Effects of High Altitude Jet Aircraft on the Stratosphere

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EFFECTS OF HIGH ALTITUDE JET AIRCRAFT ON THE STRATOSPHERE

BY

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B.S.M.E., University of Dayton, 1966

Research Report

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of Florida Technological University

Orlando, Florida
August 1973
ABSTRACT
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This paper presents a review of the basic thermal, chemical and radiation balances existing in the atmosphere and discusses the mechanisms by which jet engine exhaust products can disturb these balances. Possible effects of stratospheric pollution on plant and animal life are discussed. Methods for reducing harmful emissions through engine design modifications are outlined and current successful research programs are surveyed. The SST type aircraft is shown to be a greater threat to the environment than conventional jets because of differences in cruise altitudes. It is concluded that due to the existence of several potential environmental problems associated with contamination of the stratosphere, large scale deployment of the SST should be discouraged, at least until current studies are complete and more data is available.
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NOMENCLATURE

\( \text{km} = \) kilometers
\( \mu = \) microns = \(10^{-6}\) meter
\( e = \) energy emitted
\( b = \) subscript indicating black body conditions
\( T = \) absolute temperature of radiating source
\( n = \) index of refraction
\( N = \) number of moles
\( \lambda = \) wavelength in microns
\( \sigma = \) Stefan-Boltzman constant = \(5.668 \times 10^{-5}\) \(\text{erg/sec cm}^2\) \(\text{K}^4\)
\( \text{NASA} = \) National Aeronautics and Space Administration
\( \nu = \) frequency of absorbed radiation
SECTION 1

INTRODUCTION

Certain properties of the stratosphere make it an essential component of this planet's life-supporting systems. Changes in these properties can affect the lower atmosphere as well as endangering surface vegetation and human health. In an effort to provide the reader with an appreciation of the dangers of environmental pollution and radiation hazards associated with proposed high altitude supersonic aircraft, the objectives of this paper are as follows:

A. Define properties of the stratosphere susceptible to change with the presence of jet engine exhaust products.

B. Define jet engine emissions and the engine design variables which can be modified to reduce emissions.

C. Discuss possible interaction of the stratosphere and exhaust products and the resulting effects on the environment.
SECTION 2

SPECIAL PROPERTIES OF THE STRATOSPHERE

2.1 Thermal Characteristics

In order to fully appreciate the impact of the injection of pollutants into the upper atmosphere, it is first of all necessary to obtain a brief understanding of the existing atmospheric energy balance.

A key to the nature of this energy balance is the temperature distribution observed in the earth's atmosphere. The temperature distribution shown in Figure 1 (from the U. S. Standard Atmosphere Tables, 1962) is based on extensive research data complied by NASA, the U. S. Air Force and the U. S. Weather Bureau. The three major layers of the atmosphere are conveniently defined by the temperature-altitude relationship of Figure 1.

The troposphere (tropos - turn or change), is defined as the lower atmosphere from sea level to an altitude of about 11 km, characterized by steadily decreasing temperature with increasing altitude. The tropopause (pausis - end, cessation), marks the beginning of the stratosphere (stratus - spread out), which extends from 11 km to about 50 km. Note the constant temperature region between 11 km and 20 km. The mesosphere (mesos - middle) is the layer above the stratosphere, from 50 to about 80 km, where temperature
Figure 1 - Ambient Temperature and Ozone Concentration Vs. Altitude (1)
decreases rapidly (1). Commercial jets generally cruise near the tropopause, between 8 to 12 km, while the proposed SST cruise altitudes include the lower stratosphere, from 17 to 22 km (2). Altitudes beyond 80 km are not considered important for the purposes of this paper.

The existence of the temperature gradient just described is the result of many interacting processes involving solar and terrestrial radiation and motions within the stratosphere itself.

Incoming solar radiation can be described in terms of electromagnetic waves of various wavelengths. Figure 2 illustrates the electromagnetic wave spectrum which is useful in visualizing the significant portions of solar radiation.

Radiation in the very short wavelength portion of the spectrum (below about 0.18 microns (μ), which includes x-rays, gamma rays, and cosmic rays, is absorbed in the mesosphere, largely by molecular oxygen. The ultraviolet region, which includes wavelengths from 0.005 microns to about 0.5 microns (see Figure 2) is the most significant part of the band so far as its thermochemical effects on the lower stratosphere are concerned. Wavelengths from 0.18 to 0.29 microns are almost completely absorbed by the ozone found in the stratosphere (see Figure 1). Several of the photochemical reactions involved, which will be discussed later, are exothermic and are responsible for the peak temperature found in the stratosphere (3).
Figure 2 - Solar Wavelength Spectrum
A qualitative concept of the relative amounts of energy absorbed by the various regions of the atmosphere can be obtained by considering Planck's relations for the intensity of black body radiation as a function of wavelength. Planck's expression for energy emitted by a black body may be expressed in the form: \( e_b(T) = \int_{0}^{\lambda} e_{b\lambda}(T) d\lambda \), where \( e_{b\lambda} \) is the energy emitted at a wavelength \( \lambda \) and temperature \( T \). This equation has been expressed in dimensionless form as (4):

\[
\frac{e_b(0 - n\lambda T)}{n^2 \sigma T^4} = \int_{0}^{n\lambda T} \left[ \frac{e_{b\lambda}}{n^2 \sigma T^5} \right] d(n\lambda T)
\]

where:
- \( T \) = absolute temperature of radiating source
- \( n \) = index of refraction
- \( \sigma \) = Stefan-Boltzmann constant = \( 5.668 \times 10^{-5} \) erg/sec cm\(^{-2}\) K\(^{-4}\)
- \( \lambda \) = wavelength at which energy is emitted
- \( b \) = indicates black body source

