maximum occurs at high latitudes and in the spring of the year. Ozone is transported from the altitudes at which it is formed to the lower cruising altitudes of subsonic jets by tropopause folding and cyclogenesis (ref. 11). At the cruising levels of jet transports, the ozone concentrations are predominantly related to the height of the tropopause.

Ozone enters aircraft cabins when atmospheric air is drawn into the aircraft through the air-circulation system. Because ozone is an unstable gas, a portion is dissociated and converted into molecular oxygen as it is being compressed, heated, and drawn through the ventilation ducts. The purpose of the Gates Learjet flight tests was to establish the relation between atmospheric ozone concentration and the ozone concentration measured in the cabin of a Gates Learjet.

EXPERIMENTAL EQUIPMENT

The experimental equipment was installed in the Gates Learjet Model 23 based at NASA Ames Research Center in Moffett Field, California (fig. 1). A schematic drawing of the experimental equipment is shown in figure 2. Atmospheric air enters a 2.5-centimeter-diameter sampling probe and is pressurized with a single-stage diaphragm pump. A pressure regulator system described in reference 12 is used to maintain a pressure of 1 atmosphere (101 kPa) at the inlet to the atmospheric ozone measurement instrument. A back-pressure regulator controls the inlet manifold pressure. An absolute pressure regulator, which contains a sealed, evacuated bellows reference cell supplies a constant reference pressure to the dome of the back pressure regulator. Downstream of each instrument, a needle valve is used to set the instrument flow rate. The inlet sample pressure to the ozone instruments is independent of pressure altitude and cabin altitude. The instrument sample flow is not required to pass directly through the regulator upstream of the instrument, thus minimizing ozone destruction. The discharge flow is exhausted overboard through a static exhaust probe.

Cabin sample air is ducted to the cabin ozone measuring instrument through 3 meters of 0.95-centimeter-diameter tetrafluoroethylene (TFE) tubing. During flight, this tubing was used to sample the air at various locations in the cabin. The difference between cabin pressure and ambient static pressure was used to drive a sample through the cabin ozone measuring instrument. A 0.079-centimeter-diameter orifice and a 0.066-centimeter-diameter venturi were used downstream of the instrument to establish a sample flow rate. Pressure transducers were located near the inlet of both instruments so that the output data could be corrected to 1 atmosphere (101 kPa of pressure). A zero check on both instruments could be made by activating two three-way solenoid valves which would direct a pressurized air sample scrubbed of ozone through both instruments.

TFE tubing was used to interconnect the sample probe, pressure regulators, and ozone measuring instruments. Because of the compatibility of TFE with ozone, all components contacting the sample flow upstream of the instruments were either made of TFE or were 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 pump were tested for ozone losses in the laboratory. Ozone concentration data reported herein were corrected for these losses, which were 8.6 percent of the incoming ozone concentration.

The ozone measuring instruments use an ultraviolet absorption measurement technique. The instrument alternately passes the sample gas and an ozone-free zero gas (obtained by passing sample gas through an ozone destruction catalytic filter) through a 71-centimeter-long tube and measures the difference in intensity of an ultraviolet beam traversing the same path length. The difference is converted into ozone concentration. These measurement techniques will automatically compensate for variations in the optical components, interfering gases, and variations in the ultraviolet source. An updated concentration signal is received from the instrument every 20 seconds. Output signals from the two ozone instruments were connected to a dual-channel, strip-chart recorder. More details about the instrument can be found in reference 13.

Photographs of the installation are shown in figure 3. The pump, regulators, and the two ozone-measuring instruments were mounted in the luggage compartment of the aircraft (fig. 3(a)). The pressure transducers, zero gas scrubber, strip-chart recorder, pressure transducer readouts, and three-way solenoid valves were mounted on a special rack designed for experimental equipment on the Gates Learjet. This rack was located behind the copilot's seat (fig. 3(b)). The gas sample probe was mounted in the emergency hatch on the left side of the airplane (figs. 3(c) and (d)).

RESULTS AND DISCUSSION

Flight Test Data

The six Gates Learjet test flights are listed in table I. Approximately 15 flight hours were flown during the experiment. Figure 4 shows the flight path. Results of the data flights are plotted in figure 5. Ozone concentrations are plotted against universal time with data points spaced at 2.5-minute intervals for the duration of the flights. Because of this plotting interval, even though the ozone measuring instruments update every 20 seconds, a certain amount of ozone-concentration fine structure does not appear in the figures. Table II gives the average and standard deviations for atmospheric ozone and the cabin ozone concentration for each data flight. Also given is the retention, which is the percentage of atmospheric ozone measured in the cabin at any given time. The retention was computed for each flight from a linear regression analysis forced through zero of all the data points plotted in figure 5.

Note that two configurations are referred to in table II. In configuration A no equipment unnecessary to the experiment was carried in the cabin. In this configuration the cabin contained only the pilot, copilot, experimental equipment and one experimenter. In addition to the items carried in configuration A, configuration B contained numerous pieces of luggage, aircraft spare parts, ground-support equipment, and a passenger. These extra items were carried onboard the airplane for the flight from Cleveland, Ohio, to Moffett Field, California.

