THE PROBLEM OF POLLUTION FOR THE SST *

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Abstract

A qualitative review of the possible effects of the exhaust gases discharged by a large fleet of SST's in the upper atmosphere is given. The review indicates the importance of the NO production in the exhaust gases. The mechanism of NO formation by the combustion process is described. A method for reduction of the NO formation is presented.

I. Introduction

Recently sound scientific work has indicated that the possibility exists for the exhaust gases of a large fleet of airplanes flying in the stratosphere to shift significantly the equilibrium of the stratosphere. This important point has been raised in the past in connection with the introduction of a fleet of supersonic airplanes for commercial use. However, possibly the contribution of subsonic airplanes can have similar effects.

A study of the possibility that this effect can actually be important is extremely complex because the problem is not amenable to simple analyses or to accurate evaluation. The possible effects produced by the discharge of the exhaust gases, if they actually occur, will take place in a long period of time, and therefore are difficult to detect. In addition many different phenomena are involved in the process such as the chemical and physical processes taking place in the atmosphere, the diffusion mechanism of the exhaust gases in the atmosphere due to turbulent diffusion, and to the atmospheric motion that determines the residence time of such gases in the stratosphere. Even if these effects could be accurately estimated, it would be difficult to evaluate with some accuracy, the consequences of such effects on the climate of the future and on the detailed distribution of the radiation from the sun because of the difficulties in estimating the changes taking place naturally during a long period of time. In view of the difficulties of such analyses, and of the importance of the possible consequences of such emissions, a prudent approach for the engineer is to minimize such influence by attempting to reduce the presence of the important elements to values that are much smaller than the values presently existing in the atmosphere; it can be assumed that then these effects will not be too important. This can be obtained by two means: (1) limiting the total number of airplanes flying by introducing a selective criteria that takes into account the weighted importance of the contribution of each airplane; and (2)reducing to a minimum the contribution of important pollutants produced by each airplane. A discussion of some aspects of this approach is presented here based on what knowledge is available today.

Presently a very detailed investigation of the problem is being performed by the Department of Transportation (DOT) in the USA under a special program, CIAP (Climatic Impact Assessment Program) under the direction of Dr. Grobecker. The objective of this program is to analyze many of the points described here as accurately as possible. Some of the partial results of the study have been presented at technical meetings and are used here in order to define the problem.

The exhaust gases from turbojet engines using hydrocarbon fuels contains mainly CO_2 and H_2O. If hydrogen fuel is used then the main product is H_2O; however, they contain traces of other gases. Such traces are CO, oxide of nitrogen, either NO or NO_2 indicated here as NO_x, oxides of unburnt sulphur, hydrocarbons and carbon. The impurities that can be important for their long-range effects are the oxide of nitrogen and of sulphur. The concentration of such impurities is minimal; however, they have an important effect on the composition of the atmosphere because when injected in the stratosphere, all impurities have a very long residence time. The oxide of nitrogen presently appear to be the most important because when injected in the stratosphere it has a catalytic action which tends to reduce the ozone concentration present at these altitude. The reduction of ozone affects the amount of ultraviolet radiations reaching the surface of the earth.

The SO_2 in the engine exhaust products could increase the aerosol sulphate in the stratosphere and increases the attenuation of solar radiation. In addition, the water vapor of the exhaust gases could increase the water content in the stratosphere, and increase to long wave radiations and possibly generate stratospheric clouds. The carbon dioxide can also change the radiation flux and therefore affect the climate.

The effects due to the presence of such products in the atmosphere occur in a long period of time. Therefore, in order to evaluate the relative importance of the airplane exhaust in the atmosphere a conservative estimate needs to be postulated of a possible fleet of airplanes flying in the future, as well as a determination of the perturbation produced by such a fleet if present engine technology is used. If the contribution of such a fleet is found to be significant, an additional step is required where an analysis involving possible obtainable reduction by means of advanced technology is considered. If this analysis shows that the components of the exhaust

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gases which are potentially dangerous, can be substantially reduced, then plans to develop such technology must be made before a large fleet of airplanes is introduced. Until this technology is made available the approach that limits the number of airplanes should be used.

