SAE The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL
400 Commonwealth Drive, Warrendale, PA 15096-0001

AEROSPACE INFORMATION REPORT

Submitted for recognition as an American National Standard

SAE AIR910 REV. A

Issued 1965-11
Revised 1996-07

OZONE PROBLEMS IN HIGH ALTITUDE AIRCRAFT

INTRODUCTION

Ozone, which has a toxic effect on humans and animals and a destructive effect on many materials, is found in the earth's atmosphere from about 30,000 to 150,000 ft altitude. Today's jet transports are flying through the lower levels of this belt where ozone concentrations are relatively low. Tomorrow's supersonic transports will fly through the middle of the belt where concentrations approach maximum values. Since airplanes are pressurized and air-conditioned with air obtained from outside the aircraft, there is a possibility of excessive amounts of ozone entering the cabin with this air endangering the health of passengers and attacking materials. Serious rubber deterioration has already been observed on the subsonic jets indicating that significant levels of ozone are encountered in aircraft cabins during flight.

1. SCOPE:

The purpose of this report is to provide information on ozone and its control in high altitude aircraft environmental systems. Sources of this information are listed in the selected bibliography appearing at the end of this report, to which references are made throughout.

1.1 Atmospheric Ozone (O_3) Concentrations:

Various measurements of ozone concentrations versus altitude have been made, using instruments carried in balloons, aircraft, and rockets, and by other means. Ozone is formed in the atmosphere by the action of ultraviolet light of approximately 2000 angstroms wavelength acting upon atmospheric oxygen and is simultaneously dissociated by another portion of the solar spectrum. These photochemical actions are modified by the thickness and density of the atmosphere to cause an ozone layer to form in the stratosphere. Peak ozone concentrations generally occur around 70,000 to 100,000 ft. Above and below the altitude of peak concentration, the ozone concentration decreases rapidly and becomes essentially zero above 150,000 ft and below 30,000 ft. Maximum concentrations in excess of 10 parts per million by volume have been measured. The lower level of the ozone band appears to be the tropopause, which is the discontinuity surface dividing the troposphere and the stratosphere. The tropopause altitude varies in height from about 55,000 ft at the equator to 25,000 ft over the poles and also varies with time at any location. Generally, temperature decreases with altitude in the tropopause

1.1 (Continued):

while the stratosphere is isothermal or has an increasing temperature with altitude. The tropopause is the boundary between these two temperature-altitude structures. Measurements made in aircraft cabins show a sharp drop in ozone concentration when the aircraft descend through the tropopause altitude (7).

The total amount of ozone in the atmosphere and its distribution with altitude varies with latitude, season of the year, and weather conditions. In the northern hemisphere, the concentrations are usually highest in the spring and lowest in the fall. The total concentration and the magnitude of seasonal variation of ozone are greatest at high latitudes and least at the equator. Typical curves of ozone concentration in the atmosphere are shown in Figure 1. These curves have been replotted from various references and are more representative of maximum rather than average concentrations.

Significant amounts of ozone also occur at or near the ground, notably in Los Angeles but also in other areas. This ozone is formed by a photochemical reaction between sunlight and unburned hydrocarbons and oxides of nitrogen (9). The maximum ozone concentration ever measured in Los Angeles is about 0.9 ppmv[1] and numerous occurrences of 0.5 ppmv have been recorded (first smog alert level).

2. REFERENCES:

See Appendix A.

3. RECOMMENDED OZONE CONCENTRATIONS:

Ozone inside of aircraft is undesirable because of its toxic effect on humans and animals and because of its destructive effect on many of the materials used in aircraft construction. Many investigators have determined that ozone affects the soft tissues of the lung causing pulmonary edema, (a swelling of lung tissue due to accumulation of excess fluid), dyspnea (difficult breathing), and reduced lung capacity. Other symptoms reported are headache, dryness of mouth and throat, decreased ability to concentrate and impairment of the senses of smell and vision.

The effects of ozone are a function of ozone concentration and time of exposure. For instance, short duration exposures to ozone may produce no effects or effects that disappear after exposure is terminated while longer exposures may produce serious damage. Figure 2 shows a human tolerance chart for ozone as proposed by Lagerwerff (14) who measured the effects of ozone on human visual parameters and used his results to modify an earlier human tolerance chart published by C. E. Thorp. These charts are, however, not applicable for repeated exposures to small concentrations.