In all flights cabin ozone concentration in general follows the trend in the atmospheric ozone concentration. However, the changes in cabin ozone concentration lag the changes in atmospheric ozone concentration. This lag is related to the cabin pressurization and ventilation systems air-exchange rate, which is estimated to be 2.5 minutes. If the ventilation system is considered as a first-order system from a time response point of view, the 2.5 minutes can be taken as the time constant for this system. Thus, 2.5 minutes 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.

Results of flight 1 are plotted in figure 5(a). The lag in the ozone concentration in the cabin can be seen in this figure. For example, at 16:15 the atmospheric ozone concentration begin to decrease until 16:25, when the concentration reached a minimum of 96 ppbv. During this period the cabin ozone concentration decreased from 340 to 105 ppbv. The rate of this decrease was considerably less than the rate of decrease in the atmosphere. At 16:25 the ozone concentration in the cabin is greater than that in the atmosphere.

When atmospheric ozone concentration is changing slowly, cabin concentration follows reasonably well, but not as well when the change is rapidly up or down. It is, therefore, difficult to exactly define the retention of ozone in the cabin when the atmo-

spheric concentration is changing rapidly. The retention of ozone in the cabin computed for all the data taken during the flight is 75 percent. Peak concentrations were 474 ppbv in the atmosphere and 340 ppbv in the cabin. Cruising altitude for the flight was 13.1 kilometers.

During flight 2 (fig. 5(b)) ozone concentrations were higher than during the previous flight, and there were large fluctuations. As before, a rapid change in the atmospheric ozone concentration results in a change in the cabin concentration but at a less rapid rate. Some of the fluctuations that appear in the atmosphere are dampened out in the cabin. For example, although at 19:25 there was a sharp decrease in ozone in the atmosphere (from 256 to 78 ppbv in 2.5 min), the cabin curve shows a steady increase from 114 ppbv at 19:20 to 280 ppbv at 19:30. It is also apparent that there are large inhomogeneities in the atmospheric ozone concentration as the airplane climbed to cruise altitude or decended. Peaks in concentration were encountered at 19:10 and 19:15 during the climb to 13.1 kilometers and during the descent at 20:45. This indicates that there is not a steady increase in ozone concentration with altitude. Ozone exists in layers of relatively high or low concentrations. The peak atmospheric concentration was 640 ppbv at 19:35. The highest ozone concentration in the cabin was 410 ppbv, which occurred at 19:45. Standard deviations for atmospheric and ozone concentrations in the atmosphere and in the cabin were 150 and 95 ppbv, respectively, and indicate large inherent variability in the concentrations. Average retention was 65 percent.

During flight 3 (fig. 5(c)) ozone concentrations were low, exceeding 200 ppbv in the atmosphere on only three occasions. Throughout the flight, the ozone concentration in the cabin remained relatively steady. Ozone peaks were again recorded during the climb to 13.1 kilometers and during the descent. Average concentrations were 147 and 96 ppbv in the atmosphere and cabin, respectively. The standard deviation for the cabin ozone concentration as expressed as a percent of the average concentration was the lowest for all the flights, that is, 23 percent.

During flight 4 (fig. 5(d)) peak atmospheric ozone concentration was recorded during the climb to 13.1 kilometers at 9.4 kilometers. From 20:17 to 20:40 the altitude ranged from 11.8 to 13.1 kilometers. Since both the atmospheric and cabin concentrations were relatively low during this time, it was decided to reduce the cruise altitude to 11.3 kilometers to try to get into the higher ozone concentrations encountered during the climb. Higher concentrations were again found at the lower altitude as can be seen in figure 5(d). The average cabin concentration of ozone was 101 ppbv, and the average retention was 52 percent.

Only 45 minutes of data were recorded during flight 5 (fig. 5(e)) because of the failures of two inverters in the aircraft experiment power system. In this and flight 6 the cabin was in configuration B, in which an additional passenger, numerous pieces of luggage, aircraft spare parts, and ground-support equipment were in the cabin. Ozone retention for this flight was only 41 percent. This lower retention rate was probably

caused by the greater surface area in the cabin. The greater surface area served as sites for ozone dissociation. The tailed symbols on figure 5(e) indicate cabin data taken with the sampling inlet placed near the conditioned-air outlet. Figure 6 shows the ozone sample system inlet next to the conditioned-air outlet along the cabin floor. The first five of the six data points for the cabin exceeded those for the atmosphere, probably because the pressure-ventilation system was slow in responding to the changing atmospheric ozone concentrations. The pressure-ventilation system had a slower response because of the 2.5 minutes required for a complete change of cabin air.

