Ozone Measurement Survey in Commercial Jet Aircraft

ROBERT I. BRABETS,* CHARLES K. HERSH,† AND MORTON J. KLEIN‡
IIT Research Institute, Chicago, Ill.

The purpose of this survey was 1) to measure accurately ozone concentration in commercial jet aircraft cabins and/or flight crew compartments on flights above 25,000 ft in order to obtain a 12-month statistical evaluation with emphasis on seasonal and meteorological correlations, and 2) to locate and chart the ozone-enriched air masses in order to obtain further meteorological correlations and to establish any abnormal conditions that result in exposure to large ozone concentrations. The ozone concentration in aircraft was measured during 285 commercial jet flights between September 1, 1962 and August 31, 1963. These flights ranged over all segments of the United States and included sections of Canada and the North Atlantic. All types of commercial jet aircraft currently employed by air carriers were monitored. The ozone measurements recorded on each flight were evaluated, and the data were correlated graphically to show seasonal variations. The maximum continuous ozone exposure encountered on a domestic flight was 20 or more parts per hundred million (pphm) by volume for 140 min; the maximum on a northern flight was between 20 and 30 pphm for 4 hr; the highest concentration encountered was 35 to 40 pphm for 20 min. The most significant finding was that little or no ozone was detected on flights below the tropopause. At or above the tropopause, the internal concentration was usually above 5 pphm; in most cases it was above 10 pphm.

Introduction

SHORTLY after commercial jet aircraft were placed in operation on regular flight schedules, many passengers detected the odor of ozone in the fuselage from time to time. It was doubtful that the ozone was being generated inside the aircraft. However, since air entering the aircraft was required to pass through a compression cycle that raised the temperature to 250°F, ozone, which is thermally unstable, could be expected to decompose at this temperature. Equally curious was the fact that ozone was encountered at altitudes of 30,000 and 40,000 ft, whereas the ozone layer of the atmosphere is generally considered to exist at 80,000 ft.

The toxicity and the physiological effects of ozone at certain concentration levels have been reported in the literature, and the reactivity of ozone with certain polymeric materials is also documented.

In December 1961, under the sponsorship of the Federal Aviation Agency, a 4-month study (Contract FA2688) was initiated at IIT Research Institute. The purpose was to determine the frequency and the concentration of ozone in commercial jet aircraft. This study was made on 38 separate flights on the commercial routes of Airline "A." It covered the northern and central portions of the United States from New York to California and included five flights between California and Hawaii. The flights lasted from 60 to 325 min and covered altitudes from 9000 to 39,000 ft. The ozone concentration ranged from 1 to 22 pphm during 50% of the total flight time.

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* Research Engineer. Member AIAA.
† Manager Propellant, Research. Member AIAA.
‡ Director, Applied Chemistry Research. Member AIAA.

On the basis of these preliminary results, the FAA continued the study for 1 yr (Contract ARDS-608) and broadened the scope to include as many types of aircraft and flight patterns as possible. Seven major airlines cooperated by providing free air transportation for the research personnel who were responsible for the ozone measurements. The coast-to-coast routes were covered by flights operated by 3 airlines; the southern portion of the United States was covered by 2 airlines; the northern latitudes were covered by a polar route to London, a route to Alaska, and a route to Copenhagen. All types of U.S. type certificated jet transport-category aircraft were used. The ultimate objective was to correlate the frequency and the concentration of ozone with geographic location, meteorological conditions, flight pattern, altitude, and type of aircraft.

Measuring Techniques

The ozone analyzer is based on the microcoulomb ozone sensor conceived by A. W. Brewer of Oxford University. The basic principle is the well-known oxidation-reduction of potassium iodide, which is contained in the sensing solution. These electrochemical reactions (oxidation of potassium iodide by ozone and reduction of the released iodine by hydrogen) take place at polarized electrodes immersed in the sensing solution. The current through the external circuit is directly proportional to the mass of ozone entering the sensor per unit time. A constant-volume solution pump, a constant-volume sample pump, and a calibrated, electronic readout system complete the instrument package.