The left side of this expression is plotted versus \( n\lambda T \) in Figure 3, and is of special interest in our discussion of atmospheric absorption of radiation. If we assume a sun (source) temperature of 5600 K and \( n = 1 \) for outer space, the value of \( n\lambda T \) for the ultraviolet range (\( \lambda = 0.01 \) to 0.4) falls between 55.6 and 2222 \( \mu \)K. Figure 3 indicates that the energy emitted in this portion of the spectrum (\( n\lambda T \leq 2222 \mu \)K) is only about 10% of the total energy emitted. In other words, the upper atmosphere, which absorbs radiation over a relatively large range of wavelengths, does not absorb any high energy portions of the solar spectrum. In the tropopause there is further
Figure 3 - Energy Emitted Vs. Wavelength (4)
absorption by various gases, in addition to reflection by clouds and dust particles, so that about 80% of the total emitted solar radiation eventually reaches the earth's surface, where further absorption and reflection take place (5).

Roughly about 50% of the total solar radiation reaching the earth's surface is absorbed at the surface, with large local variations due to the varying nature of the underlying surface. In the polar regions, for instance, the ice and snow have a high reflectivity (30-70%), while in the tropics, where the oceans represent a large part of the surface area, the reflectivity is relatively low (3-8%) (6).

The condition of radiative equilibrium (steady-state climate) requires that the energy absorbed by the earth be equal to that emitted. It was shown by Wien in 1893 that the wavelength corresponding to maximum radiation intensity is inversely proportional to the absolute temperature characterizing the radiation. Stated as an equation Wien's Law (7) is:

\[
\lambda_{\text{max}} = \frac{C_1}{T} = \frac{0.289757}{T} \text{ cm}^0\text{K}
\]

Because of the relatively low temperature of the earth's surface, most of the energy radiated by the earth is, by Wien's rule, in the relatively long wavelength (infrared) portion of the spectrum. This emitted radiation is almost completely absorbed by the polyatomic gases (H₂O, CO₂ and O₃) and particles which in turn reemit the radiation both upward to space and downward to the ground (5).
The amount of radiation returned to the ground, therefore depends principally on the concentrations of water vapor, carbon dioxide, oxygen, ozone and dust and on cloudiness of the atmosphere. Changes in these variables thus affect the radiation balance and temperature distribution of the atmosphere.

Because of the important role played by clouds in the earth-solar energy balance, an understanding of the mechanism of cloud formation is essential in any discussion regarding the environmental effects of jet engine exhaust products. Clouds are originally formed by the condensation of water vapor on a particle. Clouds may consist of water droplets, ice particles or a mixture of both. Water clouds are formed above 100% relative humidity by condensation upon suitable particles. Some particles have been found to have the properties of initiating the freezing of a cloud droplet that contains them and are called ice nuclei. Ice (cirrus) clouds may be formed by rapid freezing of a liquid water cloud or by sublimation (growth of ice from the vapor phase without initial formation of liquid water). Once formed, ice particles will survive below 100% relative humidity and in fact will continue to grow until the humidity falls below that value which represents ice saturation. This characteristic indicates that once cirrus clouds form they may develop throughout the ice-saturated layer. This behavior means that formation of additional cirrus clouds due to the addition of water vapor and particulates from the exhausts of SST engines is a strong possibility.
Data on the average annual cirrus cloud cover obtained at several locations is shown in Figure 4. The addition of data on jet fuel consumption over the same time period indicates that there may indeed be a strong correlation between jet aircraft traffic and the existence of high altitude clouds. (see Figure 4) In the 10 year period from 1958 to 1968, jet fuel consumption (or jet aircraft traffic) increased by a factor of about 7, while the average annual cloud cover increased by roughly 50 to 80%, depending on location. When we consider that commercial aircraft flight has been projected to increase by a factor of 3 to 6 by 1990 (6), the chances of additional cirrus cloud formation seem to be rather definite.

2.2 Factors Affecting Distribution of Pollutants

The distribution of pollutants in the atmosphere and the resulting concentrations are strongly dependent on physical mixing or circulation. Vertical convection, which produces physical mixing, is caused by heating of the lower atmospheric layers by the earth's surface which cause them to expand and become lighter than the surrounding air. Then warm air currents move upward, being replaced by cooler descending streams. This pattern of vertical convection is important in cloud formation as well as providing a means of physically dispersing pollutants injected at lower altitudes. At higher altitudes, the earth's surface becomes less effective as a heat source and the absorption of radiative energy by ozone and other gases becomes more
Figure 4 - Average Annual High Cloud Cover Vs. Years (6)
important. The resulting temperature rise occurs uniformly throughout the absorption layer. The temperature distribution in the stratosphere is a strong function of the concentration of ozone.