Figure 5(f) shows the data from flight 6, which was also cabin configuration B. Relatively high atmospheric concentrations were encountered both at 12.5- and 13.1- kilometer altitudes, with peaks at 890 ppbv for both altitudes. Three data points were recorded again with the cabin air sample inlet tube adjacent to the conditioned-air outlet. The average retention was 41 percent, excluding the ventilation-system samples. The average ozone concentration in the cabin was 194 ppbv. Because of the problems with the experiment power system during flight 6, insufficient power was available to run the sample pressurization pump. The data were corrected for the reduced operating pressure. It is apparent from the cabin concentrations data from figures 5(e) and (f) taken adjacent to the conditioned-air outlet that a relatively small percentage of the ozone concentration going into the cabin was destroyed by the pressurization and ventilation systems before reaching the cabin. The bulk of the ozone destruction therefore occurs within the cabin.

Figure 7 is a plot of ozone concentration in the cabin versus that in the atmosphere, which includes all data plotted in figure 5. Linear-regression analysis forced through zero of these data gives a slope of 0.632 for configuration A and 0.406 for configuration B. This analysis is exclusive of the data taken with the cabin air inlet near the ventilation system outlet. The large deviation of individual data points from the calculated slope is a result of the large variations in atmospheric ozone concentrations and the lag in the response of cabin ozone concentrations. An analysis of the data from the strip-chart recorder for flight 2 indicate that it took 54 seconds for a step change in the ozone concentration in the atmosphere to become apparent in the cabin. In all cases the concentration rate of change in the cabin was considerably less than in the atmosphere.

Linear regression analysis of the data in figure 7 could also be made without the condition that the curve be forced through the origin. If this is done a slope of 0.520 is obtained for configuration A with an intercept of 42 ppbv; and for configuration B the slope is 0.197 with an intercept of 91.4 ppbv. The reason for the positive intercept of the cabin concentration curves is not certain. One possible explanation would be that there was some interferent gas present in the cabin which caused a positive response in the measuring instrument. Such a positive interferent would not be apparent during a zero check of the instrument since the zeroing gas came from the outside air.

Several sample-inlet positions in the cabin were investigated during the flight tests. There was no decernable difference in the ozone levels or retention for the locations tested if the sample-inlet position was several feet away from the conditioned-air outlet. However, a definative test was difficult because there were few periods during the flights when the atmospheric concentration was constant for even 10 minutes.

Comparison with Other Aircraft

Air exchange rates. - According to data from the aircraft manufacturer, the time for a complete air change in the Gates Learjet cabin is 2.5 minutes. This is comparable with air change rates of 2 to 3 minutes for the aircraft studied in reference 7 which represent the large, narrow-body aircraft predominating the commercial fleet at the time of that study. One of the methods 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. Reference 7 also mentions that tobacco smoke could temporarily reduce the ozone content immediately adjacent to the smoker by as much as 10 percent. There was no smoking in the cabin of the aircraft during the flights of this experiment.

Ozone measurements. - Reference 12 gives a limited amount of cabin and atmospheric ozone concentration data for a Convair 990 aircraft. For 23 data points, ozone retention varied from 41 to 59 percent with an average of 50 percent. These values must be adjusted downward somewhat because the atmospheric ozone concentration data were not corrected for losses in the pressurization system. When these losses are taken into account, the retention was reduced to 44 percent. The average ozone concentration in the atmosphere was rather low, that is, 85 ppbv.

The same aircraft was investigated by another experimenter (ref. 10) 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 given between atmospheric and cabin ozone concentration.

Reference 9 states that cabin air at some distance from the conditioned-air outlets the ozone concentration was about half that of the entering air. This investigator made no direct measurements of atmospheric ozone 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 in reference 8 are not identified but are assumed to be B-707's, B-720's, B-727's, and DC-8's. In the investigation of reference 8 although no direct measurement of atmospheric ozone were made, it was concluded that there was no significant difference in the ozone-decomposing efficiency of the various types

of aircraft. The authors did not estimate the ozone destruction rates for the various aircraft.

Reference 14 gives atmospheric and cabin ozone concentration data from a B-747 that was being used in the NASA Global Atmospheric Sampling Program (GASP). These data indicate that the retention of ozone in this aircraft is about 39 percent. Thus the B-747 aircraft reported in reference 14 had ozone retention that was roughly comparable the values obtained for the Gates Learjet.

SUMMARY OF RESULTS

A Gates Learjet was equipped with two ozone measuring instruments to measure the atmospheric and cabin concentrations of ozone. Six flights were made at altitudes to 13.1 kilometers. The following results were obtained:

1. The maximum atmospheric ozone concentration was 890 ppbv.
2. The maximum cabin ozone concentration was 410 ppbv.
3. The average atmospheric ozone concentration for individual flights ranged from 170 to 475 ppbv. The average cabin ozone concentration for the individual flights ranged from 96 to 226 ppbv.
4. The amount of atmospheric ozone retained in the cabin (retention) was probably influenced by the amount of surface area present in the cabin. The average retention for the four data flights when the surface area in the cabin was relatively low was 60 percent. The average retention for the two data flights when the surface area in the cabin was increased was 47 percent.
5. It took 54 seconds for a step change in atmospheric ozone concentration to be reflected in the cabin ozone concentration.
6. The amount of atmospheric ozone retained within the Gates Learjet cabin in this study was consistant with results obtained by other investigators but in other airplanes.
7. Ozone concentration measured in the cabin near the conditioned-air outlets was reduced only slightly from the atmospheric ozone concentration.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 25, 1978,
505-08.

