Aircraft Turbine Engine Emissions under Simulated Supersonic Flight Conditions

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The exhaust emissions were measured in the exhaust plume of a J85-GE-5 turbojet engine as part of an investigation to determine the impact on the climate of flying a fleet of supersonic aircraft in the stratosphere. Measurements were made at three axial stations (0.22, 9.3, and 19.9 nozzle diameters) downstream of the nozzle exit for both military and partial afterburning power at Mach numbers and simulated altitudes of Mach 1.6/55,000 ft and Mach 2.0/65,000 ft. A continuous sampling technique was used to measure carbon dioxide, carbon monoxide, total unburned hydrocarbons, oxides of nitrogen, and particulates. The results represent the only available full-scale turbojet engine emission data to date which have been obtained at simulated high altitude with a supersonic external stream.

Nomenclature

A/B	= afterburning engine power
ALT	= simulated geopotential altitude, m (ft)
A_8	= nozzle exit area at engine station 8, m^2(ft^2) (see Table 2)
CXX	= emission concentration, ppmv (see Table 1)
DN	= fixed nozzle exit diameter, 0.454 m (1.49 ft)
$EIXX$	= emission index, gm xx/kg fuel (see Table 3)
$(f/a)P$	= primary engine fuel-air ratio
$(f/a)T$	= total engine fuel-air ratio (Primary + A/B)
MIL	= military engine power setting (max. engine power without afterburning)
M_∞	= freestream Mach number
PTJ	= impact pressure in exhaust plume, N/cm^2 (psia)
PLS	= power lever setting
$\bar{p}_{t2}$	= average compressor inlet total pressure, N/cm^2 (psfa)
$\bar{p}_{t2}/p_{t_\infty}$	= inlet total pressure recovery
p_{t_∞}	= freestream total pressure, N/cm^2 (psfa)
R_N	= radius of fixed nozzle exit, 0.227m (0.746 ft)
R	= radial distance from exhaust centerline, m (ft)
SCF	= standard cubic feet
TTJ	= total temperature in exhaust plume, °K (°R)
T_{t5}	= turbine discharge total temperature, °K (°R)
T_{t_∞}	= freestream total temperature, °K (°R)
WA	= compressor inlet airflow, kg/sec (lb/sec)
XP	= axial probe position, m (ft), see Fig. 1
XR	= plume survey axis

I. Introduction

THE unknown environmental impact of a fleet of supersonic aircraft operating in the stratosphere has resulted in a Department of Transportation (DOT) investigation named the Climatic Impact Assessment Program (CIAP). The results from this program will be used to assess the climatic impact of exhaust emissions from turbine-powered aircraft operating in the stratosphere as projected to the year 1990.[1] The exhaust emission data presented in this paper will provide valuable information for the CIAP and should add greatly to the state of the art of aircraft turbine engine emissions. The data presented are the only known emission data which have been obtained at simulated high altitude, using a full-scale, turbojet engine.

The test was conducted at the Arnold Engineering Development Center in the Propulsion Wind Tunnel (PWT) Supersonic Wind Tunnel (16S) for DOT using a General Electric J85-GE-5 turbojet engine[2] mounted on an isolated nacelle with a NASA/Lewis Research Center mixed flow axisymmetric supersonic inlet[3] (Fig. 1). The objective of the PWT test was to determine the influence of the mixing of the engine exhaust gases with the external supersonic freestream flow on the exhaust emissions of a full-scale turbojet aircraft engine.

A unique sample probe design (Fig. 2) was required in that not only was the probe to be cooled to withstand the 2000°K (3600°R) engine exhaust, but the gas sample must be quenched very rapidly and maintained at 422 ± 5.6°K (760 ± 10°R) as it is pumped along the long transfer lines to the analyzer to prevent condensation of the various gaseous constituents. The exhaust gas transfer line from the sample probe to the analyzer had lengths of 35.0, 39.6, and 42.6 m (115, 130, and 140 ft), respectively, for probe positions 1, 2, and 3. The entire length of the transfer line from probe tip to the analyzer was concentrically water jacketed to maintain the gas temperature constant with the exception of two short sections (approximately 0.305 m) (1 ft) where a 1.27 cm (0.5 in.) inside diameter Teflon® line with external heater tape was used. A schematic of the sample conditioning system is shown in Fig. 3. A continuous sampling technique was used to obtain measurements of carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), total oxides of nitrogen (NO_x), and the total unburned hydrocarbons (THC). All measurements were made in general accordance with SAE ARP 1256.[4] The gaseous emissions contained in the engine exhaust were measured with seven instruments designed to identify and measure the concentration of six gas constituents (see Table 1). Grissom describes the operating principles of the instruments in greater detail in his recent paper.[5] A continuous sample of the flow approaching the inlet was also maintained to monitor the concentration of CO_2 and THC recirculated in the wind tunnel.