Many different predictions related to airplane traffic for the next two decades have been made by the aircraft industry and the airlines. Such projections indicate a rapid but gradual growth of the present subsonic fleet and creation of a new supersonic fleet. All of the projections are arbitrary because they depend strongly on postulated rates of progress for the technology, and for the economy, as well as for the population of the world. In addition the conclusions of such analyses are strongly affected by many different parameters such as the relative increase in the future of the value of time required for travel with respect to the increase of the value of raw materials, and the economical value of comfort, which cannot be clearly defined. All analyses by necessity neglect the possibility of major changes due to new developments of an economical, social or political nature. Many of these parameters besides the economical parameters are important for the development of future modes of transportation. Because of the many factors involved, even short range projections directed to predict traffic growth have been often incorrect. In view of the fact that we try to discuss only if new technology is required, we will assume conservatively that the SST airplanes will be successful and will be a major component of the commercial fleet without attempt to define the time required. On this basis, we will consider in the analysis presented here that the fuel burnt by the SST fleet will be large and of the order of 1.0×10^{11} kg/year (10^8 tons/yr) cruise altitude (the total world fuel consumption is about 10^{10} tons/yr). This number is of the same order of magnitude as the fuel consumption predicted by some projections for the period 1990 to 2000. The number of airplanes corresponding to this consumption of the fleet corresponds to approximately 1500 airplanes. (A large increase in airplane efficiency with respect to present SST prototypes has been postulated in arriving at such a number). Because we are not fixing the year for this projection, the only questionable assumption made here is that the air transportation will be distributed between long-range SST's and shorter-range subsonic fleets.

The burning of such amounts of fuel, if the fuel is hydrocarbon, will produce 3.2×10^{11}Kg of CO_2, and 1.25×10^{11}Kg of H_2O. In addition, the combustion produces CO depending on the temperature of the exhaust gases, SO_2, depending on the sulphur content of the fuel, NO_x depending on the combustion process, and a minimal amount of unburnt carbon and hydrocarbons. The CO produced combines in a large extent in the mixing downstream of the jet in view of the fact that at high temperatures the reactions are fast, while the mixing is slow due to the large size of the jet. A simple analysis indicates that the CO will rapidly disappear during mixing and values on the order of 10^{-3} Kg per Kg of fuel can be considered representative of the worst conditions after jet mixing The sulphur contained in present aviation fuels vary between 0.15% to 0.02% depending on the source. Removal of the sulphur content is possible. Reduction of sulphur content in the fuels to values of the order of 0.015% in weight is feasible at a small cost (of the order of 10¢ per barrel). Present combustors not designed to reduce NO_2 production produce about 20 g of NO_x per Kg of fuel burnt when measured as NO_2. Then a comparison between present global concentrations and additions due to impurities can be made. The stratospheric mass contains approxiamtely 1×10^{18} Kg of gas. The knowledge of the chemical composition of the stratospheric mass is not very accurate, approximate estimates are available which are presented here. The present composition and the additions due to the SST fleets postulated here is shown in Table I. It is evident from this comparison that when the sulphur is removed from the exhaust gases the two chemical products to be considered as possibly important are NO_x and possibly water vapour. The NO_x must be of primary concern, because the presence of NO_x in the atmosphere has important consequences on the conditions on the earth and the amount introduced by the SST fleet assumed here is about the same as the amount presently believed to exist in the atmosphere.

Residence Time of Impurities in the Atmosphere

The importance of the introduction of pollutants depends on the time required to eliminate the impurities by a mechanism of atmospheric diffusion which depends on atmospheric currents and turbulence. The information available for the diffusion in the stratosphere has been obtained mainly from tracing radioactive aerosols produced by atomic explosions.. Residence times of the order of one year have been determined for altitudes on the order of 65,000 ft that are typical for SST operations. The residence time is much shorter in the equatorial region than near the pole The residence time at altitudes on the order of 30,000 to 40,000 ft typical for subsonic operation depends also on the latitude and is of the order of a few days to a few weeks.

Possible Effects of Increase of the Water Vapor and NO_x Content in the Atmosphere

The increase of water content in the stratosphere can have several consequences: (1)it affects the infrared radiation flux; (2)it can change the precipitation and the energy balance at the earth's surface; and (3)it can change the surface temperature. In addition it can affect the NO_x cycle and can react slowly with O_3 producing destruction of ozone. An accurate determination of the effects on the weather is extremely difficult; however, the effects of the presence of H_2O on the temperature are opposite to the increase in aerosols in the stratosphere. It is believed that such effects are small. The direct interaction of the water with O_3 is also small, contrary to the initial conclusions highly advertised during the discussion on the SST in the U.S.A. The interaction of H_2O with the NO_x tends to decrease the effects of the NO_x in the depletion of ozone. Then it can be expected that the injection of large quantities of NO_x in the stratosphere is the most objectionable effect of the exhaust gas pollution because such injection is large with respect to the NO_x existing in the atmosphere and because it tends to reduce the ozone concentration in the stratosphere. Figure 1 gives an indication of the ozone distribution in the stratosphere.