Flow patterns at various altitudes have been quite well documented. Data has been obtained on the monthly variation of wind velocity at various altitudes in both the northern and southern hemispheres. Examples of this data are shown in Figures 5, 6, 7, and 8. Note that in Figure 5, for $30^\circ$ N latitude at altitudes of 11-25 km, (lower stratosphere) extremely low velocities are observed all year. In Figure 5 it is interesting to note that for a given latitude, high velocity streams of air (which, with the accompanying eddy currents, would produce good mixing) are never observed at any time in the lower stratosphere (20-25 km). Even more significant is the fact that Figure 6 shows this low velocity layer of air exists at all latitudes for the entire year. Vertical velocities ($0-1.7$ cm/sec) are almost negligible when compared to horizontal velocities ($0-500$ cm/sec). The average difference appears to be about two orders of magnitude. The constant monthly temperature characteristic of the stratosphere (20-45 km) is shown in Figure 8. In light of this data on temperature and wind velocities, it is reasonably accurate to describe the lower stratosphere as a layer of nearly stagnant constant temperature air (Figure 1, 11-25 km) which is apparently undisturbed by the
Figure 5 - Mean Monthly Zonal Wind Speeds (m/sec) for 30°N (3)
Figure 6 - Meridional Cross-section of Mean Zonal Wind (m/sec). Positive winds are from West (3)
Figure 7A - Meridional (Horizontal Plane) Velocity (cm/sec) at various times of the year (3)
Figure 7B - Vertical Velocity (cm/sec) at various times of the year (3)
Figure 8 - Mean Monthly Temperatures (°K) for 30°N (3)
more active masses of air both above and below it. The lack of a severe temperature gradient in the lower stratosphere (11-25 km) also minimizes the possibilities for vertical circulation due to convection. Note that this situation is very similar to the temperature inversions and resulting smog often observed at low altitudes over large industrial cities.

Because of the lack of vertical motion, it is not surprising that the residence time of substances deposited in the stratosphere (by volcanic eruptions and more recently, nuclear weapons testing) can be measured in months or even years, as compared to days or weeks for the lower atmosphere (3). The average lifetime of particles in the lower atmosphere depends on the local rainfall. Studies using various radioactive tracers have given lifetimes ranging from 6 days to 2 or more weeks in the lower troposphere. In the upper troposphere the residence time is about 2-4 weeks while in the lower stratosphere the residence time varies from 6 months at polar regions to about a year just above the tropical tropopause. Residence time continues to increase with altitude and is about 3-5 years in the upper stratosphere, "based on experience with specific radioactive nuclides that were injected as debris at high altitude by various nuclear tests" (5). This important difference in the stratosphere makes contamination of this region a much more serious matter than pollution of the troposphere, which has air currents and rainfall to provide mixing and cleansing effects.
2.3 Chemical Reactivity

No discussion of the properties of the stratosphere is complete without an examination of the chemical and photochemical reactions occurring here which do not normally occur elsewhere in the atmosphere. The chemical reactions which have been observed in the stratosphere are of two general types: (A) Photolysis reactions, which involve the absorption of light with subsequent chemical decomposition, and (B) Thermal reactions, which involve a chemical reaction between two or more species.

The distribution of ozone in the stratosphere is maintained by a cycle of photolysis and recombination reactions (2), namely:

1. \( \frac{3}{2}O_2 + h\nu \rightarrow O \)

2. \( O + O_2 + M \rightarrow O_3 + M + 24.67 \text{ kcal/mole} \)

3. \( O_3 + h\nu \rightarrow O + O_2 \)

4. \( O + O_3 + M \rightarrow 2O_2 + M + 47.35 \text{ kcal/mole} \)

5. \( O + O + 119.37 \text{ kcal/mole} + M \rightarrow O_2 + M \)

where:
- \( \nu \) = frequency of absorbed radiation
- \( h \) = Planck's constant = \( 6.63 \times 10^{-34} \) joule sec
- \( M \) = any third body

These reactions can constitute a continuous cycle, with UV radiation causing \( O_3 \) to change to \( O_2 \) and \( O_2 \) to \( O \) while the monatomic oxygen recombines to form \( O_2 \) and \( O_3 \).
Of particular importance are other chain reactions which can act as catalysts in using up or destroying odd oxygen atoms and/or ozone molecules. The following chain reaction is typical of several possible reactions involving the hydroxyl radical (2):

\[
\begin{align*}
\text{HO} + \text{O}_3 & \rightarrow \text{HO}_2 + \text{O}_2 \\
\text{O} + \text{HO}_2 & \rightarrow \text{HO} + \text{O}_2
\end{align*}
\]

Net effect: \( \text{O}_3 + \text{O} + \text{HO} \rightarrow 2\text{O}_2 + \text{HO} \)

This pair of reactions has the net effect of converting one oxygen atom and one ozone molecule into two oxygen molecules, while leaving the concentration of these catalyst radicals unchanged. Since the concentration of these catalyst radical ions is unchanged by this reaction, a relatively small concentration of HO and HO\(_2\) radicals could theoretically catalyze destruction of all the stratospheric ozone, except for the possibility of the HO being transported into the troposphere or being consumed by other chemical reactions.