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Index categories: Airbreathing Engine Testing; Jets, Wakes, and Viscid-Inviscid Flow Interactions; Atmospheric, Space, and Oceanographic Sciences.

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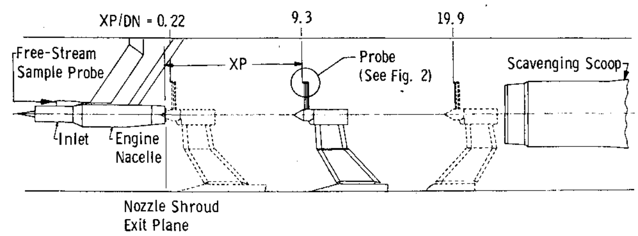

Fig. 1 DOT J85 engine exhaust emission test installation.

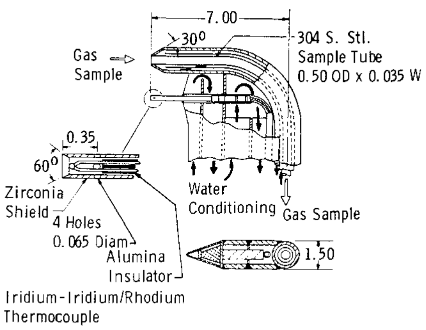

Fig. 2 Exhaust emission sample probe.

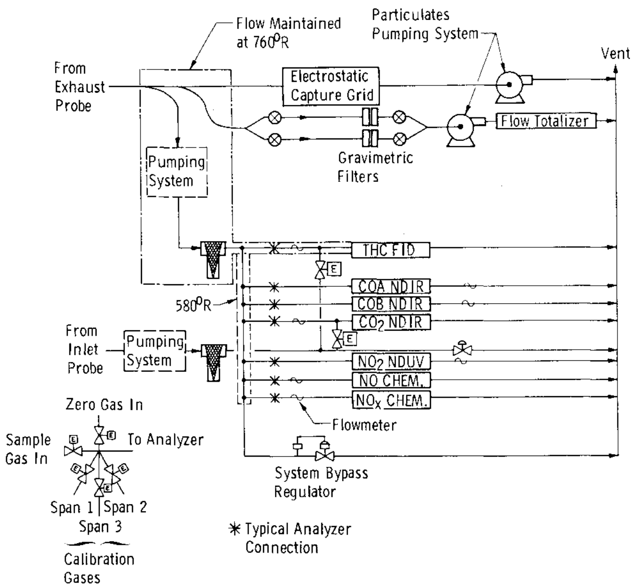

Fig. 3 Schematic of sample conditioning and emission analysis system.

The particulate emissions were measured using 1) gravimetric filters—from which total particulate weight emitted per standard cubic feet of gas flow is determined and 2) electrostatic grids—from which particle sizes and distributions are determined.

Table 1 Emission instrumentation

CONSTITUENT	MEASUREMENT DESIGNATION	UNITS	ANALYZER MODEL	ANALYSIS TECHNIQUE
CO	CCOA	ppmv	Beckman 315B	Non-Dispersive Infrared
	CCOB	ppmv	Beckman 315BL	Non-Dispersive Infrared
CO_2	CCO2	%	Beckman 315B	Non-Dispersive Infrared
Hydrocarbons	CTHC	ppmv	Beckman 402	Flame Ionization
NO	CNOA	ppmv	TECO 10A	Chemiluminescence
NO_2	CNO2A	ppmv	Beckman 255BL	Non-Dispersive Ultraviolet
NO_x	CNOXA	ppmv	TECO 10A	Chemiluminescence with Converter
Particulates	None	-	Millipore	Gravimetric Filters
	None	-	DOT/TSD	Electrostatic Capture Grid