The first analyzer used in this study was obtained commercially in 1960 and was calibrated regularly in our laboratories by comparison with the standard wet analytical method in which sodium thiosulfate is used to titrate a buffered potassium iodide solution. The analyzer was also found to agree with instruments of other manufacturers. However, because it requires a 110-v, a.c. power supply, certain modifications and auxiliary equipment were necessary before it could be operated in an aircraft.

Two additional analyzers were purchased when the scope of the program was broadened. These instruments are powered by rechargeable batteries, are more compact and hence less conspicuous, and are considerably more convenient to handle. The calibration of these instruments was checked regularly at 25-hr intervals against laboratory-established

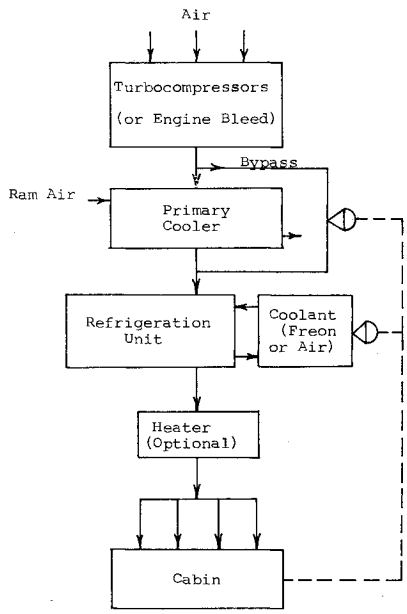

Fig. 1 Two-stage refrigeration system.

ozone concentrations of 2, 8, 16, and 40 pphm. Additional checks were made when unusual data were recorded. If the instruments did not agree to within 5% of the laboratory value, the previous data were discarded. The calibration was also checked for operation at the subatmospheric pressures found in jets. However, because of aircraft vibrations, slight temperature and pressure fluctuations, and the instruments' response time, the concentrations recorded during flights were considered accurate only to within 10%.

At the start of the program it was considered advisable to attract the least possible attention from passengers. Consequently, the analyzer was generally placed in the cockpit and started in operation before the passengers boarded the aircraft. The engineer monitoring the analyzer usually rode the observer's seat in the cockpit. His duties were primarily to record pertinent flight data such as altitude and flight path and periodically check the operation of the analyzer.

Since the analyzer was operated in the cockpit, it was necessary to know whether the ozone concentration in the cockpit was the same as that in the main cabin. The air is changed every 3 min in the cabin and every $1\frac{1}{2}$ min in the cockpit. It was also necessary to know whether the air circulation in the aircraft was sufficient to eliminate any stagnant areas. It was imperative that this information be gained early in the program. Any relationship between ozone content and instrument location had to be determined before the data were evaluated. Data from several flights with two or more analyzers aboard the same aircraft were necessary to answer these questions. The ozone content of the air was found to fluctuate rapidly; the concentration could double or halve in a matter of several minutes. This knowledge precluded the use of one instrument that could be moved to different locations in the aircraft. Thus, comparison of the ozone content of the flight deck with that of the main cabin was accomplished simply by using two analyzers. The second instrument was placed in the cabin before the passengers boarded the aircraft.

The incoming air could be analyzed by an instrument placed a few inches away from the auxiliary ventilating system, or "eyeball." The general level of ozone and the exhaust air could be analyzed by an instrument placed on the flight deck of the aircraft. Further checks could be made by turning the eyeball on and off. This technique was very successful in establishing standards in the types "M" and "Q" jets. Both these aircrafts have eyeballs located adjacent to a convenient instrument position in the flight deck. The type "Q" jets do not have as convenient a testing location; but since these jets have a faster air turnover rate, it was believed that the results would be comparable.