[1] The abbreviation “ppmv” refers to “parts per million by volume” in air throughout this paper.

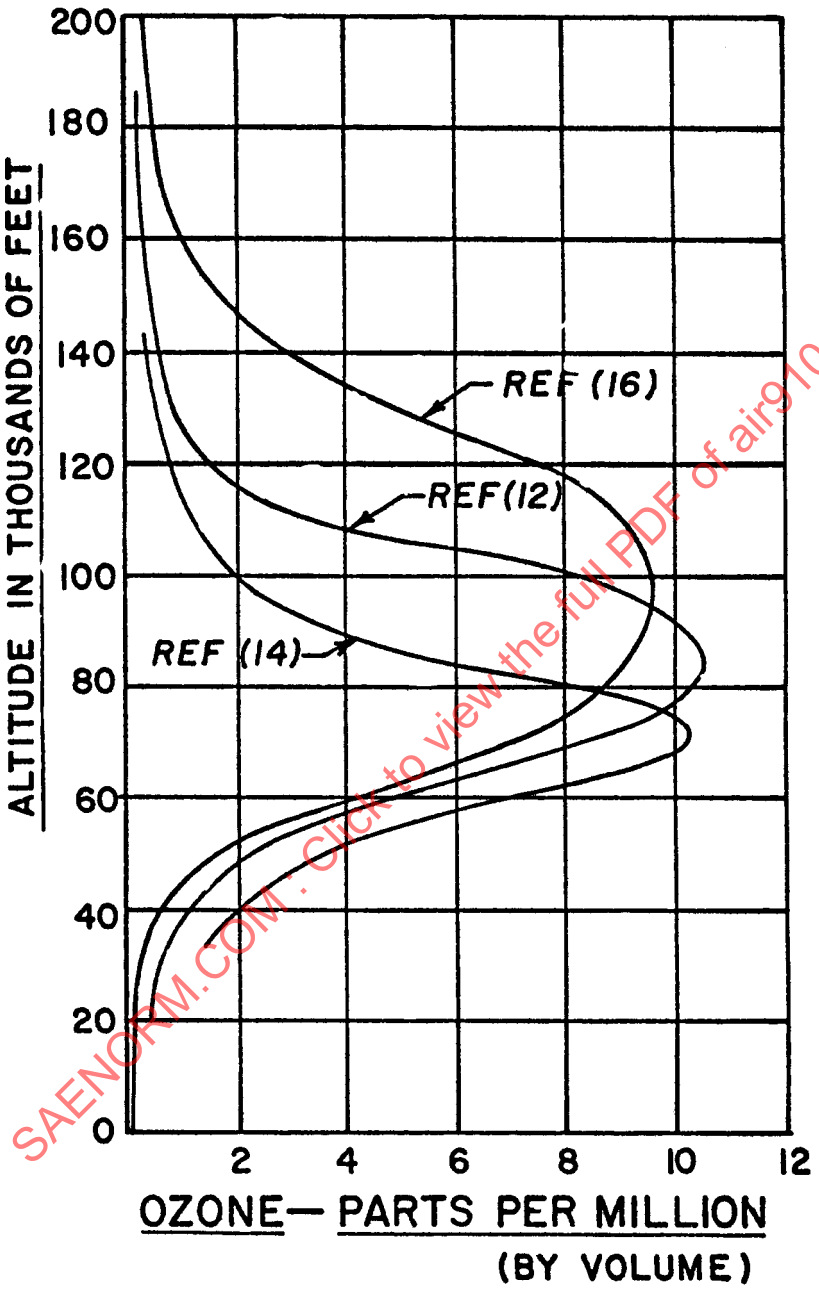
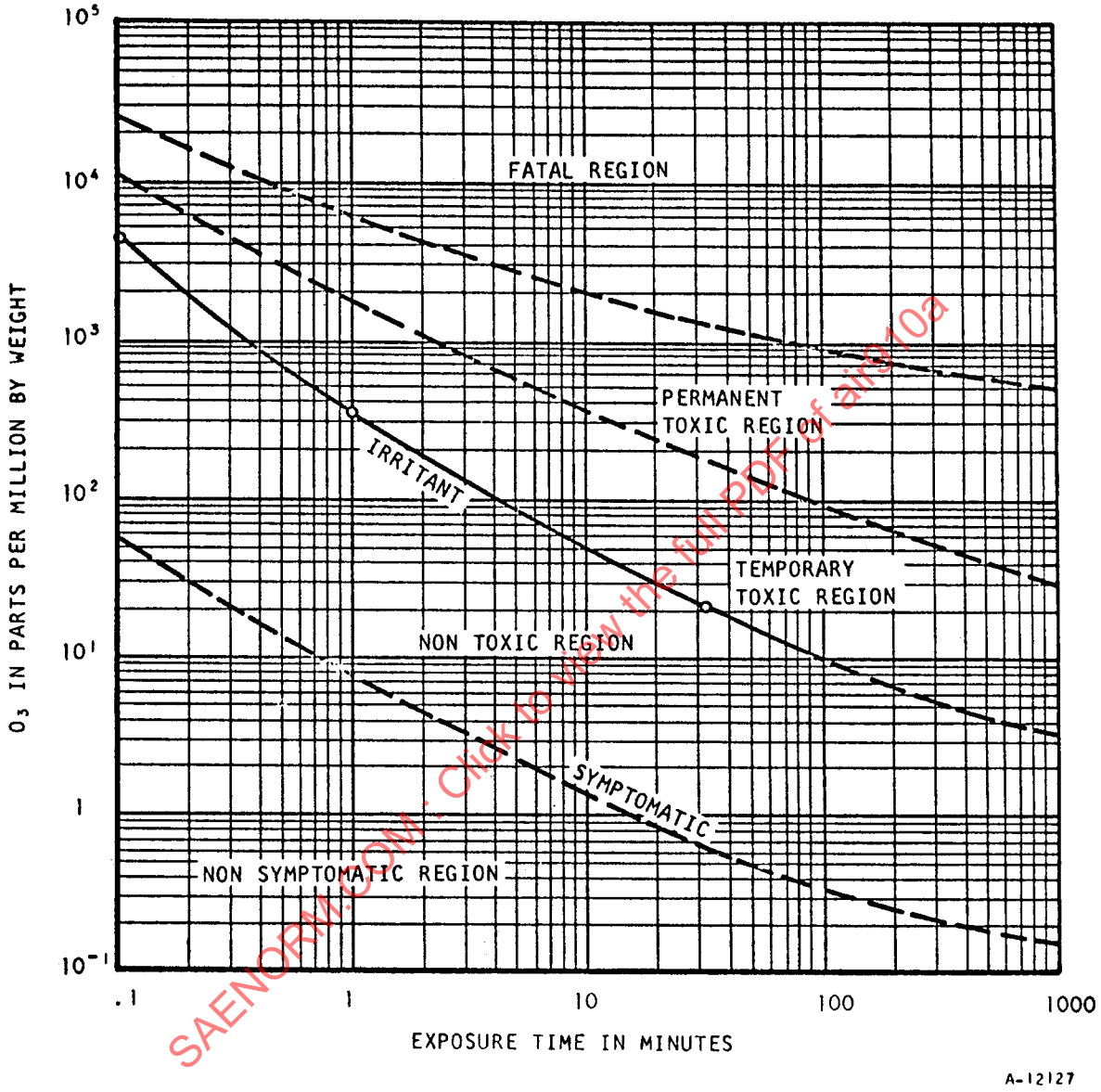