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TABLE I. - FLIGHT ORIGINS AND DESTINATIONS

Flight	Date	Origin	Destination
1	2-8-78	Cleveland, Ohio	Cleveland, Ohio
2	2-9-78	Cleveland, Ohio	Cleveland, Ohio
3	2-13-78	Cleveland, Ohio	Nashville, Tenn.
4	2-13-78	Nashville, Tenn.	Cleveland, Ohio
5	2-16-78	Cleveland, Ohio	Sioux Falls, S. Dak.
6	2-16-78	Hill AFB, Utah	Moffett Field, Calif.

TABLE II. - SUMMARY OF RESULTS FROM DATA FLIGHTS

Flight	Configuration, (a)	Atmospheric ozone concentration, ppbv		Cabin ozone concentration		Retention, percent
		Average	Standard deviation (b)	Average	Standard deviation (b)	
1	A	274	107 (39)	210	82 (39)	75
2	A	323	150 (46)	226	95 (42)	65
3	A	147	55 (37)	96	22 (23)	61
4	A	170	95 (35)	101	40 (40)	52
5	B	269	99 (36)	130	34 (26)	43
6	B	475	180 (37)	194	60 (31)	41
1 - 4 av	A	228	102 (45)	158	60 (38)	63
5 and 7 av	B	372	140 (38)	162	47 (29)	42

[a]Configuration A, cabin relatively empty; configuration B, cabin relatively full.

[b]Parenthetical values are standard deviations expressed as percent of average concentration.

Figure 1. - The NASA Ames Research Center's Gates Learjet.

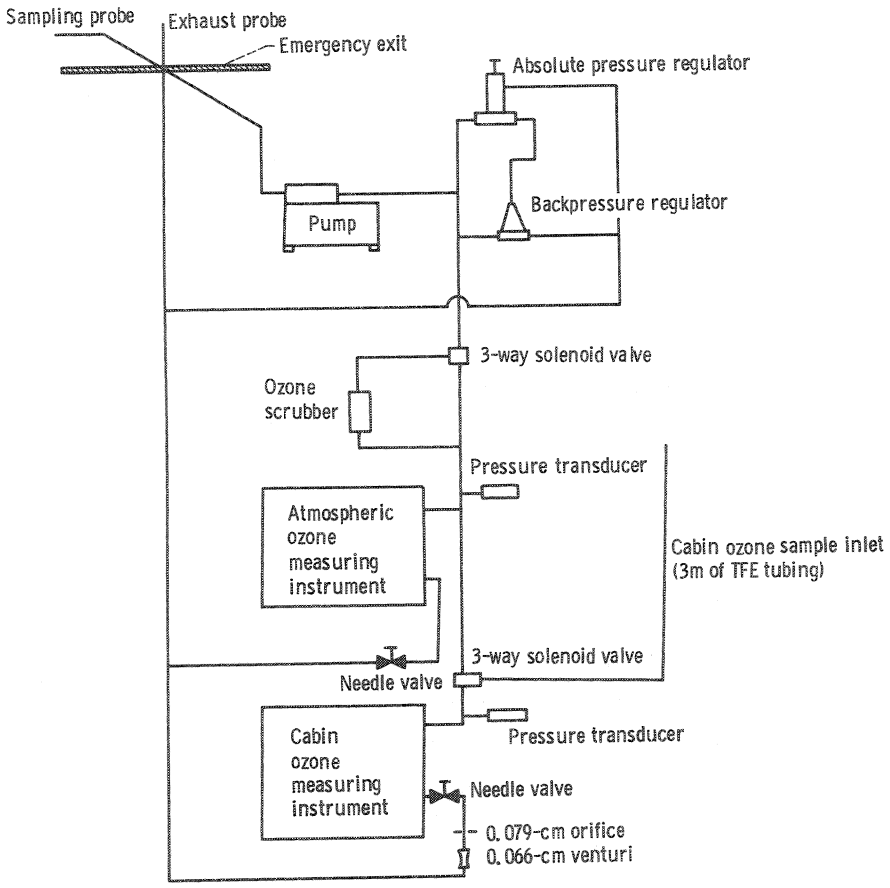
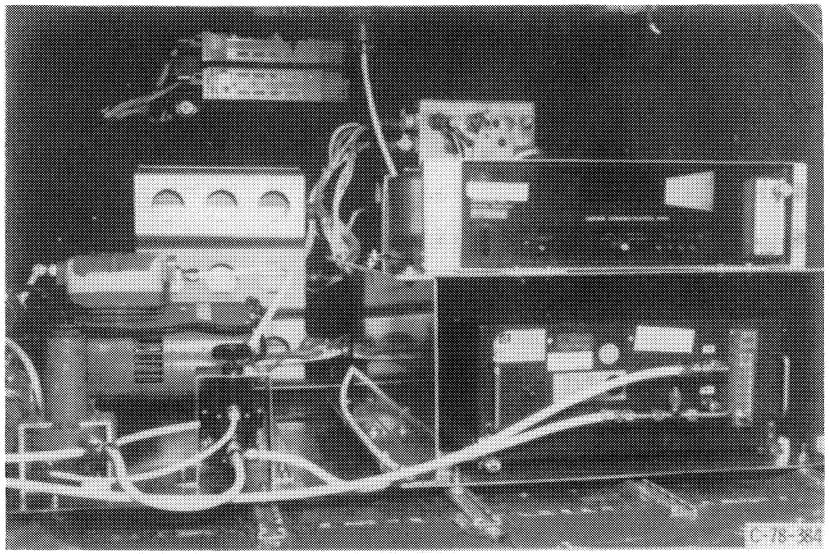
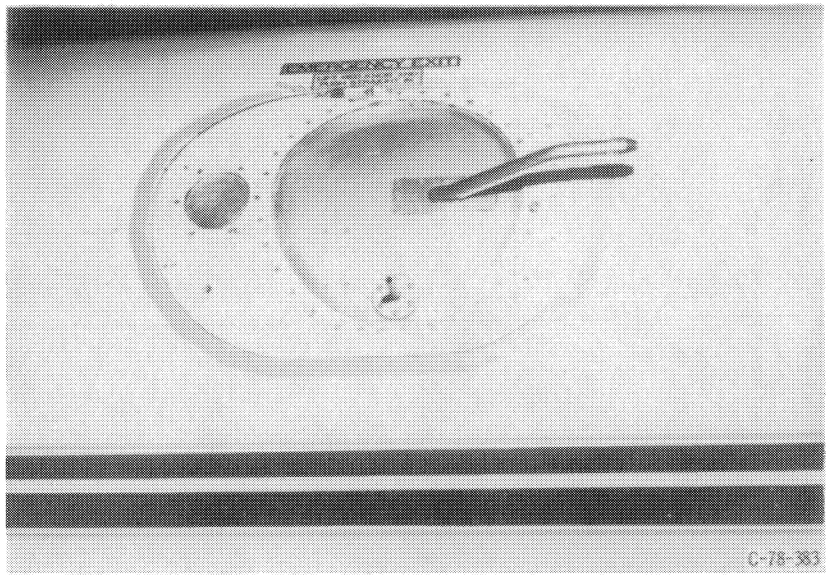