The ozone in the upper atmosphere is produced by photochemistry, while near the earth it is produced by methane oxidation and is largely destroyed by means of catalytical chemical processes involving atmospheric traces and by transport to the stratosphere. It is difficult to estimate the losses due to transport phenomena; however, it is believed that the loss rate due to chemistry are predominant. The amount of chemical losses due to the oxygen reactions as predicted by Chapman involving only oxygen and diffusion cannot justify the balance between the ozone produced and the ozone destroyed. Therefore, it has been concluded that other reactions must be important for the ozone losses. The conclusion reached by Johnston is that the balance of O_3 production and losses must be balanced largely by NO_x reactions (see Johnston, et al. Ref. 1)

The accepted reactions involved are shown below in Table II Recently the chemical reaction rates for these reactions have been determined. The results of these studies confirm the importance of the NO_x concentration as catalyst on the mechanism of destruction of the ozone, and the minor effect due to increase of water concentration. The ozone is a very important element of the upper atmosphere because it absorbs ultraviolet radiations from the sun in the range below 300 nm, and determines the temperature level in the stratosphere. The importance of the NO_x production is related to the local density of ozone which peaks around 20 Km; therefore, the production of NO_x due to the SST fleet is the most important because it has much longer residence time than the NO_x of the subsonic transport and is injected in a region where the ozone concentration is very high. The effect of a given NO_x production on the ozone depletion increases an order of magnitude if the altitude of flight changes from 14 Km to 23Km.

The reduction of ozone concentration increases the radiation reaching the earth below 300 nm. Such increase tends to increase substantially the intensity of solar ultraviolet radiation reaching the troposphere and the atmosphere at the surface of the earth.

The analyses show that for a decrease of a small percent of the total ozone present in a given region in the atmosphere the radiation intensity reaching the earth increases by a large factor. Typical relations corresponding to a 30° angle from the zenith are shown in Figure 2, Reference 2, Caldwell (pp. 386-393).

The ultraviolet radiations affect aquatic organisms, plants, and animals. Here only one of the effects on man will be described. High doses of ultraviolet radiations increases the occurence of skin cancer, and has other effects on the skin and on the eyes. An analysis has been performed on the occurrence of skin cancer in different regions where the population is exposed at different and known intensities of ultraviolet radiation because of the different latitudes. On the basis of these analyses it has been postulated that a decrease of ozone on the order of 10% with respect to the present total content could increase substantially the incidence of skin cancer close to the equator, and in the regions of North America and Europe. As stated by H. Blum, Ref. 2,(pp. 373-378): "At present we are in no position to predict the effects of increased ultraviolet radiation in sunlight, resulting from decreased ozone cover on the incidence of skin cancer in man. For example, erythema, whose optical sensitivity spectrum is currently used as the measure of UV effects on skin, is not closely enough related to cancer growth to serve as an index. But more important, only recently have ultraviolet irradiance and skin-cancer incidence been studied simultaneously in the same geographical area. Many more measurements are needed, preferably with instrumentation which takes into account scattered radiation. Even when accurate data on UV radiation, skin cancer, and the ozone cover are available, however, it will be difficult to make sound predictions.

"Laboratory experiments indicate that only wavelengths between about 0.29μ and 0.32μ normally cause cancer, but that large doses at longer wavelengths may also be effective. It has also been shown in the laboratory that the cumulative effects of successive doses result in accelerated cancer growth. If this holds true for man, the incidence of skin cancer should be a function of the square root of annual UV radiation in sunlight. The varied characteristics of the human population complicate any estimates.

"The physiological effects of reducing the ozone cover are very difficult to estimate, and education in the matter of exposure could mitigate them considerably. The greater dangers may be those which effect the ecological balance of the earth."

The same situation exists for other ecological effects. Many of the problems involved are extremely complex and not amenable to analysis. It can be concluded from what is known that a decrease of 1% in ozone or higher in the stratosphere could be dangerous for humanity. The relation between present decrease of ozone and increase of NO_x in the stratosphere depends on the local concentration, on the diffusion mechanism and on the chemical processes. It is impossible at this time to define the final equilibrium condition of the stratosphere, after an initial perturbation in the NO_x level has been introduced. However, in order to obtain orders of magnitude, on the necessary improvements required, a simple calculation can be performed on the basis of chemical processes alone. This type of analysis has been performed initially by Johnston in 1971. He considered only the reactions between the NOx and the ozone. On the basis of his simplified analysis, he concluded that an injection at 20 Km of 2×10^{9} Kg of NO_2 per year could decrease by 10%. the ozone content in the atmosphere, if the level of emission remained constant. A reduction of at least an order of magnitude in NO_x concentration is required for bringing the percentage of reduction of ozone to values of the order of 1%. More recent calculations have included in the analysis other reactions and have reached similar conclusions indicating that reductions of a factor of 10 to 50 in NO_x concentration should be considered as a prudent goal for the emission of the engines.