Few tests were required to establish the fact that the ozone content was generally consistent throughout the aircraft. The slower air turnover in the cabin tended to dampen fluctuations, but the average values were the same as those measured in the flight deck. The incoming air, of course, showed the widest fluctuations; but its average value was, for all practical purposes, the same as the others. No areas of stagnation were located, even though sections of the aft-cabin occasionally showed a temperature differential of 5°F or more. Smoke, particularly from cigars or pipes, could temporarily reduce the ozone content immediately adjacent to the smoker by as much as 10%. It was also noted that the ozone level adjacent to the galley could drop about 10% during periods when food was being prepared.

Even though these variations in ozone content could be considered minor and within normal fluctuations, the majority of the measurements were made in the cockpit, and the instrument was located close to an incoming airstream.

Table 1 Nominal comparison of aircraft pressurization systems

	Aircraft "M"	Aircraft "N"	Aircraft "O"	Aircraft "P"	Aircraft "Q"
Mode of pressurization:					
Normal	Turbocompressor	Turbocompressor	Turbocompressor	Turbocompressor	Turbocompressor
Alternate	Bleed air, 7th stage	Bleed air, 7th stage	Bleed air, 17th stage	Bleed air, 17th stage	None
Location of air inlet	Inboard engine pods	Inboard engine pods	Bottom of fuselage, forward of wings	Bottom of fuselage, forward of wings	Lower front of fuselage
Fuselage volume	9400 ft³	8400 ft³	4500 ft³	5300 ft³	9300 ft³
Average time per air change:					
In flight deck	1.5 min	1.5 min	1 min	1.25 min	1.5 min
In cabin	3 min	3 min	2 min	2.5 min	3 min
Volume of ductwork upstream of prime cooler	12 ft³	12 ft³	0.25 ft³	0.25 ft³	1.1 ft³
Ductwork material	Type 321 Stainless steel	Type 321 Stainless steel	Stainless steel	Stainless steel	Aluminum
Airflow per turbocompressor at 35,000 ft	1600 ft³/min	1600 ft³/min	830 ft³/min	830 ft³/min	700 ft³/min
Pressure in duct at 35,000 ft	18 psia	18 psia	14 psia	14 psia	14 psia
Temperature in duct at 35,000 ft	250°–275°F	250°–275°F	290°F	290°F	200°F
Residence time of air in hot zone	0.45 sec	0.45 sec	0.02 sec	0.02 sec	0.1 sec

Results and Discussion

Source of Ozone

The source of ozone is the external air. This fact is readily apparent from examination of the recordings. Operation of the analyzer for periods of up to 1 hr before takeoff but with all aircraft equipment operating established the base or zero level for each flight. During many flights, no ozone was detected for various periods of time. As a general rule, no ozone was detected below 25,000 ft, although a few exceptions were noted. For example, ozone was recorded at an altitude of several thousand feet over the Los Angeles smog basin and in areas adjacent to thunderstorms.

Differences among Aircraft

It was not possible to determine which type of aircraft contained more ozone when traveling through a high external concentration. This is apparent from a study of the pressurization system and the data obtained on parallel flights.

The design characteristics of various aircraft pressurization systems were investigated. Specifications for each type of aircraft vary. In addition, further modifications are encountered in the same basic type of aircraft according to the preferences of a particular airline. Table 1 shows that the pressurization systems differ with respect to compression temperatures and time periods at these temperatures. At first glance, it appears that correlation of these factors with internal ozone concentration would give an ozone decomposing factor for each type of aircraft. This factor, in turn, could be used to calculate the ozone concentration of the outside air. Unfortunately, the actual operation of these various pressurization systems precludes any correlation.