FIGURE 1 - Typical Curves of Atmospheric Ozone Concentration



NOTE: 1 ppm O_3 by volume equals 1.65 ppm O_3 by weight

FIGURE 2 - Chart of Human Tolerance to Ozone as Proposed by Lagerwerff (14)

3. (Continued):

For repeated exposures, a widely quoted standard is the one adopted by the American Conference of Governmental Industrial Hygienists (1) which specifies a maximum concentration of 0.1 ppmv for exposure 8 hours a day, 5 days a week over a number of years.

The maximum level for aircraft cabins recommended by Bennett (3) is 0.2 ppmv for a 6000-ft cabin altitude. The basis for this value is the results of experiments conducted by Bennett on two volunteer groups, one exposed to 0.2 ppmv for 3 hr daily for 12 weeks and another exposed to 0.5 ppmv for the same period.

Jaffe and Estes, of the Aviation Medical Service, Federal Aviation Agency, have suggested a maximum cabin concentration of 0.2 to 0.3 ppmv for repeated exposures, with higher concentrations permitted for very short exposures (11, 12).

The California Department of Public Health has adopted standards of air quality for use in controlling air pollution. A figure of 0.15 ppmv of oxidant was established as harmful, based on years of experience showing that when oxidants exceed this level, a significant part of the population complains of eye irritation and plant damage is readily noticeable (9). In this case the oxidant is mostly ozone with smaller contributions from oxides of nitrogen and organic peroxides, which together may be more toxic than ozone alone.

Very recently, investigators have suggested that low concentrations of ozone can produce blood-cell and body-tissue damage similar to the damage produced by X-rays. Brinkman, Lamberts, and Veninga (20) have found evidence that ozonized air produces these effects even when the ozone is only present in the very low concentrations normally considered safe (0.1 to 0.2 ppmv). The authors express concern about the wide-spread use of commercial ozonizers for air purification in homes, factories, and hospitals, since even the small ozone concentrations produced by these devices may prove to be harmful for chronic exposure.

While 0.1 to 0.3 ppmv is the suggested maximum allowable concentration range, atmospheric ozone ranges in excess of 10 ppmv at supersonic transport cruise altitudes. It is apparent that these large ozone concentrations must be removed from the air supply prior to entry into the cabin to prevent damage to or impairment of the passengers' health.

4. OZONE MEASUREMENTS IN SUBSONIC TRANSPORTS:

Many of the present jet transports fly above the tropopause where significant ozone levels are encountered. A number of measurements of ozone in aircraft interiors made by various investigators have been reported in the literature. One of the earlier reports is that of Young, Shaw, and Bates (17) who measured ozone in four DC-8's operating between Vancouver, B.C., and London. Stretched bands of natural rubber which crack in the presence of ozone were used for the measurements. To determine what ozone levels were encountered, the bands were then compared with laboratory samples exposed to known concentrations. The authors conclude that concentration of 0.3 to 0.4 ppmv were attained in the cabins of these aircraft.

4. (Continued):

Bennett (3) reported on ozone measurements obtained in a Boeing 707 and a Comet aircraft. Correlation of cabin ozone concentration with ambient ozone concentration was claimed. The instrument employed to measure ozone concentration used the oxidation-reduction of potassium iodide method, which is briefly described in 6.2. In the Comet, which delivers pressurization air at about 460 F, a maximum concentration of 0.065 ppmv at 41,000 ft was recorded, while the Boeing 707 which delivers air at about 300 F had a maximum concentration of 0.12 ppmv at 39,000 ft. Based upon the given ambient ozone concentration, 90% of the ingested ozone was destroyed by heating in the first aircraft but only 75% was destroyed in the second. It is implied that this difference in measurements between the two airplanes is caused by the difference in temperatures to which the pressurization air is heated; the higher the temperature, the more thermal decomposition that occurs.

Under Federal Aviation Agency sponsorship, the Armour Research Foundation measured ozone in the cockpits of various DC-8's on 38 separate flights for which Brabets (6) reports a maximum ozone concentration of 0.22 ppmv. Ozone concentrations were measured by the oxidation-reduction of potassium iodide method. For comparison with the previous data, the pressurization air is heated to only about 200 F in the DC-8. No difference was noted between the day and the night observations of the frequency and concentration of ozone. Concentration fluctuated widely when the aircraft was flying at constant altitude indicating that altitude is not a good criterion for determining ozone concentrations.

On the basis of the preliminary study results, the FAA contracted the IIT Research Institute (formerly the Armour Research Foundation) to continue this ozone measurement survey for a one-year period and to broaden its scope. Interim data from this continuation study is reported by Brabets, Hersh, and Klein (7). The continuation study involved the services of six U.S. airline companies flying domestic and intercontinental routes providing opportunity to take measurements in Boeing 707's and 720's, Convair 880's and 990's, Sud Caravelles, and Douglas DC-8's. The report covers a total of 149 flights over various routes and shows that ozone in excess of 0.1 ppmv is encountered a significant amount of time, especially at the northern latitudes. Findings confirm that ozone concentrations in the northern hemisphere are greater in spring than in the fall and greater at high latitudes than of middle latitudes.