The Mechanism of NO_x Production in Present Combustors

Present combustors for turbojet engines inject liquid fuel atomized by a spray nozzle in a combustion region where high turbulence is produced. The liquid fuel droplets vaporize and react with the air reaching locally high temperatures (Ref. 3). Then the combustion gases are diluted with additional air in order to produce gases having temperatures acceptable by the turbine. In this process three steps are taking place. The fuel is injected as a liquid droplet. A typical droplet size has diameter between 10 microns and 100 microns. When the droplet is injected in the air, first the fuel evaporates, then pyrolizes and finally reacts with the air. This process is strongly affected by the turbulence of the air; however, because of the small dimensions of the droplet, the droplet moves locally with the surrounding air (Reference 3); therefore, the mixture during vaporization and combustion can be visualized as a volume containing mainly fuel surrounded by a gas that is mainly air. The fuel diffuses into the air, and locally a diffusion flame is generated in the region surrounding the droplet. The air temperature downstream of the compressor is of the order of 500°K to 1000°K. The flame is generated in the combustion in a region of low velocity and is maintained by creating recirculation zones, where very high temperatures are obtained; therefore the combustion occurs in a very short time in the region where the fuel/air ration is close to stoichiometric (Refs. 3 and 4). Then locally, very high temperatures are obtained. For this type of combusion mechanism the combustion takes place in a region where the mixture is close to stoichiometric, then the maximum temperature reached locally depends mainly on the temperature of the air downstream of the compressor which is a function of Mach number of flight and compression ratio of the compressor. The final temperature is higher for higher initial air temperatures.

A chemical kinetic analysis can be coupled with the fluid dynamic process (Reference 4 and 5) in order to determine the amount of NO_x produced in the process. The chemical process is divided into two steps: vaporization and pyrolysis of the fuel, then combustion. Typical chemical reactions for combustion includes two groups of reactions the C H O reactions and the N O N H O reactions. Typical N O reactions to be considered are shown in Table III Then the time history of the NO formation can be obtained Some typical time histories are shown in Figures 3 and 4 (References 3 and 4). The figures give the variation of temperature as a function of time for a stoichiometric mixture of hydrocarbons and air, and the variation of concentration of different species as a function of time. The figures show several important points: the time involved in the chemical process is of the order of 10^{-4} sec. Then in a flow moving a few hundred feet per second as the flow in a burner the time corresponds to travel of the order of fractions of inches. No appreciable diffusion can take place in this time; therefore, the combustion around the droplet can be accurately represented on the basis of local phenomena, and therefore occurs at mixtures close to stoichiometris values. The NO formation occurs near the end of the carbon hydrogen reactions, when the temperature is high because only for these conditions the nitrogen molecule dissociation take place. The delay time is very small and the NO forms in large quantities practically immediately, and then increases slowly after the initial rapid formation. It is impossible to reduce substantially the local temperature in a few 10^{-4} sec. by mixing; therefore, the minimum value of NO produced in this type of process will correspond to the first level of NO formation. However, rapid cooling of the exhaust gases prevent the gradual increase of NO which can increase the NO concentration by an order of magnitude. A practical mixing time is of the order of 2 to 5×10^{-3} sec. Then the value of NO produced can be evaluated by determining the value of quick concentration in terms of initial air properties for existing burners. This analysis has been done in Reference 4. Figure 5 gives the maximum local temperature after combustion in terms of the initial air temperature for this mechanism (stoichiometric combustion) and Figure 6 gives the NO produced rapidly defined as NO in terms of the maximum temperature reached in the combustion region. Present engines for the SST operation at M = 2.7 will have compression ratios at cruise between 5 and 10. Then the index of NO_2 emission will be in the range shown in Figure 6. The data for the Concorde engine at cruise have been measured. This value is also indicated in Fig. 6. In addition the experimental data in actual combustors are also shown.

A large reduction of NO_x production cannot be obtained unless the combustion mechanism is changed. A different combustion mechanism has been suggested in Reference 3 which permits such reduction. The final temperature required for the mixture is fixed by the turbine design. The maximum temperature predicted for advanced engines are of the order of 1800°K or lower. The data of Figure 6 shows that even if the maximum value reached in the burner is slightly higher than the required value then the NO_2 produced would be two orders of magnitude lower than the values produced in present combustors. In order to achieve this result the scheme proposed in Reference 3 is to gassify the fuel and premix as uniformly as possible with the air at a ratio below stoichiometric selected to give after combustion the value of the temperature required by the cycle. If this is obtained then the reaction occurs at a molecular scale and thermal equilibrium with the non-reacting molecules is reached in much shorter time, because of the high pressure, than the 10^{-4} seconds required for the formation of NO, and the NO is not formed. This approach requires to burn a mixture at very low fuel air ratio. This is difficult to do when the air temperature is low. However, for conditions of supersonic flight it is possible to have efficient combustion at low fuel mixtures. Analyses performed, References 4 and 6 indicate that short and efficient flames are possible. Experiments have been performed that prove that this concept is sound. Some have been published in Reference 3; others more detailed have been performed recently for NASA, Reference 8. The apparatus used is shown in Figure 7. The fuel is injected in the stream as a spray. The fuel vaporizes immediately because of the high air temperature. The length of the vaporizer of the test was 12"; some of the results are shown in Figure 8, where the emission index is plotted as a function of the equivalence ratio ϕ , that is, the fuel-air ratio rates measured with respect to the stoichiometric fuel-air ratio. It is seen that values of about 0.4 to 0.6 can be obtained. The theoretical values for perfect mixture are also indicated in Figure 8.