Table 2 Nominal freestream and engine-inlet operating conditions

Free-Stream Conditions	Inlet Conditions			Engine Conditions				
M_∞ / Alt., ft	$T_{t\infty}$, °K (°R)	$\bar{P}_{t2}/P_{t\infty}$	WA kg/sec (lb/sec)	PLS	T_{t5}, °K (°R)	(f/a)P	(f/a)T	A_8, m² (ft²)
1.6 / 55,000	328 (590)	0.935	5.7 (12.6)	Mil	933 (1680)	0.017	0.017	0.0687 (0.74)
				A/B	933 (1680)	0.017	0.035	0.0938 (1.01)
2.0 / 65,000	390 (702)	0.910	5.1 (11.2)	Mil	928 (1670)	0.016	0.016	0.0697 (0.75)
				A/B	928 (1670)	0.016	0.036	0.0957 (1.03)

II. Emission Characteristics in Exhaust Plume

Exhaust emission data were obtained at three axial stations downstream of the nozzle exit of a J85-GE-5 turbojet engine XP/DN = 0.22 (nozzle exit station), 9.3 (midstation), and 19.9 (aft station) at two simulated flight conditions (see Table 2) (M_∞/ALT = 1.6/55K and 2.0/65K) for two engine power settings (military, or max. engine power without afterburning, and partial afterburning). The power lever settings were held constant to maintain fuel flow constant for each probe position. The inlet recovery was set and maintained constant at each Mach number.

One of the first steps taken to investigate the exhaust emissions was to calculate the expansion and mixing of the exhaust plume into an external supersonic flowfield using known engine exhaust performance parameters. A calculation procedure which combines the inviscid flow from a Lockheed method of characteristics solution[6] and a Patankar[7] viscous mixing solution was used to accomplish this. A sketch of the results for Mach number 2.0, 65,000 ft military power is shown in Fig. 4. The plume was sampled at 12 to 13 locations in one or more of four radial planes at each of the three axial probe positions.

Effect of Downstream Distance

The variation of the emission characteristics for CCO, CCO$_2$, CNOX, and CNO shown in Fig. 5 for Mach = 2.0/65,000 ft, military power setting, follow the trends of

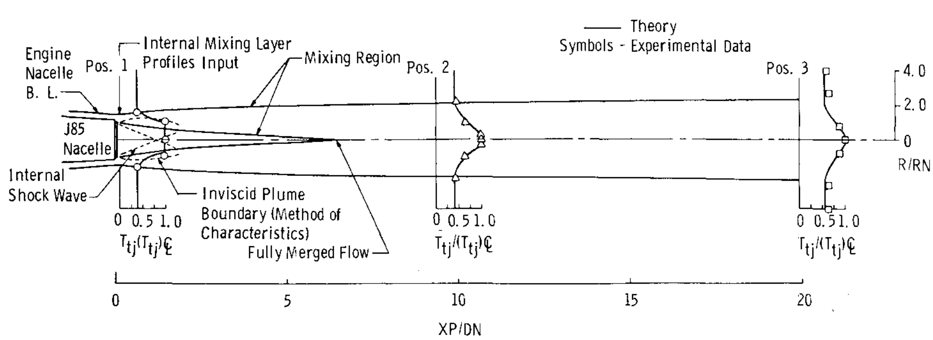

Fig. 4 Theoretical plume expansion with typical exhaust temperature profiles (M_∞ = 2.0/65,000, mil).