When an aircraft cruises at high altitudes, some of the heat compression is removed from the incoming air to control the internal cabin temperature. All the aircraft have two-stage refrigeration systems similar to the schematic illustration in Fig. 1. In addition to the heat removed by the refrigeration system, considerable heat is also removed by conduction and radiation from the ductwork of the ventilating system. During the majority of flights, the primary cooler is regulated to control the cabin temperature. This is accomplished simply and economically by cooling only a portion of the incoming air. The bypassed hot air is mixed with the cooled air to produce the desired temperature in the cabin. This control is easily automated and rapidly corrects for fluctuations in the temperature of the external air, which often varies by 20°F in a matter of minutes.

The secondary refrigeration unit is not required unless the passenger load is high, the outside temperature is higher than normal, or the flight personnel prefer a cooler cabin. Because of the additional heat supplied by the sun, daytime flights require more cooling than nighttime flights. Other variables include changes in the outside temperature with altitude and changes in the barometric pressuring during a flight. One last feature that eliminates any possibility that the internal ozone concentration can be correlated with the pressurization systems is the fact that the aircraft are operated by personnel who have individual preferences. Some crews prefer a warm cabin, some a cool cabin. Some maintain a smaller differential between the inside and outside pressure than others. Some crews anticipate altitude changes and maintain a constant pressure throughout a flight. Sometimes the cabin is cooled a little more during meal times. These differences preclude any calculation of the time that the incoming air is retained in the hot zone during an entire flight.

Table 2 Ozone detected on two different aircraft during parallel flights between Seattle and Chicago on April 9, 1963

	Aircraft "N"		Aircraft "O"	
Checkpoint	Altitude, ft	Ozone conc., pphm	Altitude, ft	Ozone conc., pphm
Spokane	37,000	14	33,000	5
Mullan Pass	37,000	8	33,000	8
Billings	37,000	10	33,000	10
Dupre	37,000	12	33,000	5
Sioux Falls	37,000	4	37,000	3
Mason City	37,000	5	37,000	3
Dubuque	37,000	5	37,000	5

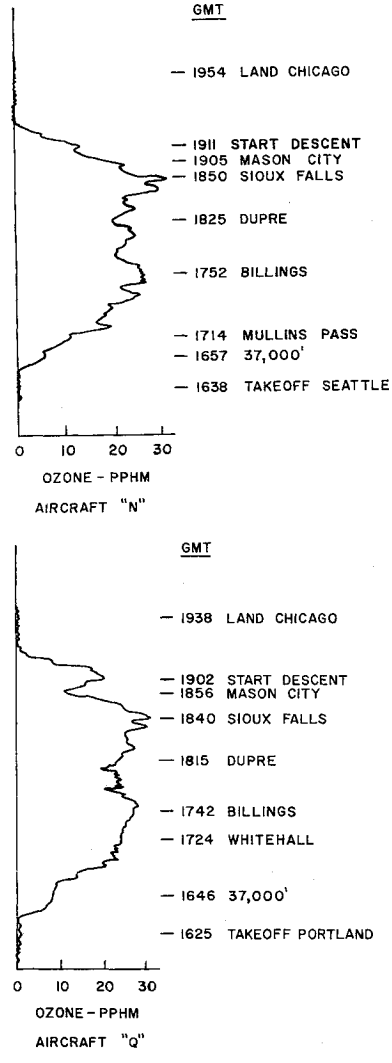

Fig. 2 Parallel flights made on April 23, 1963.

Numerous attempts were made to determine the relative effectiveness of the various pressurization systems in decomposing ozone. For example, the data listed in Table 2 were obtained on parallel flights between Seattle and Chicago on April 9, 1963. A "N" jet made the flight at 37,000 ft; it was followed 45 min later by "Q" jet at 33,000 and 37,000 ft. The pressurization systems of both aircraft were operating in a normal manner, i.e., with part of the incoming air bypassing the primary cooler. Evaluation of these data and comparison of the data obtained on similar parallel flights (Figs. 2 and 3) lead to the conclusion that there is no significant difference in the ozone-decomposing efficiency of the various types of aircraft.