A comparison of ozone data with actual tropopause altitude along a flight path shows that ozone is found only above the tropopause (except in special cases of low level ozone generation such as above Los Angeles). Although the aircraft would fly a constant altitude, the tropopause would vary in height along the flight path causing the airplane to be sometimes above, sometimes below the tropopause. Below the tropopause, ozone level dropped to zero. It is concluded that ozone concentration is related to height above the tropopause rather than absolute altitude, a conclusion also reached by Bennett and others.

4. (Continued):

An attempt was made to determine if the temperature to which the pressurization air was heated and the time held at this temperature had any effect on cockpit ozone concentration. It might be expected that the aircraft with the highest temperature air delivery system might show the least cockpit ozone because of thermal decomposition of some of the ingested ozone. To determine the validity of this assumption, flights of two aircraft of different types over the same route at the same time were made. Ozone measurements made in both aircraft showed no significant differences. The authors conclude that ozone concentration inside the airplane is essentially the same as outside the airplane apparently because the temperatures involved are not sufficient to decompose ozone at a fast enough rate. This conclusion is in disagreement with that of Bennett.

A final report on this one-year continuation study covering 285 commercial flights has been issued by Brabets (21). In addition to the six U.S. airlines mentioned previously, this report indicates that measurements were also made in the aircraft of one foreign carrier. The conclusions and data of the final report agree with those given previously for reference 7. The only major change in conclusions is in regard to the difference between internal and external ozone concentration. Measurement of ozone concentration external to the aircraft was found to be very difficult, but the external concentration was approximated using data obtained by the Air Force on the Ozonesonde Program. These data indicate that ozone decomposition does take place in the pressurization and air conditioning system and that ozone concentration inside the aircraft is less than that outside.

From the data taken in various types of aircraft on parallel flights, the author concludes that there is no significant difference in ozone-decomposing efficiency among the various types of aircraft.

The maximum concentration detected inside the aircraft during any of the flights was 0.35 to 0.40 ppmv for a 20-minute period.

Readings of about 0.5 ppmv were recorded in a KC-135 at 41,000 ft in a Weather Bureau Study (11, 12). This high reading is attributed to a low level of the tropopause, about 25,000 ft, so that the aircraft was flying well above the point where ozone is first encountered. Brabets (7) however, plots data for a flight at 35,000 ft where the tropopause altitude dipped to about 21,000 ft, yet the maximum ozone value recorded was only about 0.1 ppmv.

Although the previous information was gathered on subsonic airplanes which fly only in the lower levels of the ozone layer, it shows that significant amounts of ozone are often encountered in airplane cabins. This ozone enters with the pressurization air supply. The supersonic transport will be flying at high altitudes which place it in the maximum ozone levels and there is a good possibility that excessive amounts of ozone will enter the cabins of these aircraft unless certain precautions are taken.

5. OZONE CONTROL:

The time of exposure to the amounts of ozone encountered in commercial jet transports is not sufficient to constitute a hazard to the passenger's health. At any rate, no special devices for ozone removal are being used although they might be installed in the future. Ambient ozone concentrations at supersonic transport flight levels are excessive, however, and must not be allowed to exist in the cabin. Various means of decomposing ozone in air are known, although none has been proven in commercial aircraft use. The following section describes some of these possible methods.

5.1 Thermal Decomposition:

Ozone in air decomposes at a rate determined by the temperature. Boberg and Levine (5) present an equation for ozone decomposition rate as a function of temperature using the rate constant values measured by Benson and Axworthy (4). This equation in a slightly different form and using the average values of the rate constant from reference 4 is:

$$t = 4.62 \times 10^{-11} \left| \frac{1}{O_{3_{final}}} - \frac{1}{O_{3_{initial}}} \right| e^{27720/T}$$

where:

O_3 = ozone/air ratio, ppmv
T = absolute temperature, R
t = time in seconds required for given amount of decomposition
e = 2.718

According to this equation, ozone decomposition is very strongly dependent on the absolute temperature. For example, a reduction from 10 ppmv to 0.1 ppmv takes 27.5 minutes at 500 F but only 1/3 sec at 900 F. One-third of a second is about the length of time the cabin fresh-air supply spends at these elevated temperatures before being cooled, emphasizing the rapidity with which air passes through the engine compressor or turbocompressor and the hot section of the air conditioning system. If the preceding equation is approximately correct for this application, then the air must be heated to a high temperature to insure decomposition of the ingested ozone. It should be noted that initial concentration has little effect on the time required to decompose to a concentration of 0.1 ppmv.