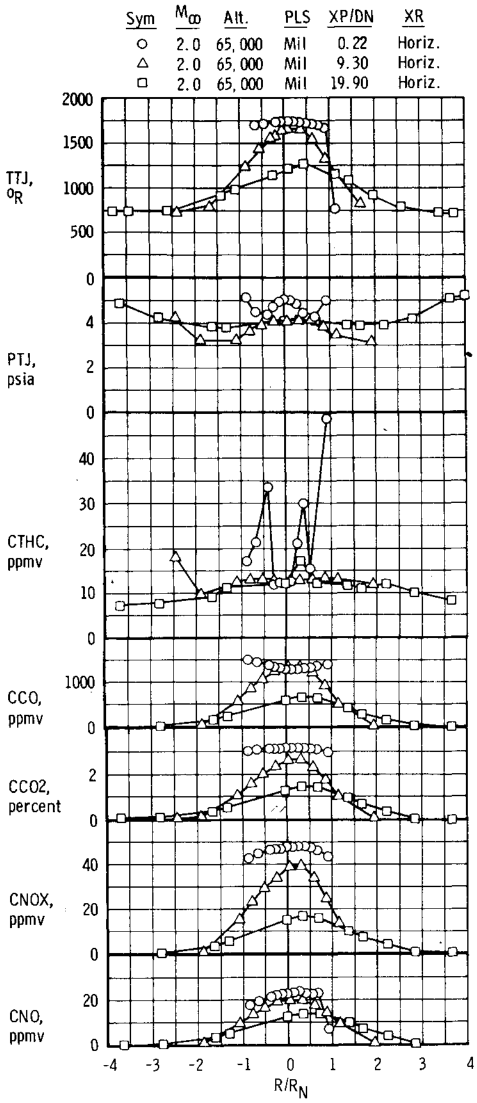

Fig. 5 Variation of emission characteristics with axial probe position (M_∞ = 2.0/65,000, mil).

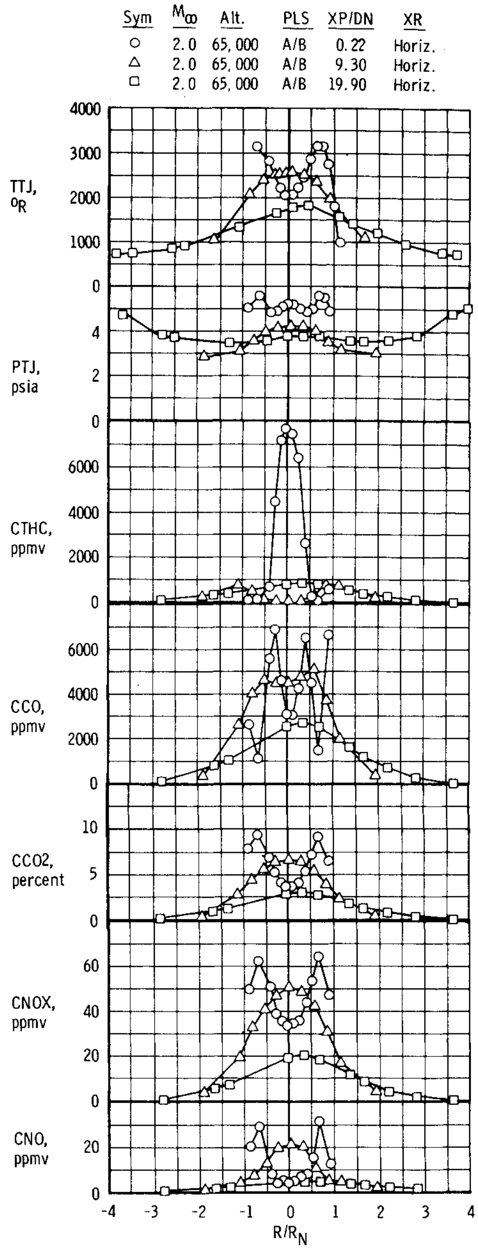

Fig. 6 Variation of emission characteristics with axial probe position (M_∞ = 2.0/65,000, A/B).

the temperature. It is noted that a rather uniform distribution of these parameters exists at the nozzle exit station, but the concentrations and temperature decrease toward the outer edge of the plume for the mid and aft stations. This is the result of the mixing that exists in the downstream plume. The centerline values of these concentrations decrease due to dilution as the plume spreads. The concentrations of THC are not uniform at the nozzle exit. High THC values occur at a radial position approximately equal to the location of the afterburner flameholders. The CTHC profile changes as the flow moves downstream in the plume; however, the centerline concentration remains constant as a result of the complete burning which occurs on the nozzle centerline.

The measured CNO_2 and a calculated value of CNO_2 = (CNOX − CNO) were found to differ significantly. Because the measured CNO_2 values appear to be in error, these data are not presented here. However, these results are presented and discussed in Ref. 8.

Data obtained at Mach 1.6/55,000 ft, military power setting, show the same general trends, differ only slightly in levels, and exhibit a smaller plume diameter. Because of the limited scope of this paper, those results are omitted.

