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EFFECT OF PROPELLANT FLOWRATE AND PURITY ON CARBON DEPOSITION IN LO_2/METHANE GAS GENERATORS

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ABSTRACT

The generation and deposition of carbon has been studied in the Carbon Deposition Program (NAS 3-34715) using subscale hardware with LO_2/Liquid Natural Gas (LNG) and LO_2/Methane propellants at low mixture ratios. The purpose of the testing was to evaluate the effect of methane purity and full scale injection density on carbon deposition.

The LO_2/LNG gas generator/preburner testing was performed at mixture ratios between 0.24 and 0.58 and chamber pressures from 5.8 to 9.4 MPa (840 to 1370 psia). A total of seven 200 second duration tests were performed. The LNG testing occurred at low injection densities, similar to the previous LO_2/RP-1, LO_2/propane, and LO_2/methane testing performed on the carbon deposition program (Ref. 1). The current LO_2/methane test series occurred at an injection density factor of approximately 10 times higher than the previous testing. The high injection density LO_2/methane testing was performed at mixture ratios between from 0.23 to 0.81 and chamber pressures from 6.4 to 15.2 MPa (925 to 2210 psia). A total of nine high injection density tests were performed.

The testing performed demonstrated that low purity methane (LNG) did not produce any detectable change in carbon deposition when compared to pure methane. In addition, the C* performance and the combustion gas temperatures measured were similar to those obtained for pure methane. Similar results were obtained testing pure methane at higher propellant injection densities with coarse injector elements.

INTRODUCTION AND BACKGROUND

In non-reusable hydrocarbon engines, soot accumulation in the turbine drive system was low enough that it did not severely penalize the design of expendable engines due to their short operating life. Accumulated soot buildup in the turbine nozzles of a gas generator cycle engine will not be tolerated in future reusable booster engines. While several LO_2/RP-1 fueled engines have been developed in the past, an investigation into the carbon generation and deposition characteristics for hydrocarbon fuels of interest to the next generation booster engines has not been generated over the relevant range of operating conditions.

The first two phases of this program, started in 1982 and reported in Reference 1, attempted to address these concerns by studying the generation and deposition of carbon using subscale hardware. LO_2/RP-1 was studied at main chamber mixture ratios. LO_2/RP-1, LO_2/Methane and LO_2/Propane were studied at low mixture ratio, gas generator/preburner conditions. One universal test set-up and the same fine pattern triplet injector was used throughout the testing.

Carbon deposition during main chamber operation with LO_2/RP-1 was studied at mixture ratios of 2.0 to 4.0 and chamber pressures of 6.89 to 10.34 MPa (1000 to 1500 psia). Very high combustion efficiency, greater than 99%, was achieved at the nominal design mixture ratio of 3.0. Efficiency dropped slightly at both higher and lower mixture ratios but still remained relatively high compared to the 90-93% range of the operational LO_2/RP-1 engines developed during the 1955-1965 era. Thermal data together with visual post-test inspection showed no evidence of carbon deposition on the chamber walls.

The deposition of carbon on the turbine simulator tubes during preburner/gas generator testing was evaluated for LO_2/RP-1, LO_2/propane, and LO_2/methane at mixture ratios of 0.20 to 0.60 and at chamber pressures from 4.96 to 11.38 MPa (720 to 1650 psia). A total of 55 tests were conducted at preburner/gas generator conditions. Nearly 2000 seconds of test data were collected for each fuel for a total of 6832 seconds in the same test setup. Test durations ranged from 100 to 200 seconds. The mixture ratios tested covered the range of interest for state-of-the-art turbopump machinery, 978 to 1144°K (1300 to 1600°F) gas temperature. The results showed that the carbon deposition rate is a strong function of mixture ratio and a weak function of chamber pressure. The results also indicated that there was a mixture ratio that minimized deposition for LO_2/RP-1. Gas generator testing with LO_2/propane revealed a threshold mixture ratio for which carbon deposition begins and becomes very heavy. Carbon deposition was not detected for LO_2/methane at any mixture ratio tested. From the carbon deposition analyses, the turbine drive operating limits were defined for each fuel tested. Data from this program indicated that methane is the only hydrocarbon fuel tested that can be run without carbon deposition over the desired gas generator operating temperature range.