Another catalytic-type chain reaction which is currently thought to be considerably more important than the HO reaction, involves oxides of nitrogen (8). One of the simplest of these chain reactions:

\[
\begin{align*}
\text{NO} + \text{O}_3 & \rightarrow \text{NO}_2 + \text{O}_2 \\
\text{NO}_2 + \text{O} & \rightarrow \text{NO} + \text{O}_2
\end{align*}
\]

Net effect: \( \text{O} + \text{O}_3 \rightarrow 2\text{O}_2 \)
The effects of additional $\text{H}_2\text{O}$ and $\text{NO}_x$ in the stratosphere on the ozone concentration depends on several unknown factors (2):

1. The rate constants and yields of all reactions related to $\text{H}_2\text{O}$ and $\text{NO}_x$.

2. The concentrations of $\text{H}_2\text{O}$ and $\text{NO}_x$ in natural conditions.

3. The relative efficiency of natural sources and sinks for $\text{H}_2\text{O}$ and $\text{NO}_x$.

4. The wavelengths of the solar radiation spectrum present at various altitudes.

5. The importance of atmospheric dynamics in influencing the chemistry of the stratosphere.
SECTION 3

JET ENGINE EXHAUST CHARACTERISTICS

Having considered the physical and chemical structure of the atmosphere in some detail, it is now appropriate to consider the other half of this paper's topic, the characteristics of the jet engine exhaust.

3.1 Basic Exhaust Composition

The basic exhaust products from a turbojet engine using hydrocarbon fuel are fairly well known. A stoichiometric chemical equation shows that the only combustion products are carbon dioxide and water vapor. Non-stoichiometric composition, incomplete combustion, dissociation at high temperatures, the presence of nitrogen in the air, and fuel impurities add other substances to the exhaust, which in addition to $\text{H}_2\text{O}$ and $\text{CO}_2$ includes carbon monoxide ($\text{CO}$), oxides of nitrogen ($\text{NO}_x$), sulfur dioxide ($\text{SO}_2$) and partially oxidized hydrocarbons (HC) as well as smoke, free carbon and other particulate matter. Smoke, which consists largely of minute carbon particles, is objectional from an esthetic standpoint and reduction of this product has received the most attention to date. Work on the reduction of non-visible gaseous emissions from turbine engines is relatively recent. Research by NASA
has produced considerable information on the variables affecting the emission of carbon monoxide (CO), unburned hydrocarbons (HC), and other oxides of nitrogen (NO). Carbon monoxide and hydrocarbons are generally a result of inefficient combustion, stemming from poor fuel atomization, low burner inlet temperature and pressure levels, and excessive air velocities in the burner (9). The combination of nitrogen with oxygen is a relatively rare reaction, except under conditions of extremely high pressures and temperatures and even then it is characterized by slow reaction rates (10).

3.2 Basic Design Variables Affecting Exhaust Emissions

With this background information in mind, it is not surprising that the various emissions from a gas turbine engine are a strong function of power setting. At idle power, fuel flows are low (causing poor fuel atomization) and pressure and temperature levels are also low, resulting in inefficient combustion and production of maximum amounts of HC and CO, and very low concentrations of NO. As power is increased combustion efficiency, temperature and pressure increase, resulting in more NO and smoke and less CO and HC.

Let us now look at what hardware modifications can be taken to minimize the various types of emissions from gas turbine engines. I shall first discuss the combustion chamber, or combustor which is the leading candidate for emission-reducing improvements. A typical combustor
Figure 9 - Typical Gas Turbine Combustor (11)
(Figure 9) consists of: (1) a diffuser to decelerate air from the compressor and increase static pressure in the burners; (2) fuel nozzles, where fuel is atomized and mixed with air; (3) primary and secondary combustion zones which are characterized by different fuel/air ratios. Two different zones are necessary because the fuel/air ratio required for stable combustion (lean limit-0.04; rich limit-0.15) produces gas temperatures on the order of 2200 K, which greatly exceeds maximum allowable turbine inlet temperature. In the primary zone the fuel/air ratio is maintained near the stoichiometric value (about 0.066) for efficient stable combustion (11). A large amount of excess (secondary) air is then introduced in the secondary zone to reduce the temperature of gases to an acceptable value at the turbine inlet. The large amount of excess air required reduces the overall fuel/air ratio to about 0.02. Combustion chamber design is therefore largely dictated by the mixture ratio requirements. The primary and secondary airflows must be proportional such that acceptable performance is maintained over the entire operating range, from full power (where a uniform exit temperature profile is critical) to high altitude relight conditions where low pressures make stable combustion difficult to achieve (11).

Reductions in smoke levels from commercial engines have been obtained by redesigning the combustion chambers to increase the primary zone airflow, thus leaning out the primary combustion zone (12). Improved mixing of the fuel and air through increased turbulence has also been found
to reduce smoke formation. These changes generally reduce or give unsatisfactory altitude relight capability however. NASA is pursuing further research to determine if other techniques such as diffuser wall bleed (see Figure 10) can be used to control primary zone airflow. A diffuser wall bleed would allow lean primary zone fuel/air ratios to be obtained during take off and cruise to reduce smoke formation but would also allow the use of richer primary zone fuel/air ratios during starting and altitude relight situations (9).

Since the presence of CO and HC are a result of incomplete combustion, the elimination of these compounds is simply a matter of improving the combustion process at low power settings. Poor fuel atomization is known to occur at low power settings and fuel flows because conventional fuel nozzles, which depend on high fuel pressure to obtain good atomization, do not work well at the low fuel pressure encountered at idle. Some improvements have been made by using fuel nozzles with two orifices, one for low fuel flows and a secondary orifice to handle high fuel flows which operates as a function of the pressure differential across the nozzle. Significant improvements in fuel atomization at low power conditions have been attained using air assist fuel nozzles (figure 11). NASA tests of a J-57 combustor with air assist nozzles, demonstrated idle power hydrocarbon emissions 3 times lower than the production configuration. A slight reduction in carbon monoxide emissions was also observed in the same test (9) (see Figure 12). No data was
Diffuser wall bleed can be used to control combustor inlet airflow profile and combustor airflow distribution.