Ambient air entering an airplane flying supersonically is heated very rapidly by the adiabatic compression -- first in a supersonic compression through a series of shock waves, then in a subsonic ram compression and then in a compressor. It remains to be determined whether this rapid change of state will cause the rate of ozone decomposition to be markedly different from that measured under equilibrium conditions in the laboratory.

5.1 (Continued):

The temperature to which the fresh air is heated during compression is a function of the pressure ratio and the ambient temperature; the higher the pressure to which the air is compressed the hotter it gets. Obviously the fresh air must be compressed to a pressure somewhat higher than the desired cabin pressure but the actual pressure, and, hence, temperature, to which the air is compressed depends upon the type of air conditioning system used.

Vapor cycle systems require only that the air supply be sufficiently higher than cabin pressure to account for pressure drop in the ducting and air-conditioning equipment, the work of refrigeration being supplied by electric motors or by shaft power. The other common type of refrigeration method, the air cycle, extracts power from the air itself to provide the energy needed for refrigeration. This requires the air supply to be delivered at a pressure much higher than in the vapor-cycle system and, consequently, much hotter.

For operating economy, the air supply should not be over-compressed because this represents wasted energy and additional heat to be removed in the air conditioning system. Therefore, the low pressure vapor cycle units usually operate with separate cabin compressors designed to produce air at the pressure required. At high Mach numbers, it may be possible to pressurize the cabin with ram air alone during much of the flight. Ram air is of course the coolest fresh air supply available aboard any airplane. On the other hand, air-cycle units are often supplied with bleed air from the engine compressor which is the hottest fresh air supply available. Generally, bleed air is at higher pressure than needed in the refrigeration unit and is, therefore, at higher temperature than it would be if a specifically designed cabin compressor was used. Cabin compressors are also used with air-cycle machines, and in some supersonic transport designs it may be desirable to use both methods.

It is obvious then that the temperature to which the fresh air supply is heated can vary widely depending on the type of air-conditioning system used. For the supersonic transport this can range from about 500 F for a plane using a vapor cycle unit up to 1200 F for an air cycle system using engine bleed air. Therefore, the effectiveness of thermal decomposition in destroying ozone, if any, will depend upon the method used for supplying the fresh air to the cabin. For aircraft using vapor-cycle systems (low-temperature supply air), thermal decomposition may be ineffective, while in aircraft using engine bleed air supplies, thermal decomposition may remove all ozone from the fresh air supply as indicated by the preceding equation.

5.2 High Temperature Catalysis:

Thermal decomposition can be increased by allowing the air-ozone mixture to come in contact with various metals or other materials which catalyze the decomposition reactions. By this means ozone can be decomposed at lower temperatures than are required by thermal decomposition alone. Boberg and Levine (5) tested various materials for catalytic effectiveness and found that nickel and manganese dioxide were both excellent under the conditions of the tests (5.5 to 7 ppmv ozone, 600 F). Aluminum, stainless steel, and other common metals were all found to have some catalytic effect on ozone at 600 F. They also found that the catalytic efficiency dropped off sharply below about 400 F indicating that temperature must be accounted for in the design of catalytic filters.

5.2 (Continued):

Recognition should be taken of the fact that various components in the air-conditioning system such as the ducting and heat exchangers will act as catalytic filters. The primary heat exchangers, which precool the air after it is delivered from the cabin compressor or engine bleed port, will likely be constructed of stainless steel in the supersonic transport because of the high temperatures. These stainless steel exchangers may have fins of nickel, an excellent high-temperature ozone decomposition catalyst. The fins of these heat exchangers present a very large surface area to the airflow and, therefore, may prove effective in decomposing ozone.

Generally, there are a number of heat exchangers in series in an air-conditioning system. While those at high temperatures may prove to be more effective than those at low temperatures, they may all have some effect in catalyzing the ozone decomposition reaction. Note that in the bootstrap-type of air-cycle system the air experiences a secondary compression and heating in the bootstrap compressor which also may aid the removal of ozone.

If the combined effects of thermal decomposition and catalytic decomposition due to the system do not prove sufficient to limit the ozone concentration to desirable levels under all conditions, it will be necessary to install a special device in the system for satisfactory ozone control.