Effect of Engine Power

Examination of the data for afterburning power for either Mach 2.0 or 1.6 shows that the temperature on the nozzle centerline is slightly higher at the midstation during afterburning, Fig. 6. This can be accounted for by continued burning that occurs in the plume, as evidenced by the large reduction in THC on the centerline at the midstation. The other concentrations follow very closely the variation in total temperature. A comparison of the concentrations for military and partial afterburning show generally that the increase in temperature at afterburning results in an increase in the concentration levels.

Effect of Radial Probe Position

Two or more planes were surveyed at each probe station to obtain an accurate indication of the emission profiles. The data show little, if any, circumferential variation in the emission characteristics at the nozzle exit.

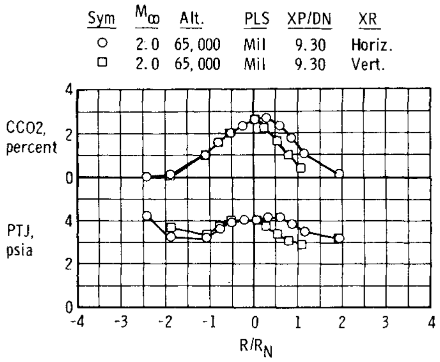

Fig. 7 Typical radial emission profile characteristics at midprobe station.

Table 3 Summary of emission indices

M_∞	Engine Setting	Probe Position Exit	EICO2	EITHC (as CH_4)	EICO	EINO (as NO_2)	EINOX (as NO_2)
			(gm xx/kg Fuel)				
0.0 (Ref. 9)	Military	Exit	3540	5.800	46.0		5.45
1.6	Military	Exit	3004	0.486	85.4	1.47	3.25
		Mid	2963	2.270	108.3	1.84	1.99
		Aft	3013	5.550	70.0	1.75	2.32
2.0	Military	Exit	3003	0.889	85.3	2.30	4.25
		Mid	2985	1.676	88.8	2.88	3.97
		Aft	3002	5.370	77.5	2.96	3.20
1.6	Partial A/B	Exit	2906	21.6	105.8	0.78	1.99
		Mid	2838	29.8	132.5	0.73	2.38
		Aft	2905	21.1	107.7	0.83	1.10
2.0	Partial A/B	Exit	2945	13.3	97.3	0.86	2.15
		Mid	2779	36.7	156.9	0.69	2.20
		Aft	2795	29.0	161.7	0.63	1.78

As one moves to the mid-probe station, a slight change in the profiles is noted. The radial variation of CCO_2 in Fig. 7 for $M_\infty = 2.0/65{,}000$ ft is typical of the emission characteristics at the midstation. It is believed that the decreased concentration at $+R/R_N$ for the vertical survey (which is in the top quadrant) is the nacelle strut effect. This is further verified by the pressure data in Fig. 7. At the aft station, complete mixing has occurred to remove any noticeable variation in the emission characteristics for the planes investigated.

Emission Indices

Since the plume profiles were not completely uniform, the emission indices were calculated using an integrated mass technique. The gas properties were calculated from the measured impact pressure and total temperature. The mass flux of the species being emitted was then divided by an integration of the experimental point by point values of CCO_2, jcco, and CTHC which represented the fuel flow. The method and procedure are described by German et al.[8] This procedure is complicated by the relatively few experimental points taken across the plume, which makes numerical integration difficult. An analysis of the calculated emission index as a function of the axial distance from the exit plane provides information on the influence of external stream mixing on emission characteristics. If the emission index of a species is nearly constant as a function of axial position, then there has been a conservation of species and either no significant reactions have taken place during the plume mixing or no afterburning occurred outside the engine. Table 3 shows the values of the emission indices obtained at each axial location for each gaseous emission measured. (Values for the military case at static sea level[9] are shown for comparison.) Several observations can be made concerning the values shown starting with the first column and proceeding across the table. The $EICO_2$ is, as expected, nearly constant since the CCO_2 level depends primarily on the fuel/air ratio and combustion efficiency. Very good agreement is seen at military power for Mach 1.6 and 2.0.