The efficiency of the combustion has been measured in the tests and is shown in Figure 9. The difference between experiments and analysis is due to the fact that in the experiments, the mixing of the fuel and air at high fuel injection was far from uniform. When large amounts of fuel is injected because of the high pressure of injection, then some fuel reaches the walls of the mixer and vaporizes and burns near the wall. Then the concentration near the wall is much higher than the average selected value. These experiments indicate that indices below 1 and as low as 0.3 have actually been obtained, and indicates that better results can be obtained by controlling the mixing.

A possible mechanization scheme of such a system in an engine is shown in Figure 10 . At high Mach number flight, the fuel is injected downstream of the compressor before a vaporizer, then the combustion takes place downstream in the burner. For take-off and low speed flight, the fuel injected at the burner and part of the air is bypassed by moving the entrance flap. Since the fuel is injected at the flame holder as liquid spray as for the present engines, the performances of the burner will not change. This scheme can be mechanized if required.

Concluding Remarks

Recent available information on the interaction of the exhaust gases discharged by airplanes with the upper atmosphere tends to indicate that important chemical effects can be produced. The effects are important when large fleets of airplanes fly in the stratosphere where the residence time is long. It is presently believed that these effects are due mainly to the formation of nitric oxide and SO_2. The sulphur can be removed from the fuel at a small cost. The NO_x can be reduced by a factor of 50 if required by changes in the combustor designs. Then the danger of large effects can be eliminated even if a substantial number of airplanes are utilized. More detailed conclusions will be obtained from the CIAP study. The time involved in the production of a large fleet of airplanes is large; therefore, time is available to perform more accurate evaluation of all the aspects of the problem and to introduce the required changes in the burner if required.

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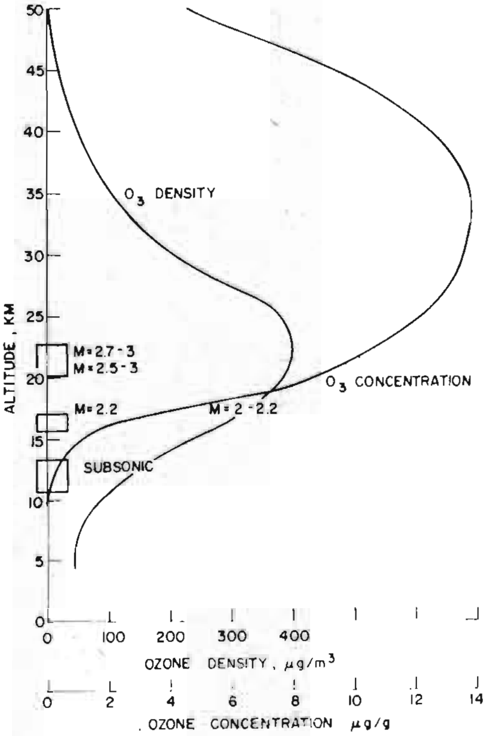


Fig. 1 Ozone Distribution in the Stratosphere.

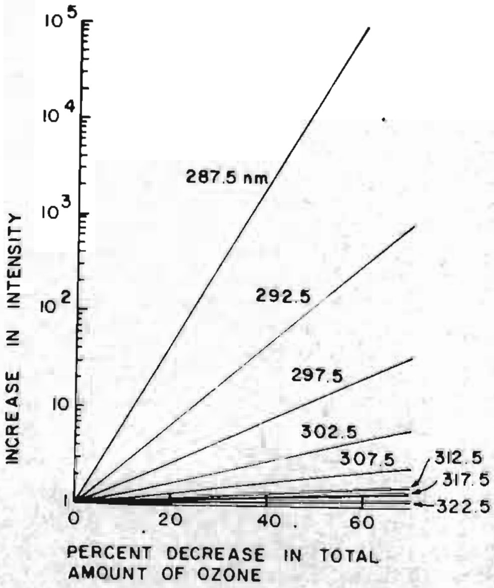


Fig. 2 Increase of Radiation Intensity at Different Wave Lengths as a Function of Percent Decrease of Ozone for 30° angle from the zenith.