Figure 10 - Combustor with Diffuser Wall Bleed (9)
Figure 11 - Sketch of Air Assist Fuel Nozzle

Air swirlers give clockwise swirl to air

Angled fuel jets give counter-clockwise swirl to fuel

Fuel in

Air
Figure 12 - Air Assist Vs. Conventional Fuel Nozzles (9)
shown for $\text{NO}_x$ in these tests, but $\text{NO}_x$ is not considered a serious problem at idle power.

Of all the emissions from the future SST engines, the oxides of nitrogen are probably the most significant, for several reasons: (1) The SST cruise environment produces an unavoidable combination of high combustion chamber inlet temperatures and pressures (resulting from compression in the engine air intake system at high flight Mach number). High pressures and temperatures are conducive to formation of $\text{NO}_x$; (2) $\text{NO}_x$ can have an important effect on the stratosphere since it is one of the primary catalysts in the various ozone destroying reactions; (3) $\text{NO}_x$ is technically the most difficult of all emissions to control, because its reduction requires fundamental changes in the combustion process.

The complete mechanism of the formation of oxides of nitrogen is not fully understood, but it is known that the reactions are strongly dependent on time and temperature. Reducing the residence time of the hot gases in the combustion chamber will reduce reaction time between $\text{N}_2$ and $\text{O}_2$ and lead to lower contractions of $\text{NO}_x$. This can be done by quenching the flame by moving the dilution (secondary air) holes further upstream, which shortens the flame length, or by increasing the flow velocity through the primary zone (10). (There is a practical limit on velocity due to flame stability considerations). The effects of reducing residence time and primary zone fuel/air ratio on $\text{NO}_x$ emissions are shown in Figure 13.
Figure 13 - Effects of Reduced Residence Time and Lean Primary Zone on NO\textsubscript{x} Emissions (10)
Another method for reducing reaction-zone dwell time has been investigated by NASA-Lewis (13). In a new burner design the recirculation path in the turbulent primary zone has been reduced by incorporating a large number of individual burners or swirl-cans. This modular combustor has no well defined primary and secondary zone like the conventional combustor. Instead, nearly all the airflow (except liner cooling flow) passes through or around the individual burner cans, in which fuel and air are premixed, and then the mixture swirled into the main combustion chamber (see Figure 14). Burning and mixing downstream of each module is very rapid which allows a reduction in total combustor length. Although this combustor is about 30% shorter than conventional burners, it was successfully operated to nearly stoichiometric fuel/air ratios (14). NO$_x$ emissions were significantly reduced compared to more conventional combustors, (see Figure 15, 16, and 17) so this configuration appears promising for future engine designs requiring short, high temperature combustors having a minimum amount of NO$_x$ emissions.

Another approach to reduction of NO$_x$ emissions is based on the strong temperature dependence of the NO$_x$ reactions (they are exponential with temperature) so that small reductions in flame temperature result in large reductions of NO$_x$. One of the simplest ways to reduce the maximum primary zone temperature is to introduce more air at that point, thereby reducing the local fuel/air ratio and
Combustor Module Details

120 swirl cans localized recirculation zones

Carburetor Swirler Flame Stabilizer

Plate Flame Stabilizer

Figure 14 - NASA Swirl Can Burner (9)
Figure 15 - NO\textsubscript{2} Emissions: NASA Swirl Can Burner vs. Conventional (J-57) Burner (9)

- J-57
  - $P_3 = \text{atm}$
  - $V_r = 50 \text{ ft/sec}$
  - fuel/air ratio = 0.013

- Swirl-can
  - $P_3 = 4$ to 6 atm
  - $V_r = 99$ to 109 ft/sec
  - fuel/air ratio = 0.016
Figure 16 - Effects of Reference Velocity on NOx Emissions (9)
Figure 17 - Effects of Fuel/Air Ratio on NO\textsubscript{x} Emissions (9)
the corresponding flame temperature. The flame temperature can also be reduced by vitiating the combustion air with inert products such as water or recirculated exhaust products (10). Figure 18 shows the effects of water injection on NO\textsubscript{x} emissions. Effects of recirculating exhaust gases are shown in Figure 19. Note that this is the situation occurring in an afterburning engine. Preliminary data indicates that afterburning does not significantly add to NO\textsubscript{x} emissions from supersonic aircraft (13).

Although the combustion chamber and fuel nozzle designs are the principal factors which govern the emissions from a given engine, the combustor designers task can be made easier or more difficult by the general engine configuration and selection of the thermodynamic cycle. Engine configurations for high altitude supersonic aircraft include the turbofan and pure turbojet, with various thrust augmentation devices to provide additional thrust during the transonic acceleration phase of a typical SST flight. The pure turbojet is generally the most efficient configuration for supersonic flight, while the turbofan is a compromise providing more efficient operation during the subsonic and transonic modes than the turbojet. The choice between these configurations depends on the subsonic/supersonic time split and the lift/drag characteristics of a particular aircraft. The final selection on an engine configuration is usually based on a rather complex mission
Figure 18 - Effects of Water Injection on NO\textsubscript{x} Emissions (10)
Figure 19 - Effects of Recirculation on NO\textsubscript{x} Emissions (10)
analysis in which aircraft and engine performance characteristics are combined in a mathematical model to calculate aircraft range, fuel consumption and payload.