The operational results of the carbon deposition and gas temperatures as a function of mixture ratio for all three propellant combinations tested are summarized in Figure 1. The curves on each plot indicate the measured gas temperature as a function of mixture ratio tested for each fuel. Superimposed on each plot is the desired temperature range for the operation of state-of-the-art turbine drives. The highlighted area indicates the region where operation for each fuel will not incur or at least minimally incur carbon buildup. The intersection of the highlighted area with the area delineating the desired temperature range indicates the region of acceptable performance for a gas generator for each fuel.

Figure 1 indicates LO_2/RP-1 cannot be operated in the desirable temperature range for gas generators without incurring undesirable carbon buildup. LO_2/propane can be operated in the desired temperature range up to a maximum of 1088K (1500°F). Operation with LO_2/methane is unrestricted over the desired gas generator operating temperature range. Therefore to minimize carbon deposition, methane is the hydrocarbon fuel to choose for operation in a bipropellant hydrocarbon engine.

This paper presents the results of a test program sponsored by the NASA George C. Marshall Space Flight Center on contract NAS3-34715.

OBJECTIVES

The objectives of this phase of the program were to verify that carbon buildup does not occur on the turbine simulator when methane is used at injection densities representative of full scale hardware and extend the database to include LNG testing at low injection densities. Both test series were performed at gas generator/preburner conditions. The testing was performed at mixtures ratios between 0.25 and 0.60, and at chamber pressures as low as 5.17 MPa (750 psia) and as high as 13.79 MPa (2000 psia).

EXPERIMENTAL APPROACH

The LNG and the high flow rate methane testing were conducted using the apparatus depicted pictorially and schematically in Figure 2. For the LNG testing, all of the modular components used were the same as those used in the previous methane testing described in Reference 1 with one exception. The upstream L' section had boroscope access ports machined into it allowing a boroscope into the chamber to view the turbine simulator without having to disassemble the hardware. For the high injection density testing several components were modified to accommodate the increased propellant flow rates. These were the injector, turbulence ring insert, turbine simulator, and the exit nozzle. All of the remaining components were common to both test setups.

LNG TESTING

For the LNG testing, the fine pattern injector was used. It has a Nickel 200 faceplate and body. This injector, illustrated in Figure 3a, has an impinging triplet, F-O-F face pattern and a design flowrate of 1.62 kg/sec (3.48 lb/sec). The resonator ring consists of an OFHC copper insert brazed into 2 CRES 304 flanges. Both the 22.3 cm (8 in) and 30 cm (11.8 in) calorimetric barrel sections are of Nickel 200, with the 22.3 cm section having 6.35 cm (25 in) of copper plating (.005 - .010 cm) on the downstream side. The turbulence ring insert is made of CRES 316, with a CRES 304 flange. The upstream and downstream L' sections are made of CRES 304L. In the previous testing, the tubing in the turbine simulator was made from CRES 304L, but the severe transient thermal strain caused the tubing to crack. For the LNG testing, the turbine simulator tubes were made from INCONEL 600 to make them more resistant to cracking. The water-cooled turbine simulator has six .952 cm (.375 in) diameter tubes with .165 cm (.065 in) thick walls, each brazed into an OHFC copper body. This body is then brazed into a CRES 304 flange. Pressure taps were located on the turbine simulator flange upstream and downstream of the six tubes.

Increasing pressure drop across the turbine simulator would imply carbon buildup, and thus would be a quantitative measurement of carbon deposition effects. The turbine simulator is shown in Figure 4. Lastly, the uncooled exit nozzle was made from CRES 304L and had a throat diameter of 1.27 cm (.5 in) inches, with a contraction ratio of 22:1.

HIGH FLOW RATE METHANE TESTING

With the exception of the injector, turbulence ring insert, turbine simulator, and the uncooled exit nozzle, all other test components remained the same as in the previous testing. The high flow rate injector was designed to accommodate flow rates of 6.58 kg/sec (14.5 lb/s) using liquid oxygen and liquid methane propellants. These values are representative of full scale hardware. The initial fine pattern injector sought to achieve complete combustion as rapidly as possible to separate chemical kinetic effects apart from injector design effects. While retaining the impinging triplet, F-O-F pattern, the ox and fuel orifice diameters were enlarged, and the triplet elements were canted at a 30° angle to provide increased mixing. The faceplate was made from Zirconium Copper, and increased in thickness from .38 cm (.15 in) to .76 cm (.3 in), allowing for the orifice L/D to remain constant. The body was made of CRES 304. Figure 3B shows the injector. The turbulence ring insert was increased in I.D. from 2.54 cm (1 in) to 5.08 cm (2 in); and was made of CRES 304. The flange remained unchanged. For the high flow rate testing, the water cooled turbine simulator had seven .635 cm (.25 in) diameter tubes with .071 cm (.028 in) walls to increase the flow area for the combustion gases to 7.1 cm^2 (1.1 in^2). The tubes were made of INCONEL 600. Finally, the uncooled exit nozzle throat diameter was increased to 2.54 cm (1 in), with a contraction ratio of 5:1. It was made from CRES 304L. A summary comparison of test hardware used in the LNG testing and the methane testing is shown in Table 1.