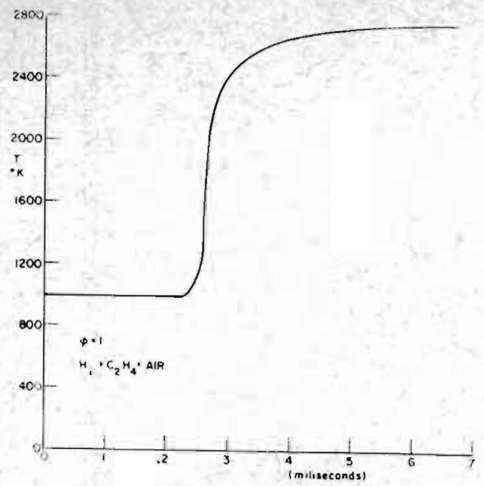


Fig. 3 Temperature Variation as a Function of Time During Combustion.

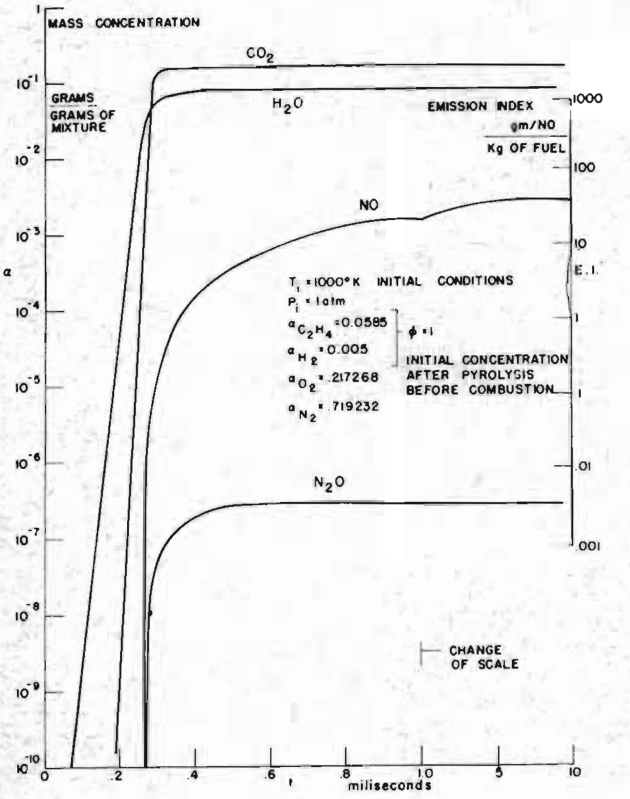


Fig. 4 Variation of Concentration of Species as a Function of Time During Combustion

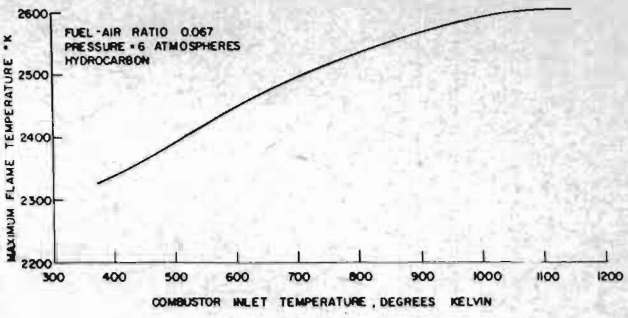


Fig. 5 Maximum Combustion Temperature at Stoichiometric Conditions as a Function of Initial Conditions.

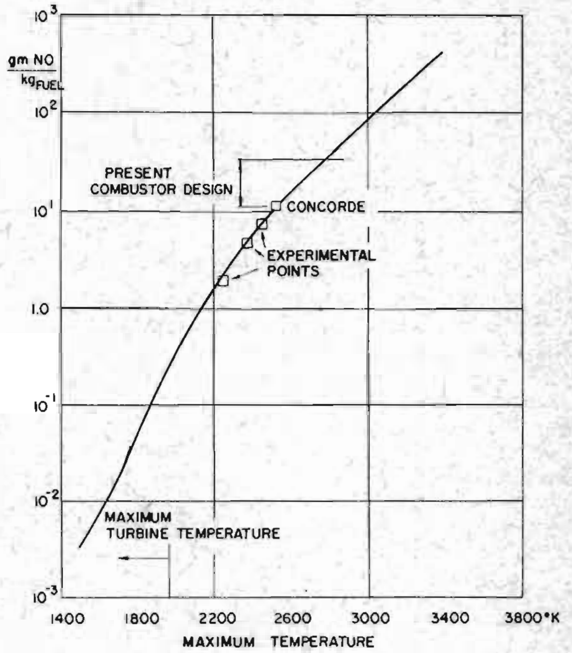


Fig. 6 Emission Index of NO as a Function of Maximum Temperature Reached in the Combustion.