After an engine configuration has been selected, further, decisions on the engine cycle must be made. Recalling that high pressures tend to cause more NO\textsubscript{x} emissions one should keep engine compression ratio as low as practical. While high compression ratio is essential for low fuel consumption in subsonic engines, it is much less important in an engine optimized for supersonic cruise. As flight Mach number increases, compression in the supersonic inlet/diffuser in front of the engine increases rapidly as shown by the compression ratio relationship for an isentropic inlet, namely:

\[ \frac{P_t}{P_{am}} = \left[ 1 + \frac{\gamma - 1}{2} \cdot M^2 \right]^{\frac{\gamma - 1}{\gamma}} \]

Thus the effect of the engine compressor becomes less important as flight Mach number increases. In fact, at speeds near Mach 3, engines like the J-58 and J-93 produce only about 25% of the thrust propelling the aircraft, with the inlet duct pressure distribution providing 50-60% of the thrust and the exhaust ejector the rest. The engine is actually only a flow inducer for the supersonic inlet system (15). While a reduction in engine compression ratio is certainly in the right direction to reduce NO\textsubscript{x}, large reductions cannot be made without incurring a severe
penalty in specific fuel consumption in the subsonic portion of the flight envelope. At this point, further research in combustion technology appears to be more promising than cycle modifications which trade increased fuel consumption (and more total pounds of pollutants) for an unproven amount of reduction in \( \text{NO}_x \) emissions.

In the case of the turbofan engine, an additional cycle parameter must be determined, i.e., the bypass ratio, or ratio of fan duct bypass air to main combustor air. Maximum cycle performance at supersonic cruise would dictate a very low bypass ratio (the engine wants to be as close to a turbojet as possible at this flight condition). A higher bypass ratio could help in reducing \( \text{NO}_x \) emissions. The reason is that, although the bypass air is still heated in either a duct burner or afterburner, the inlet pressure and temperature levels in the duct section are somewhat lower than in the main combustor and these conditions will tend to produce lower \( \text{NO}_x \) emissions than the main burner of a pure turbojet.

The last important cycle parameter, turbine inlet temperature, is for practical purposes, not really a variable; it will generally be set as high as possible for best cycle efficiency. It generally ends up being set by metallurgical limits and turbine airfoil cooling technology. As the temperature rise in a burner increases more fuel must be burned in the primary zone, leaving less air available for cooling or flame quenching in the secondary zone.
The resulting increase in flame length and residence time of \( \text{N}_2 \) molecules in the high temperature primary zone can potentially increase NO\(_x\) emissions. The achievement of low NO\(_x\) emissions is possible, however, as shown by the NASA swirl can burner (14), which has run to exit temperatures of \( 2256^\circ \text{K} \) with low levels of NO\(_x\).

Another major engine component is the thrust augmentation system, which is mandatory in supersonic engines. The choice is either afterburning, which can be used on either a pure turbojet or a mixed flow turbofan, or a duct heater, which was used on the Pratt and Whitney JTF-17, a demonstrator engine for the US SST. Any additional NO\(_x\) emissions from an afterburner are negligible due to the effects of vitiated air used in the combustion process. Carbon monoxide and hydrocarbons could be a problem however, due to low combustion efficiency (see Figure 20). Afterburners typically operate at lower efficiency levels (70-90%) than either main or duct burners, which approach 100% efficiency at high power conditions. (Note - efficiency is defined as: \( \eta = \frac{\Delta T_{\text{measured}}}{\Delta T_{\text{ideal}}} \) where \( \Delta T_{\text{ideal}} \) can be calculated from chemical equilibrium). Since pressure levels in either a fan duct or augmentor would tend to be roughly the same, the duct heater would tend to have higher NO\(_x\) emissions than the afterburner, since it does not run with vitiated air. Duct heaters are basically identical to main burners, however, and thus may be cleaned up by using methods developed for main burners, such as the NASA swirl cup burner.
Figure 20 - Effects of Combustion Efficiency on Emissions of HC and CO. (9)
EFFECTS OF ENGINE EXHAUST PRODUCTS ON THE THERMAL AND CHEMICAL BALANCE OF THE STRATOSPHERE

Having now considered the jet engine exhaust characteristics and the properties of the stratosphere separately, we should be better prepared to analyze their interaction.

4.1 Effects of Increased Concentrations of Carbon Dioxide Water Vapor, Sulfur Oxides, Unburned Hydrocarbons, and Oxides of Nitrogen.

The addition of CO$_2$ and water vapor to the stratosphere might be of some concern simply because there are no engine modifications which can be made to eliminate these products. Calculations made of the additions of CO$_2$ from the proposed SST fleets show that the global average concentration of CO$_2$ is expected to be increased less than 1 part per million (PPM) compared to an existing concentration of 300 PPM (6). In other words the increase in CO$_2$ is practically negligible.

The effects of sulfur oxides and unburned hydrocarbons cannot be predicted accurately because very little is known about the emissions of these substances at the SST cruise conditions. SO$_2$, which originates from the sulfur contained in jet fuel, tends to form sulfate particles,
which could theoretically change the atmospheric temperature distribution by absorption and scattering of solar radiation. Any problems associated with \( \text{SO}_2 \) could be partially remedied by reducing the sulfur content of SST fuels.