One such device is a catalytic filter consisting of a large surface area of nickel, manganese dioxide, silver or other catalyst in a high surface-to-volume form such as screens, wool, or granules. A filter of this type should be located in that part of the system where the temperatures are highest to maintain effective catalysis during all of the high altitude portions of the flight.

There are some differences involved with thermal-catalytic decomposition. If a vapor-cycle system is used for refrigeration, then the fresh air supply delivery temperature to the unit will be relatively low during all of the flight, possibly too low at times for effective catalytic action. Additional heating of the air to remove ozone is undesirable because this excess heat must then be removed in the refrigeration unit.

In most systems, the delivered air temperature will be greatest at high altitude cruise which is good from the standpoint of ozone decomposition. There may be a critical period during descent, however, when the airplane is still at altitudes of high ozone concentration, but the temperature of air supplied to the refrigeration units is lower than at cruise. An air-cycle system operating from engine bleed air can experience a large drop in temperature during the first part of descent and if the temperature falls below the level needed for catalytic decomposition before the plane descends below the tropopause, undesirable amounts of ozone may enter the cabin. Even if a greater than desired amount of ozone does enter the cabin, the duration of exposure will be short.

For systems obtaining the air supply from cabin compressors, the situation may be more difficult because of the lower temperatures attained during all portions of the flight.

5.3 Low-Temperature Catalysis:

A number of catalysts are effective in low-temperature decomposition of ozone. Those reported to have some degree of effectiveness include activated charcoal, molecular-sieve-type zeolites, silver and silver oxide.

Activated charcoal, a specially processed charcoal manufactured from nut shells and other materials, has a high capacity for removing ozone from air (2). The adsorption effectiveness of charcoal is best at low temperatures requiring an adsorber of this type to be located at the outlet of the air-conditioning system.

Data published by Boberg and Levine (5) show that the effectiveness of charcoal for ozone removal decreases in service. During one test, in which 20 lb/min of air with 5.5 ppmv ozone at 75 F were passed through a charcoal filter, the initial concentration of ozone at the outlet was 0.045 ppmv but after 1.5 hour this increased to 0.40 ppmv, indicating a large decrease in effectiveness. Although these values apply only to the filter used in the test, it is apparent that charcoal has limited capacity for ozone necessitating the design of a filter large enough to last a suitable length of time before requiring replacement.

Activated charcoal is also effective in removing most odors from air and in eliminating the irritating constituents of Los Angeles smog, including oxidants (15), and may be installed on some aircraft for these purposes, in which case it would be well to consider the combined use of the charcoal for ozone removal, also, if needed. It should be noted that charcoal filters of sufficient size for suitable ozone removal service life will be heavy and bulky compared with catalytic filters and should not be used unless odor and smog removal is also desired, or if conditions are such that other methods of decomposition are not practical.

Zeolites are a class of hydrated silicates of aluminum and either sodium or calcium. Natural and artificial types are used mainly for water softening by cation exchange. Artificial types are also manufactured with a porous molecular sieve structure making them suitable for gas adsorption. When suitably activated, molecular sieve type zeolites have been shown to be excellent decomposition catalysts for ozone contaminated gases at 75 F.

Silver has also been shown to be effective at room temperatures in catalyzing ozone decomposition.

5.4 Photochemical Methods:

Ozone is formed in the atmosphere by the photochemical action of that portion of the solar spectrum with wavelength less than 2450 angstroms which is in the ultraviolet part of the spectrum. Concurrently, zone is decomposed by light of longer wavelength but not over 11,500 angstroms. Wilkins (16) reports that visible red light will decompose ozone. For comparison, the visible spectrum ranges from about 4000 angstroms (deep violet) to 7700 angstroms (deep red).

5.4 (Continued):

It should be practicable to construct an ozone filter consisting of lamps emitting light at the proper wavelengths. The air containing ozone could be passed through a chamber or other device where exposure to the radiation would decompose the ozone. The light sources would have to be protected from or designed for the pressures and temperatures encountered at the location of the device.

6. OZONE MEASUREMENT:

Various methods of measuring ozone concentration have been devised and instruments based on some of these methods are commercially available. This section describes briefly the principles of some of the more common methods.