Figure 2. - Schematic of ozone measuring system.

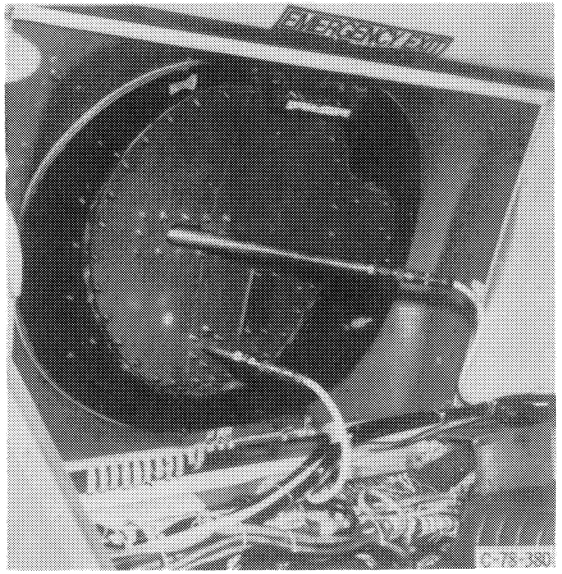


(a) Pump, regulators, and ozone measuring instruments in baggage compartment.

(b) Equipment rack located aft of copilot's seat.



(c) Sampling probe, exterior view.



(d) Sampling probe as seen in aircraft interior.

Figure 3. - Equipment installation.