Due to relatively high temperatures of the afterburner in the GE-4 engine (selected for the now cancelled Boeing SST), hydrocarbon emissions are expected to be very small, and would be important only to the extent that they effect the ozone chain reactions (8) (Currently unknown).

The increase in stratospheric water vapor concentration from a typical 1990 SST fleet (600 aircraft, 5 flights per day) has been calculated to be about 0.3 PPM. This appears to be small compared to the perturbation required to produce saturation (50 to 100 PPM) at the observed ambient temperature (5). Exactly how much this amount of additional water vapor will effect the cloud cover is unknown at this time, but it is at least an item of concern, and contrail (condensed water vapor trails from engine exhausts) formation along the SST routes should be monitored closely.

4.2 Effects of a Decrease in Ozone Concentration in the Stratosphere

The effects of additional \( \text{NO}_x \) and water vapor on the ozone concentration are also unknown at this time, but this problem is probably more significant than any others,
for the simple reason that we know that jet engines tend
to produce large quantities of these emissions. Furthermore we know that a certain (unknown) amount of these
substances could drastically and rapidly change the ozone
distribution with corresponding drastic results at the
earth's surface. The only things unknown at this time are
the reaction rates and interaction of the various ozone
destroying chains, which would, for instance, tell us how
much NO\textsubscript{x} is too much.

It is possible to determine, however, how much
reduction in O\textsubscript{3} is too much, by using the corresponding
increase in ultraviolet radiation (UV) as a guide. A study
recently released (February 15, 1973) by the National
Academy of Sciences and Engineering has estimated that
"a 5% decrease in average ozone concentration of the mid-
latitude of the United States would cause a 26% increase in
ultraviolet radiation at 0.2975 microns" (17). This
report indicated that 0.2975 microns is one of the most
biologically detrimental wavelengths of solar radiation.
Potential increases in the incidence of various forms of
skin cancer is only one of several problems associated with
an increase in this type of UV radiation.

Probably the single most important biological effect
of light is the consequence of the absorption of specific
wavelengths of light by specific chemical molecules in
a cell and the resultant photochemical alteration.
Biologists have discovered that the molecule (DNA)
(deoxyribonucleic acid) is the most important molecule in a cell since it carries the genetic information of that cell. DNA is easily modified by exposure to ultraviolet radiation and this is why ultraviolet radiation is detrimental to living organisms. Although most living cells have a remarkable capacity to repair damage to their DNA, there is a delicate balance between the continual destruction of cellular components by solar radiation and their biochemical repair mechanism. If this balance is upset by exposure to increased amounts of radiation or by interference with repair, the organism will be injured and may die, or mutations may appear in offspring. The ease with which bacterial strains, genetically deficient in repair capacity, are killed by UV radiation is shown in Figure 21, where their survival rate is compared to that of a repair proficient strain (13).

Most people are aware that excessive sun exposure can cause sunburn (and skin cancer in some people), the fading of colors and the aging of many materials, especially plastics and paints. In spite of these detrimental effects on man, the more serious question to be considered is what effect an increased amount of ultraviolet radiation might have on plants and animals.

It has been found that most insects see in the near ultraviolet (0.3-0.4 microns) as well as in the middle portion of the solar spectrum. Near-ultraviolet (UV) is a distinct color for many species and has special
Figure 21 - The sensitivity of different strains of Escherichia coli K-12 to UV radiation (0.254 microns). The survival curve marked "original" is the "wild type" parent strain from which the other strains were derived. The uvr-A6 mutant is deficient in the excision repair of radiation damage. The rec-13 mutant is defective in the postreplication repair of radiation damage. The double mutant uvr-6 rec-13 is deficient in both repair systems and is much more UV sensitive than either of the single mutants, which, in turn, are sensitive than is the wild type strain. (17)
significance in influencing behavior (13). Since near-UV is the most effective spectral region in attracting insects, light traps use UV lamps. On the other hand, lamps that are poor in blue and UV light offer much less stimulation to insects, so yellow bulbs are frequently used on porches and patios.

Research has revealed other less obvious but vastly more important examples of the ecological importance of UV radiation: Many insects, particularly bees, appear to use a type of "celestial navigation" using the patterns of polarized UV light which vary in a systematic way with the position of the sun (17). This system works with solid cloud cover because UV radiation will penetrate clouds.

UV reflectance is important in the pollination process in flowers. It has been found that many flowers, which have no pattern to the eye of man, display to insects characteristic patterns which guide bees to the center of the blossom, thus aiding pollination (17).