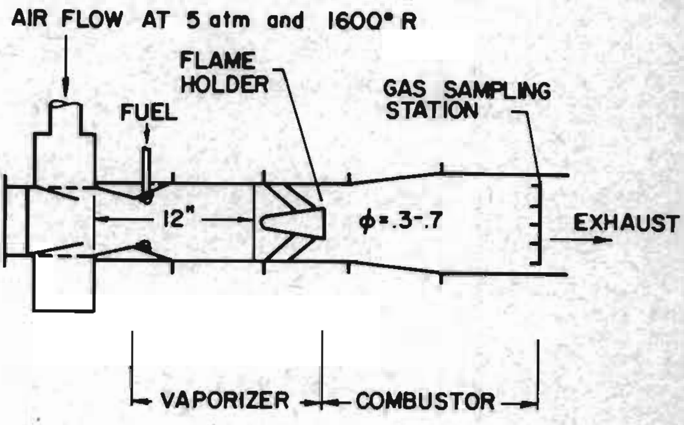


Fig. 7 Apparatus Used in the Tests

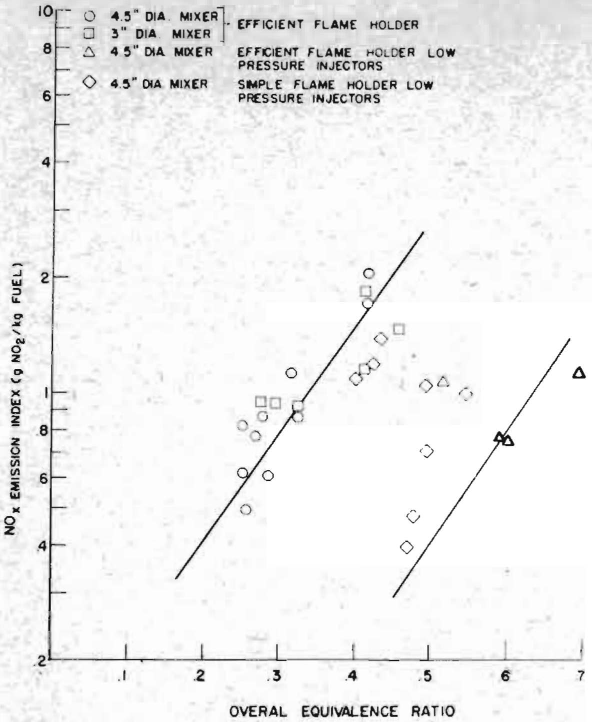


Fig. 8 NO_2 Emission Index as a Function of Fuel Air Ratio Obtained Experimentally.

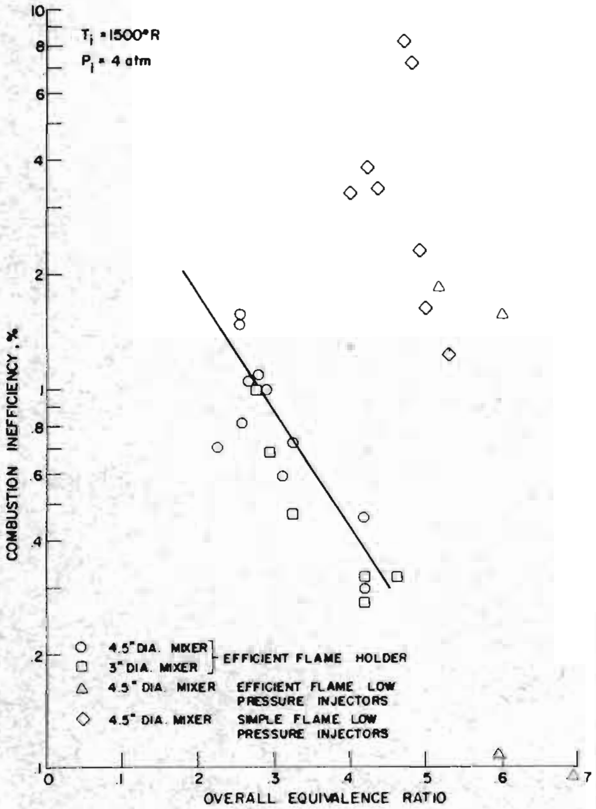
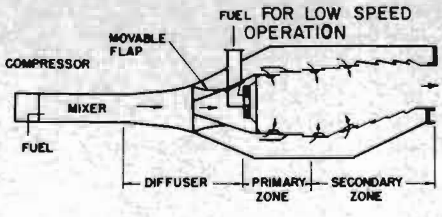
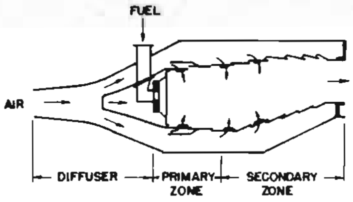


Fig. 9 Combustion Inefficiency for the Results Presented in Fig. 8, from Ref. 8.



a) MODIFIED



b) CONVENTIONAL

Fig. 10 Schematic Representation of Low NO_x and Conventional Low NO_x Combustor Installation.