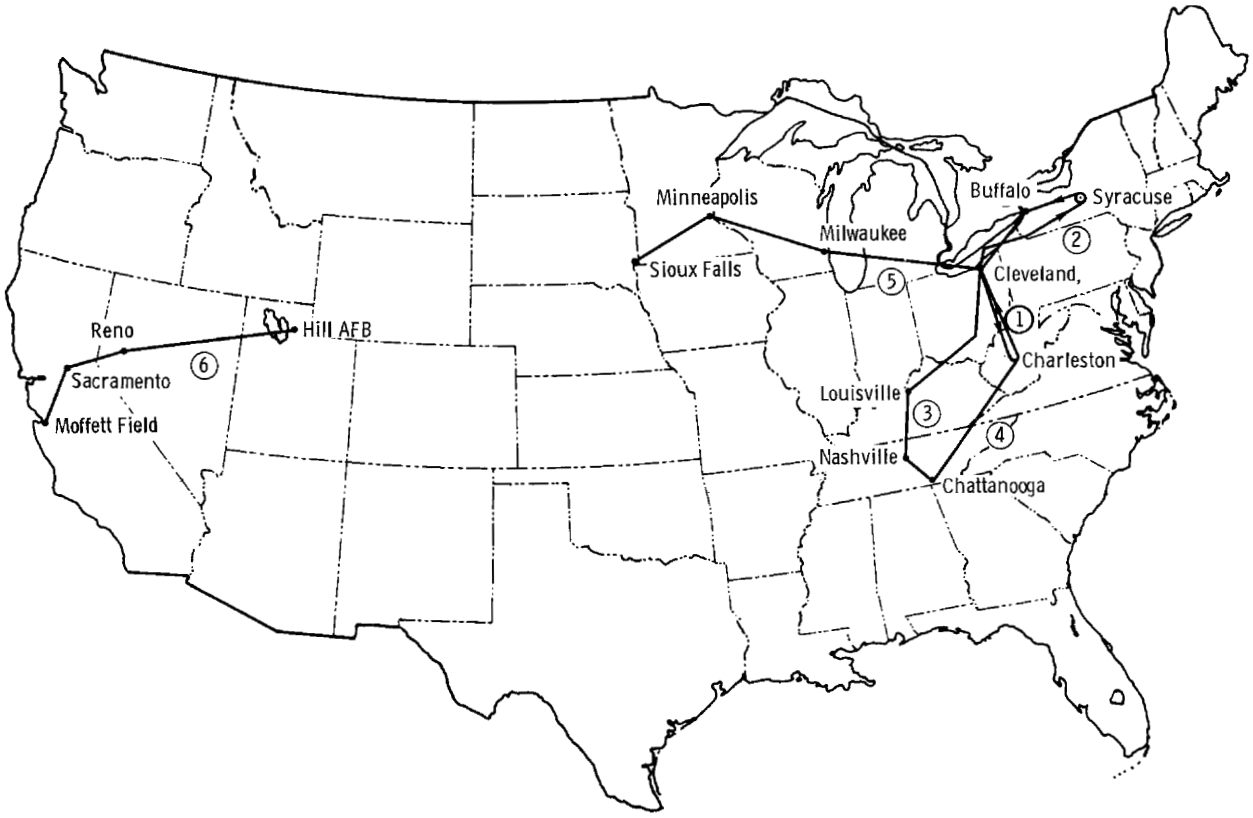
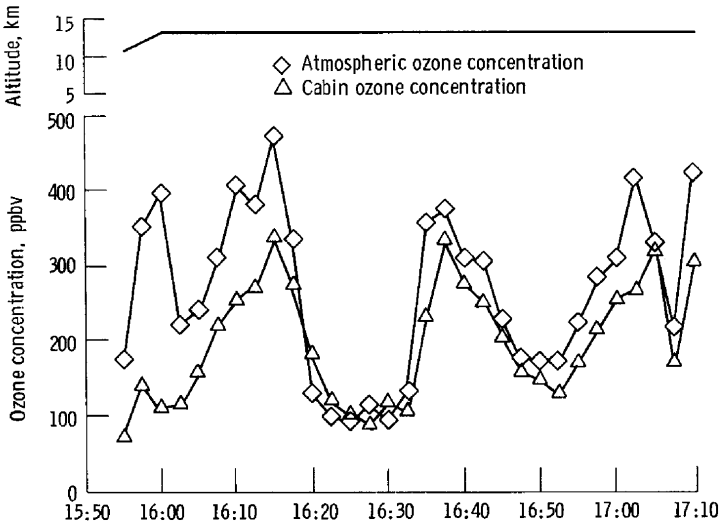
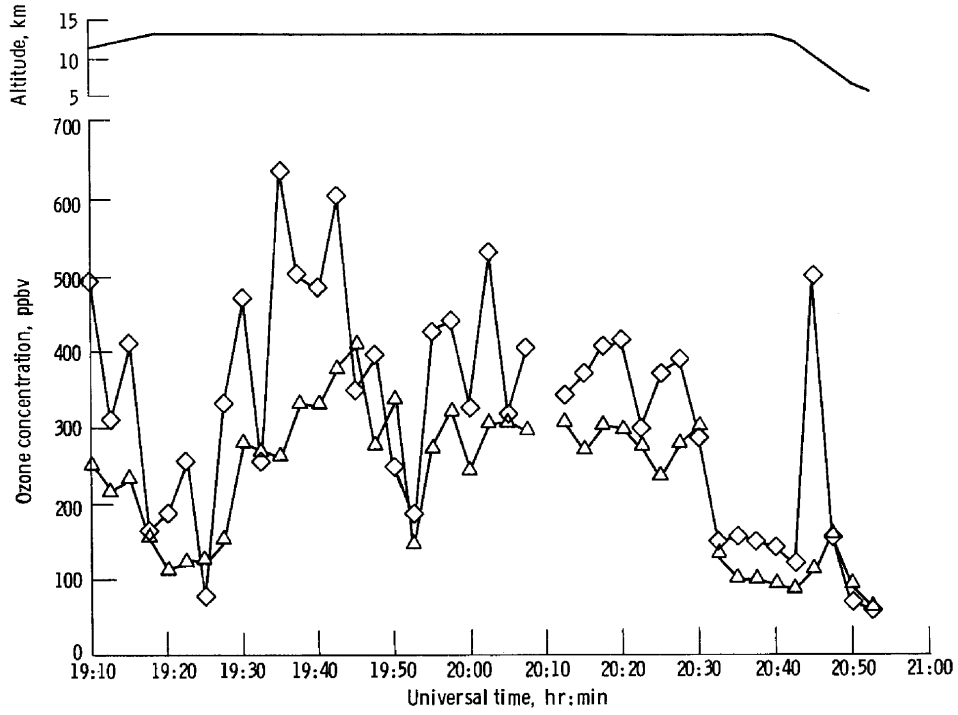


Figure 4. - Flight routes. (Numbers refer to flight numbers.)