The EITHC at the exit plane which are calculated on a CH_4 basis are very low for military power. The results show that the EITHC increases with axial distance. This can be attributed to the entrainment of hydrocarbons from the tunnel flow, which for the military power setting had tunnel levels (6–10 ppmv) that were a significant fraction of those measured at the exit plane. An estimate of the increase in EITHC at the mid and aft-probe stations for the $M_\infty = 2.0$, military condition was made by using the tunnel levels of the THC measured at the engine inlet and the theoretical entrainment rates for the turbulent mixing calculations. The EITHC calculated, considering those CTHC entrained from the freestream, show that the increase is not unexpected. This is further discussed by German et al.[8] The level of the CTHC in the tunnel was not significant enough to affect the EITHC computed for the afterburning power setting. During afterburning power the EITHC increased from the exit to the midplane probe station. One possible explanation for this increase is that around the periphery of the nozzle the engine may have emitted significant unburned hydrocarbons that were not detected at the exit plane because the radial probe travel was limited. Evidence of this can be seen in Fig. 6, which shows isolated points of increased levels of unburned hydrocarbons out near the edge of the jet. These were mixed with the colder external stream and were not consumed during combustion. These unburned hydrocarbons were then mixed and subsequently measured at the next two axial locations. The most reliable EITHC for these particular conditions would probably be that measured at the aft position since the amounts entrained from the tunnel flow were very much lower than the levels in the plume.

The EICO values are fairly consistent for a given power setting, showing an increase with afterburning. At present, no good reason can be given for the apparent increase in the CO levels at the midposition for the $M_\infty = 1.6$ conditions since no instrumentation errors occurred during these measurements.

The emission indices of the oxides of nitrogen which are calculated on a NO_2 basis are almost the same for each axial location and show the correct trends between the different tunnel and engine conditions. The EINOX for each condition shown exhibit the best behavior as far as being constant for each axial location.[8]

It is felt that the emission indices given in Table 3 as computed from the procedure outlined by German et al.[8] are very reliable since any error involved in numerical integration and in computing the gas properties tends to cancel out when the two integrals used in evaluating the emission index are divided. A check on the numerical integration was made by comparing the integrated fuel flows at the exit plane with those measured by a flowmeter during the engine operation. The best agreement was a calculated fuel flow within 2.7% of the measured value at the $M_\infty = 2.0$ military condition, and the worst was a 20% difference at the $M_\infty = 1.6$ military condition, with the calculated values always being higher. These errors are traceable to the inability to properly define the edge of the plume where all of the flow properties return to their freestream values. The inaccuracies resulting from the sampling technique are discussed by German et al.[8]

Particulate Emissions

The analysis of the gravimetric filters indicates a very low particle distribution. A very low ratio of particle weight to mass flow through the filter resulted during the test with the highest weight-to-mass flow (10.0×10^{-5} to 17.7×10^{-5} gm/SCF) occurring at the nozzle exit station during afterburning.

Although the afterburning results show a general downward trend in the weight-to-mass flow ratio with axial position downstream of the nozzle exit, the results are inconclusive because of certain uncontrolled variables such as the amount of time the probe was at a given sampling point for each test condition. The requirement to cool the turbojet engine every 15 min during afterburning and the probability of generating a different particle distribution when a return to the power setting was made on a given survey also introduced variables into the analysis.

III. Conclusions

The exhaust emissions were measured at three axial stations in the exhaust plume of a J85-GE-5 turbojet engine while operating at two simulated high altitude test conditions with a supersonic external stream. Two Mach numbers and two engine power settings were investigated for each axial sample probe position. A continuous sampling technique was used to measure the emission constituents. The major results of the test program are summarized below:

1) The constituents of the exhaust including concentrations of carbon dioxide, carbon monoxide, total unburned hydrocarbons, oxides of nitrogen, and particulates were measured successfully at three axial stations (0.22, 9.3, and 19.9 nozzle diameters) downstream of the nozzle exit for both military and partial afterburning engine power at Mach numbers and simulated altitudes of Mach 1.6/55,000 ft and Mach 2.0/65,000 ft.

2) In general, the concentration profiles obtained at each axial station in the exhaust plume exhibit characteristics of freejet mixing with an external, supersonic freestream. The mixing did not result in further reactions of the gas constituents, other than the conditions where combustion was occurring in the exhaust plume.

3) A calculation of the emission indices at the three axial stations in the exhaust plume indicated no significant reaction of the oxides of nitrogen.

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