Table I

	Approximate Mass in the Stratosphere, Kg	(Present Engines) Perturbation from SST 10^{11} Kg fuel/year	Fractional Perturbations
CO_2	5×10^{14}	3.2×10^{11}	6×10^{-4}
H_2O	2×10^{12}	1.3×10^{11}	6.5×10^{-2}
CO	3×10^{10}	1×10^{8}	3.3×10^{-3}
$NO2$	2×10^{9}	2×10^{9}	1
SO_2	2×10^{9}	2×10^{7}	1×10^{-2}

Table II

Chapman Scheme: (it predicts large net excess of O_3)

$$\left.\begin{array}{lll} (1) & O_2 + h\nu(\lambda < 242 \text{ nm}) & \rightarrow 2O \\ (2) & O + O + M & \rightarrow O_2 + M \end{array}\right\} \quad \text{Mainly above 60 km}$$

$$\left.\begin{array}{lll} (3) & O_3 + h\nu(\lambda < 310 \text{ nm}) & \rightarrow O_2 + O \\ (4) & O + O_2 + M & \rightarrow O_3 + M \\ (5) & O + O_3 & \rightarrow 2\ O_2 \end{array}\right\} \quad \text{Mainly above 30 km}$$

Catalytic Cycles for Ozone Depletion

Generally accepted:

a. $O_3 + OH \rightarrow O_2 + HO_2$

b. $O + HO_2 \rightarrow O_2 + OH$

Net: $O + O_3 \rightarrow 2\ O_2$ — Mainly above 45 km; reaction (a) may also be significant at 15-20 km.

c. $O_3 + NO \rightarrow O_2 + NO_2$

d. $O + NO_2 \rightarrow O_2 + NO$

Net: $O + O_3 \rightarrow 2\ O_2$ — Mainly above 25 km

e. $O_3 + NO \rightarrow O_2 + NO_2$

f. $O_3 + NO2 \rightarrow O2 + NO3$

g. $NO3 + h\nu(\text{red}) \rightarrow O2 + NO$

Net: $2\ O_3 + h\nu(\text{red}) \rightarrow 3\ O_2$ — Above 15 km

Table III

Chemical Reaction System

1. $2O + X = O_2 + X$
2. $N + N + X = N_2 + X$
3. $N + O + X = NO + X$
4. $N + NO = N_2 + O$
5. $N + O_2 = NO + O$
6. $N + OH = NO + H$
7. $H + N_2O = N_2 + OH$
8. $O + N_2O = N_2 + O_2$
9. $O + N_2O = NO + NO$

DISCUSSION

G. Kappler (Motoren- und Turbinen-Union, Munich, Germany): Is the EPA Parameter which can be divided in a part strictly to combustion (EI) that is pollutant emission and a part of fuel consumption i.e. the thermodynamic cycle going to prevail? As you know it presents problems for us engineers. And if it is going to stay with us for a while what value would you suggest is reasonable for the SST?

A. Ferri: I believe that a value of acceptable emission index of the order of 2 will be acceptable, however I suggest the program of research selects as goal a value of 0.2-0.4, which can be achieved.

D. Brown (National Aeronautical Establishment, Ottawa, Canada): Could Professor Ferri indicate the amount of weight increase his proposals for combustor geometry change to reduce NO production might entail?

A. Ferri: I believe that the increase will be small, of the order of 50 to 100lb. In fact, if the premixed approach can be used all the time then the weight could decrease.

F.W. Armstrong (National Gas Turbine Establishment, Pyestock, U.K.): Professor Ferri had suggested, in reply to an earlier question, that the increase in engine weight required to accommodate his concept of low pollution combustion chamber, would be small - perhaps 50 lb. per engine.

I gave an opinion that the total weight penalty would probably be considerably higher than the author had suggested - on the basis that the longer rotating shaft system in the engine, plus the longer engine casings and cowlings, would add much more weight than the longer combustion chamber itself.

A. Ferri: I am not convinced at all that the new mixer must be longer. The length between the last stage of the compressor and the entrance to the combustor can be used for the mixer.