Ozone Measurements

During the period from September 1, 1962 through August 31, 1963, the ozone concentration was monitored on 285 flights, which ranged from short (e.g., Chicago to New York)

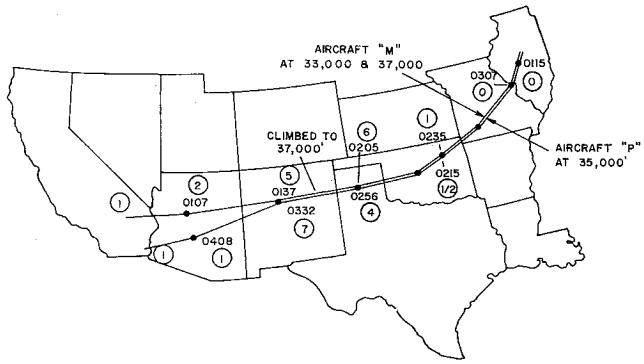

Fig. 3 Parallel flights made on April 28, 1963.

to medium (e.g., Chicago to San Francisco) to long (e.g., transcontinental, London to San Francisco). The average domestic flight lasted $3\frac{1}{4}$ hr; transcontinental flights over the northern latitudes averaged $7\frac{1}{4}$ hr. The flights were chosen at random; the only controls were to have at least two flights per week and to cover as large an area as possible. During the spring months the number of flights was increased to 6 or 8 per week.

The record for a typical domestic flight, shown in Fig. 4, shows that a substantial ozone concentration was encountered shortly after the aircraft reached cruising altitude. As the flight continued westward, the ozone concentration increased and then quite suddenly dropped to zero. No ozone was encountered over the plains states. Then, another region of appreciable ozone was encountered. Fifteen minutes before the aircraft started to descend, the ozone level again dropped to zero. From takeoff to landing, this particular flight lasted 5 hr and 22 min; 4 hr and 41 min of this total were spent at the cruising altitude of 35,000 ft. Ozone in excess of 3 pphm was encountered for $2\frac{1}{2}$ hr, or 46% of the total flight time. Ozone in excess of 5 pphm was encountered for $2\frac{1}{4}$ hr, or 42% of the total flight time.

All the flights were evaluated in this manner. An example of a northern flight is presented in Fig. 5. The data, assembled in monthly groups, are summarized in Tables 3, 4, and 5.

Examination of the individual flights shows that no ozone was recorded during some of them, whereas appreciable quantities were detected during others. With respect to domestic flights, the highest concentration of ozone detected for the longest period of time occurred in April 1963 on a flight from Seattle to Chicago: The concentration exceeded 20 pphm for the entire 140-min period that the plane was at cruising altitude, 37,000 ft. With respect to the northern latitudes, the highest concentration detected for the longest period also occurred in April 1963: on a flight from London to Seattle, the concentration fluctuated between 20 and 30 pphm for 4 hr. The highest concentration detected during any of the flights occurred in March 1963 on a flight from Anchorage to New York: a concentration of 35 to 40 pphm was recorded for 20 min. The concentration was above 30 pphm for 1 hr before the maximum concentration was recorded.

The expected seasonal variations are quite evident when the data are presented graphically, as in Figs. 6 and 7. The difference between the ozone level detected over the middle