6.1 Rubber Cracking Method:

Ozone readily attacks natural rubber causing surface cracking and bleaching. To measure ozone content in air, stretched bands of natural rubber are exposed to the air for a suitable length of time. Determination of average ozone concentration during the exposure period is then made by visually comparing the exposed bands with standard samples and by measuring the modulus of elasticity. This method is not very exact and further the long exposure time required means the bands cannot be used to indicate rapid variations in ozone concentration.

6.2 Potassium-Iodide Method:

Air-containing ozone is bubbled through a solution containing potassium iodide. The ozone reacts with the potassium iodide forming free iodine and potassium hydroxide. The amount of free iodine formed is proportional to the amount of ozone passing through the solution and may be measured by titration with sodium thiosulphate or by changes in color of the solution. Although ozone content can be determined with good accuracy using this method, the relatively long sampling period required means the readings are average values for the period of sampling. Response to rapid changes in ozone content is not obtained.

A modification of this method, which is widely used, substitutes amperometric titration for color-change-indicator titration, thereby permitting continuous readings of concentration and fast response (about 1 to 2 minutes) to changes of concentration. Here the gas sample is pumped at constant rate through the analysis cell containing the potassium iodide solution. Two electrodes connected to external circuitry are immersed in the solution. The iodine liberated by the ozone reacts at the cathode to produce electrical current in the external circuit proportional to the rate at which ozone enters the cell. Since the gas flow rate through the cell is constant, the current is also proportional to the ozone concentration of the gas. A microammeter measures this current and is calibrated to read ozone concentration directly. Instruments based on this method are available from such companies as Welsbach Corporation, Mast Development Company, and Beckman Instruments, Inc. Meters of this type are suitable for measuring ozone concentrations from 0 to 1 ppmv and may be used up to 25 ppmv.

6.3 Spectrophotometric Method:

Ozone has a strong absorption maximum in the ultraviolet at about 2537 angstroms, a wavelength produced by mercury vapor lamps. Ozone concentration in air or oxygen can be determined photometrically by passing light of the above wavelength through a cell containing the sample gas stream. The light not absorbed falls on a photoelectric cell generating an electric current. This current is then compared with the reading obtained when light is passed through the same gas sample but from which the ozone has been removed. The amount of light passing through the sample and the amount of current generated is related to the ozone concentration.

Response to rapid variation in ozone content can be obtained by using two cells and splitting the sample gas flow between them, first removing the ozone from one of the streams.

By proper construction, instruments can be made for measuring various concentration ranges from ppmv to several percent.

6.4 Thermal Conductivity Method:

The electrical resistance of a wire sensing element varies with the wire temperature. When an electric current is passed through the wire element, heat is generated and the wire temperature rises until the rate of heat transfer from wire to surroundings equals the rate of heat generation. If the wire is exposed to a flow of gas, the heat transfer from the wire is dependent on the overall thermal conductance between the wire and gas. The thermal conductance is a function of many things including the composition of the gas. Therefore, if the effects of all other variables are eliminated or accounted for, a change of ozone concentration in the gas stream will change the thermal conductivity causing a change in wire temperature which in turn changes the wire's electrical resistance. The value of the resistance can then be indicated on a meter calibrated to show corresponding ozone concentration.

The Welsbach Corporation produces a meter using this principle in which the sensing elements form part of a Wheatstone bridge circuit. The air sample passes over one sensing element, then through a heater which destroys the ozone, and then over a second element. With proper electrical circuitry and calibration a voltmeter across the bridge reads out the ozone concentration. This meter is suitable for high concentrations up to 4% of volume and has rapid response (about 1 minute) to concentration changes.

6.5 Radioactive Krypton Method:

Hommel, Chleck and Brousaides (10) report on an ozone analyzer developed at Tracer lab. In this device the sample air stream is passed through a molecular sieve to remove water vapor and then through a bed of quinol clathrate containing Kr^{85}. A clathrate is an inclusion complex (not a true compound) in which the molecules of one substance (Kr^{85}) are completely caged within the crystal lattice framework of the other substance, in this case quinol, a white crystal with formula $C_6H_4(OH)_2$. Ozone oxides the quinol to quinone, $C_6H_4O_2$, and water releasing the trapped krypton. The air stream sweeps the released radioactive krypton from the clathrate bed into a detector that contains a Geiger-Muller tube. Decaying krypton atoms are counted and the count rate converted to ozone concentration.