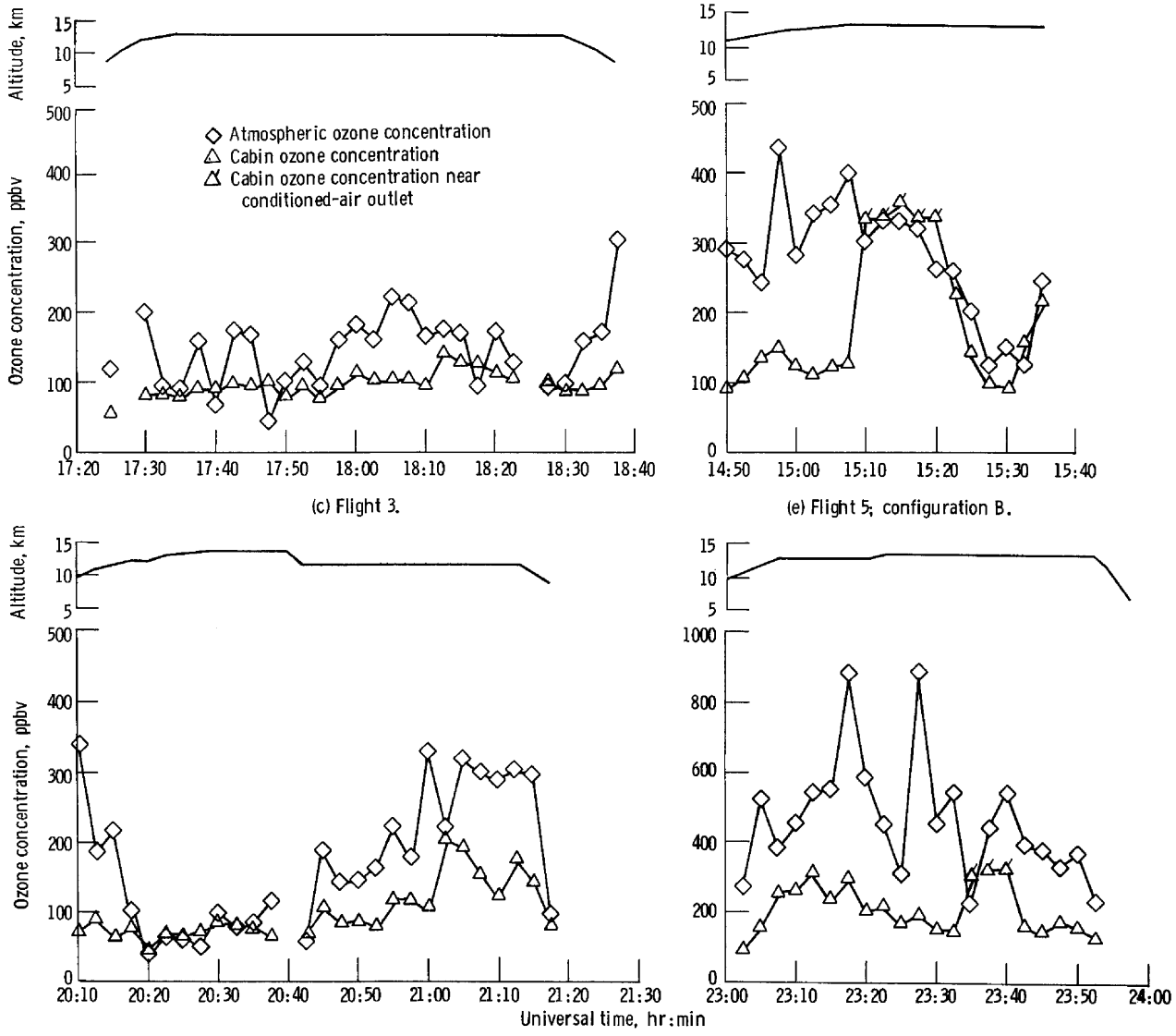


(a) Flight 1.



(b) Flight 2.

Figure 5. - Comparison of atmospheric and cabin ozone concentrations.



(c) Flight 3.

(e) Flight 5; configuration B.

(d) Flight 4.

(f) Flight 6; configuration B.

Figure 5. - Concluded.