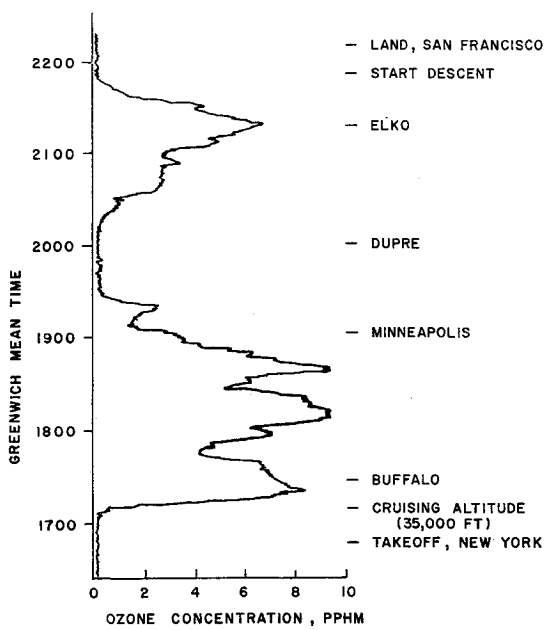

Fig. 4 Record of ozone detection (New York to San Francisco, February 14, 1963).

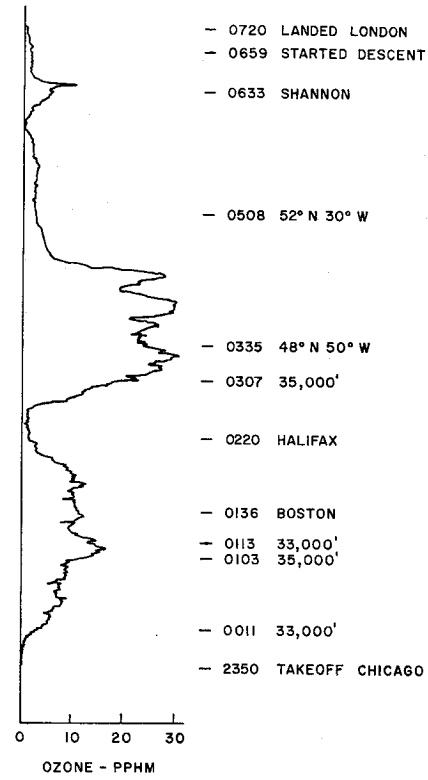

Fig. 5 Record of ozone detection (northern routes) April 25, 1963.

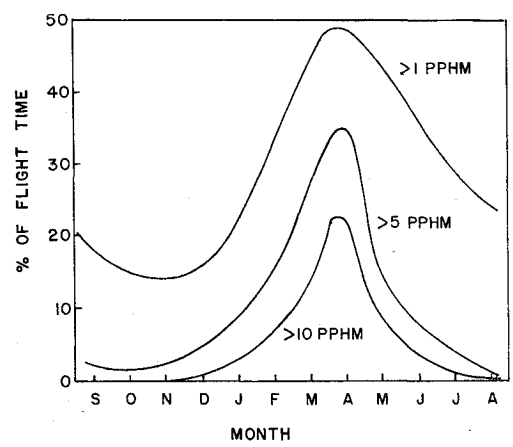

Fig. 6 Ozone detected during flights over middle latitudes.

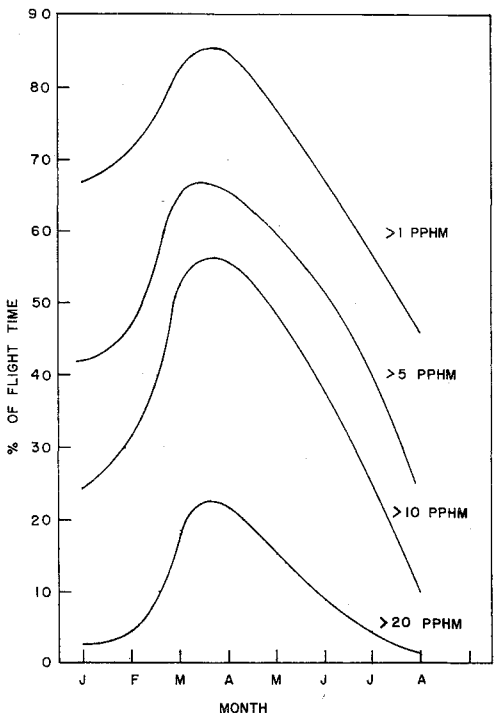

Fig. 7 Ozone detected during flights over northern latitudes.