The effects of UV radiation on plants is not quite as well documented as on insects, but basic facts have been determined. There is considerable variation among plants in their sensitivity to UV radiation. Grasses and conifers seem to be more resistant than broad leaf species, while some agricultural species (such as tomatoes, sugar beets, clover, lettuce, and watermelon) appear to be the most sensitive. These differences in sensitivity have been attributed to differences in orientation and optical properties of the outer tissue layers of various plants (17).
SECTION 5

SUMMARY AND CONCLUSIONS

How does one summarize all these related, (and some unrelated), bits and pieces of information? In researching this admittedly wide ranging subject and attempting to organize all the aforementioned data in my own mind, I have become particularly aware of several recurring conclusions:

1. Data on the concentration and distribution of many compounds in the atmosphere is far from complete, particularly with regard to NO, NO₂, SO₂, HC and water vapor. While this was somewhat frustrating to one researching this subject, it is a fact, and at this point all we can do is realize these limitations in the data and use it with caution. The situation should improve measurably in the next year or so, because numerous government programs, initiated by the great debates on the SST question in 1967, are targeted for completion in 1974. The coming year should produce some very interesting information on this subject. Weather satellite data and the current Skylab experiments will further increase our knowledge of the atmosphere.
2. In one area where we do have considerable data, namely the nature of the ozone layer and its role in absorbing UV radiation, the prospects of large scale contamination of the stratosphere by a fleet of SST aircraft is extremely serious. Circumstantial evidence certainly indicates a potential problem: Jet engines produce NO\textsubscript{x} emissions and water vapor; the ozone concentration can be catalytically reduced by small concentrations of either of these compounds; and lastly an increase in UV radiation can have severe impacts on man and his environment. It would be poor judgement not to proceed with utmost caution in encouraging SST development while the NO\textsubscript{x}, H\textsubscript{2}O ozone interaction problem is unresolved.

3. The biological effects of increased UV radiation are particularly impressive and the significance of these effects probably outweighs any other possible changes to the earth's climate discussed in this paper. This concern was well articulated by Dr. Kendric Smith, a prominent radiologist in an address to the Survey Conference of the Climatic Impact Assessment Program (4). He stated, "In spite of the detrimental effects UV has on man, the more serious question to be considered is what effect increased UV radiation might have on plants and animals. If plants (including plankton) were killed by an increase in radiation or if the
behavior of insects is altered such that they no longer pollinate plants, the ecological consequences would be much more severe than even the production of thousands of extra cases of skin cancer in humans."

4. In the areas of low-emission jet engine development, it appears that much of the necessary technology is already available. The NASA efforts seem to have been particularly successful and should certainly be continued. Incorporation of this technology into an engine with acceptable cost and performance is an engineering problem, and the various engine manufacturers should be encouraged to work on this aspect.

In summary, I believe that due to the existence of several potential environmental problems associated with injection of uncontrolled jet engine emissions into the stratosphere, large scale operation of the current crop of SST aircraft (the British/French Concorde and the Russian TU-144) should be discouraged or at least limited to altitudes below the stratosphere. Sound engineering judgement would dictate that endorsement of the high altitude SST aircraft should be withheld until better data on engine emissions, and atmospheric composition and reaction rates can be obtained.
Heat of Reaction Calculations

The general expression for heat of reaction \( (H_r) \) is:

\[
\Delta H_r = \sum N_f \Delta H_{f_f} - \sum N_i \Delta H_{f_i}
\]

where:

- \( N \) = number of moles
- \( i \) = subscript indicating initial conditions
- \( f \) = subscript indicating final conditions
- \( \Delta H_f \) = Standard heat of formation - the increment in enthalpy associated with the reaction of forming the given compound from its elements, with each substance in its thermodynamic standard state. Values are tabulated as a function of temperature in the JANAF Thermochemical Data Tables, compiled and calculated by the Dow Chemical Company, Thermal Laboratory, Midland, Michigan.

The following tabulation is taken from the JANAF Tables:

<table>
<thead>
<tr>
<th>Compound</th>
<th>( \Delta H_f(T) )</th>
<th>( T = -50^\circ C = 223^\circ K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>59.418</td>
<td></td>
</tr>
<tr>
<td>0(_2)</td>
<td>-0.5293</td>
<td></td>
</tr>
<tr>
<td>0(_3)</td>
<td>34.219</td>
<td></td>
</tr>
</tbody>
</table>

**REACTION(1)**

\[
\text{0}_2 + h\nu \rightarrow 20
\]

or \( \frac{1}{2}\text{0}_2 \rightarrow 0 \)

\[
\Delta H_r = (1)(59.418) - \frac{1}{2}(-0.5293) = +59.682 \text{ kcal/mole}
\]

**ENDOTHERMIC**
REACTION (2)

\[
\begin{align*}
0_2 & \rightarrow 0 + M \\
\Delta H_r & = (1)(34.219) - (1)(-0.5293 + 59.418) \\
& = -24.67 \text{ kcal/mole} \quad \text{EXOTHERMIC}
\end{align*}
\]

REACTION (3)

\[
\begin{align*}
0_3 & \rightarrow 0 + 0_2 \\
\Delta H_r & = (1)(59.418 - 0.5293) - (1)(34.219) \\
& = +24.67 \text{ kcal/mole} \quad \text{ENDOTHERMIC}
\end{align*}
\]

REACTION (4)

\[
\begin{align*}
0 + 0_3 + M & \rightarrow 20_2 + M \\
\text{or} \quad \frac{1}{2}0 + \frac{1}{2}0_3 + M & \rightarrow 0_2 \\
\Delta H_r & = (1)(0.5293) - (\frac{1}{2})(59.418 + 34.219) \\
& = -47.348 \text{ kcal/mole} \quad \text{EXOTHERMIC}
\end{align*}
\]

REACTION (5)

\[
\begin{align*}
0 + 0 & \rightarrow 0_2 \\
\Delta H_r & = (1)(-0.5293) - (2)(59.418) \\
& = -119.365 \text{ kcal/mole} \quad \text{EXOTHERMIC}
\end{align*}
\]
Section 7

References