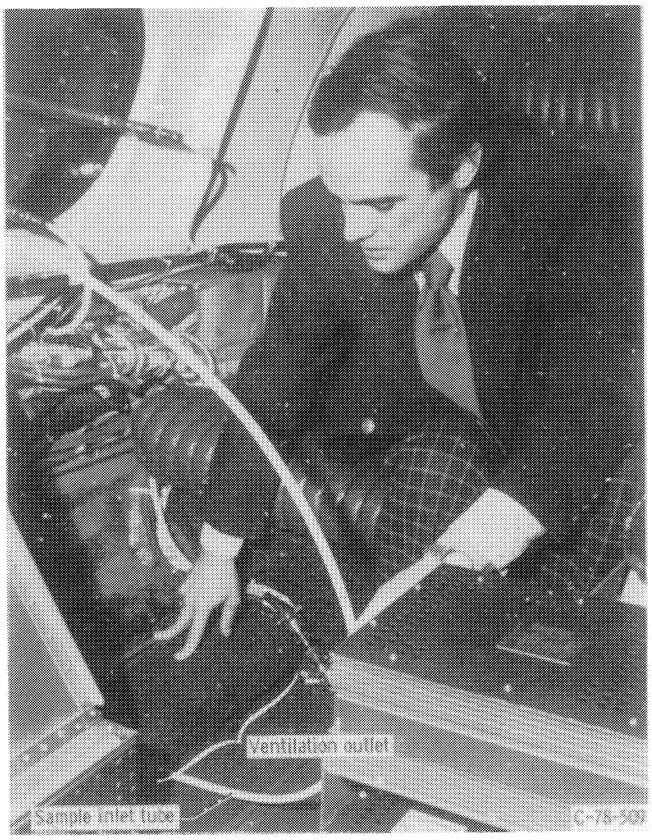


Figure 6. - Placement of sample inlet near ventilation system outlet.

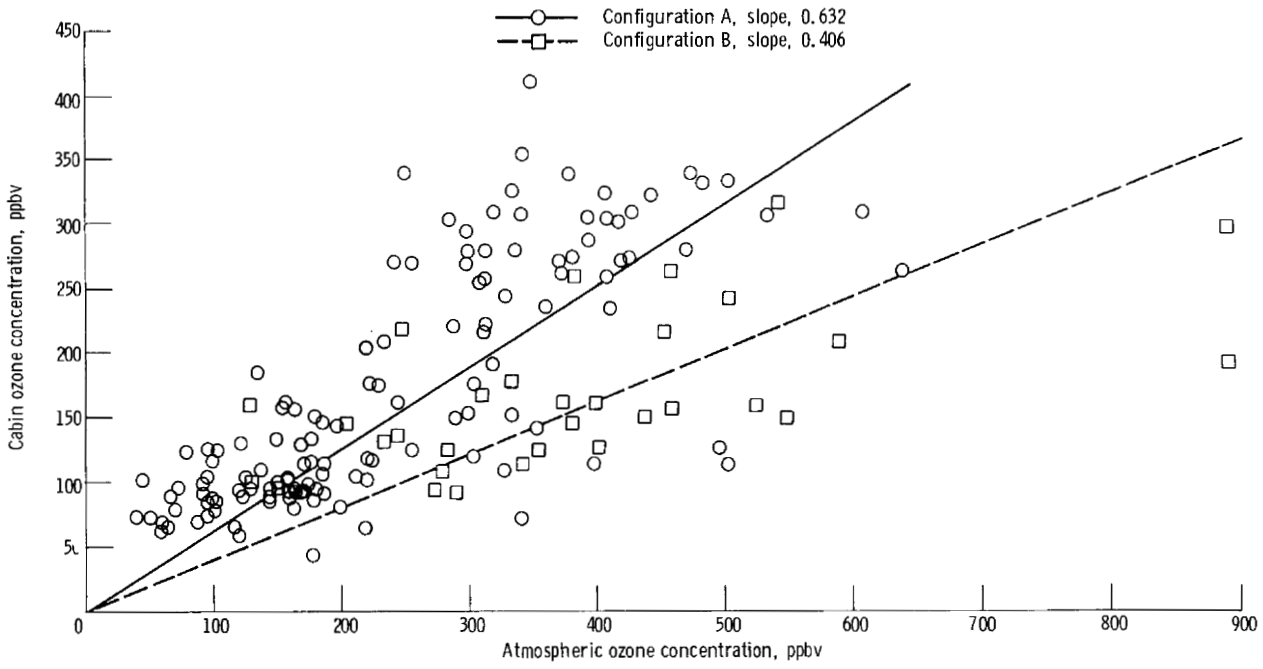


Figure 7. - Cabin ozone concentration versus atmospheric ozone concentration for configurations A and B.

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15. Supplementary Notes

16. Abstract

A Gates Learjet Model 23 was instrumented with monitors to measure simultaneously the atmospheric and the cabin concentrations of ozone at altitudes up to 13 kilometers. Six data flights were made in February 1978. Results indicate that a only a small amount of the atmospheric ozone is destroyed in the cabin pressurization system. Ozone concentrations measured in the cabin near the conditioned-air outlets were only slightly lower than the atmospheric ozone concentration. For the two cabin configurations tested, the ozone retention in the cabin was 63 and 41 percent of the atmospheric ozone concentration. Maximum cabin ozone concentration measured during these flights was 410 parts per billion by volume.

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