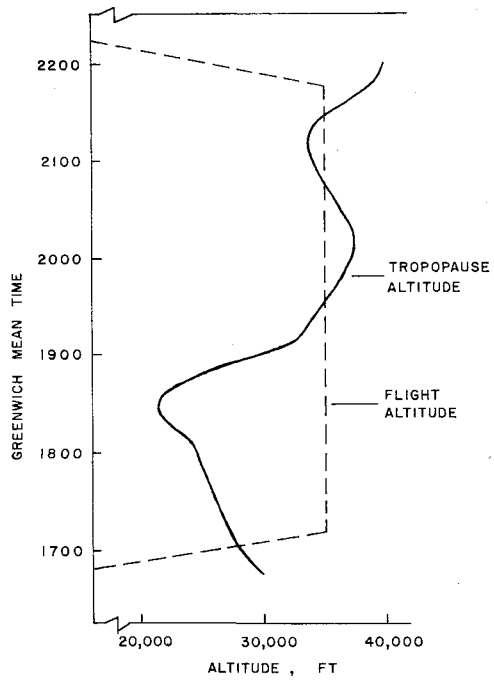

Fig. 8 Profile of flight of February 14, 1963, and tropopause altitude.

latitudes and that detected over the northern latitudes is clearly shown in the figures.

The ozone data can also be compared with the altitude data. As expected, the frequency and the concentration of ozone generally increases as the flight altitude increases. However, rather than the absolute altitude, the altitude of the tropopause appears to be the deciding factor. Figure 8 is a profile of the meteorological conditions during the flight illustrated in Fig. 4. When Figs. 4 and 8 are combined (Fig. 9), it is obvious that ozone is encountered above the tropopause. Very seldom is ozone detected below the tropopause. Further correlations of the quantity of ozone with height above the tropopause, with variations in latitude, and with seasonal variations are lengthy and complicated. One of the airlines is studying the data for significant trends.

Internal and External Ozone Concentrations

No correlation has yet been established between internal and external ozone concentrations. Later in the program, attempts were made to determine whether a constant relationship existed between the ozone concentration inside and outside the aircraft. This problem proved to be more difficult than expected. The data obtained were too sparse to provide an adequate correlation.

However, an approximation is available through comparison with data obtained by the Air Force on the Ozonesonde program. This comparison indicates that the aircraft pressurization system efficiently destroys low concentrations of ozone, but the efficiency decreases as the concentration of ozone increases. In other words, if the external air contains 5 to 10 pphm ozone, little or none of this ozone will reach the cabin. An external ozone concentration of 50 pphm will introduce perhaps 10 to 15 pphm into the cabin, and an external concentration of 75 pphm might be sufficient to produce the 30 pphm occasionally recorded in the cabin. This correlation is very tentative and is based on readings from two different types of analyzers. The correlation should be narrowed by making controlled flights in the same area and at the same time as the Ozonesonde balloon ascents with instrumentation that measures both the internal and the external ozone concentration.

Conclusions

The principal objectives of the program were attained. The average and the maximum exposures of flight personnel and passengers to ozone were determined.

Table 3 Summary of data on ozone detection during domestic flights (middle latitudes)

Month	Number of flights		Total flight time, min	Time above 25,000 ft., min	Time ozone detected, min							
					1 pphm	3 pphm	5 pphm	10 pphm	15 pphm	20 pphm	25 pphm	30 pphm
September	62	11	2269	1690	513	153	73					
October	62	11	2257	1731	265	80	10					
November	62	17	3938	3002	1232	290	32					
December	62	13	2427	1787	745	235	150	25				
January	63	25	4566	3357	748	443	730	110	85	70	50	10
February	63	18	3168	2237	1048	810	610	250				
March	63	30	5840	4419	2569	1903	1554	785	275	35		
April	63	26	4758	3451	2396	1927	1715	1125	904	644	290	105
May	63	24	4689	3391	1712	871	650	198	70	15		
June	63	23	3660	2476	1194	370	287	110	40			
July	63	11	1655	1134	594	71	56	21				
August	63	19	3035	1897	610	30	5					

Table 4 Summary of data on ozone detection during flights in northern latitudes

Month	Number of flights	Total flight time, min	Time above 25,000 ft, min	Time ozone detected, min							
				1 pphm	3 pphm	5 pphm	10 pphm	15 pphm	20 pphm	25 pphm	30 pphm
January 63	8	3628	3105	2483	1904	1548	937	285	100	30	15
February 63	5	2544	2253	1761	1461	1131	601	260	85		
March 63	11	4666	4104	3687	3311	3151	2273	1433	744	454	175
April 63	6	3166	2833	2753	2341	2110	1804	1276	716	191	86
May 63	9	3441	2962	2632	1524	1419	1109	839	587	215	30
June 63	7	3374	2960	2105	1835	1735	1148	624	152		
July 63	4	1330	1113	796	604	589	481	302	95		
August 63	4	1271	1089	595	320	265	45				

Table 5 Summary of data on ozone detection during domestic flights (middle latitudes) in Spring 1962

Month	Number of flights	Total flight time, min	Total above 25,000 ft, min	Time ozone detected, min					
				>1 pphm	>3 pphm	>5 pphm	>10 pphm	>15 pphm	>20 pphm
February	14	2880	2375	930	380	270	185	5	
March	14	3095	2495	1885	595	390	115		
April	8	790	435	425	150	125	115	85	10

The ozone concentration varies with altitude, latitude, and season. The ozone-enriched air masses were located and identified as segments of the lower stratosphere. The altitude of the tropopause thus determines whether ozone will be detected inside the aircraft. The internal ozone concentrations can be considered negligible (1 to 3 pphm) on flights made below the tropopause. Fluctuations in the altitude of the tropopause are directly correlated with latitude and season.

Thus, only one factor must be determined in order to predict whether a significant concentration of ozone (5 pphm or more) will be encountered on any projected flight. This one-variable correlation also allows extrapolation of the averaged data to specific routes. For example, routes that are consistently flown above the tropopause, i.e., polar flights, will have a higher-than-average ozone exposure. Individual airlines can compare their flight patterns with tropopause data and obtain a better indication of the concentration of ozone likely to be encountered by their personnel. Unfortunately, time was not available to establish the relationship between ozone concentration and distance above the tropopause or seasonal variations in the height of the tropopause.

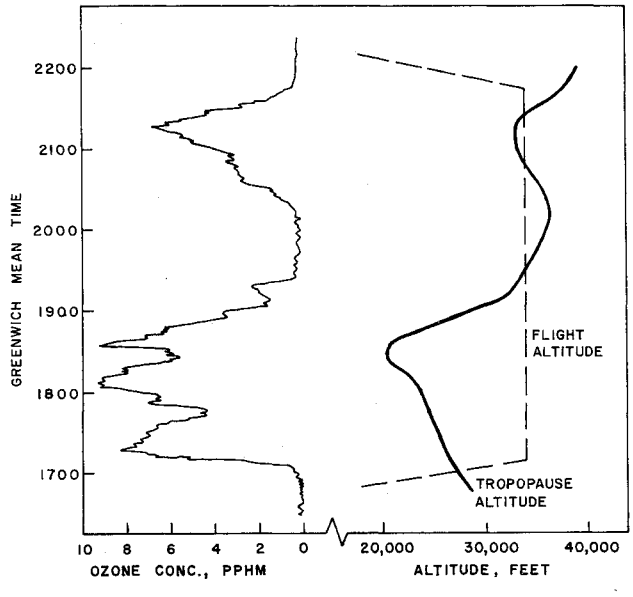

Fig. 9 Ozone detection and tropopause altitude.

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