DESCRIPTION OF THE TEST APPARATUS

The test apparatus was identical for both the LNG and the methane testing, with the exception of the hardware changes previously noted, and is shown in Figure 5. The liquid oxygen was supplied to the test stand from a 189.2 l (50 gal) vacuum-jacketed run tank. The LNG and liquid methane came from a 567 l. (150 gal) cryogenic run tank. The GO_2/GH_2 torch igniter was used to ignite the propellants. An electric spark initiated the igniter.

TEST RESULTS

A summary of the LO_2/LNG fine pattern triplet tests and the LO_2/methane coarse pattern triplet tests is shown in Table 2. The number of tests, operating ranges, cumulative test durations, and cumulative mass burned are listed. The chamber pressure ranged from 5.79 to 15.24 MPa (840 to 2210 psia); and the mixture ratio range covers the range of interest for state-of-the-art high pressure turbine technology, 555 to 1372 K (540 to 2010 °F) gas temperatures.

The 200 second LNG test durations with the fine pattern triplet covered the nominal 160 second mission duty cycle requirements for typical booster engines. The durations for the coarse pattern triplet methane tests were limited by the fuel run tank capacity to less than 60 seconds. A comparison of the total mass burned in the LNG and methane tests showed that more mass was burned in the methane tests than the LNG tests in spite of the four-fold decrease in methane test durations.

Ignition was reliable and smooth once the start sequence was tailored for each fuel. The ignition startup sequence, as indicated by the pressure rise in the inlet manifold, for each propellant combination was as follows:

15 msec oxidizer lead for LO_2/LNG
15 msec oxidizer lead for LO_2/methane

LNG COMPOSITION

The tested LNG contained 5 to 8 percent impurities. Ethane was the major impurity at 5.5 percent. Table 3 details the LNG composition in more detail.

CARBON DEPOSITION RESULTS

Hardware Inspection

The most graphic way to characterize carbon deposition was by observation of the turbine simulator tubes during hardware disassembly. Figures 6 and 7 show the condition of the turbine simulator at the completion of the LNG and methane tests programs, respectively. The hardware was coated with carbon but the deposits did not buildup on the tubes. Previous Carbon Deposition testing (Ref. 1) with propane and RP-1 produced significant buildup of carbon deposits, as shown in Figures 8 and 9.

Turbine Simulator Pressure Ratio

Monitoring the chamber pressures upstream and downstream of the turbine simulator was one method of observing carbon deposition during the actual hot fire tests. A build-up of carbon on the turbine simulator causes an increase in the upstream chamber pressure and a corresponding decrease in the downstream chamber pressure due to a decrease in available turbine simulator flow area. Accordingly, the ratio of the downstream to upstream turbine simulator pressure measurements decreases as carbon build-up occurs on the turbine simulator. The turbine simulator pressure ratio changes for the LNG and methane tests are plotted in Figure 10 against previous Carbon Deposition fine pattern triplet methane test results (Ref. 1). No appreciable pressure ratio reduction across the turbine simulator is evident, indicating no significant carbon deposition.

Turbine Simulator Flow Area Reduction

The turbine simulator pressure ratio measurements were also used to calculate the reduction in the turbine simulator flow area using the isentropic compressible gas flow equations. Figure 11 shows that the average flow area reduction was 5 percent for the LNG tests and 1.9 percent for the methane tests. These results indicate little, if any, carbon deposition occurred.

Exhaust Plume Appearance

The observed exhaust plumes were also used to characterize carbon deposition since the amount of carbon buildup on the tubes is a function of the amount of carbon generated. The darkness of the exhaust plume is proportional to the amount of carbon generated. Figures 12 and 13 shows representative exhaust plumes for the LNG and methane tests. Compared to previous Carbon Deposition results for LO_2/propane and LO_2/RP-1 which exhibited carbon buildup, shown in Figures 14 and 15 (Ref. 1), the exhaust plumes in the LNG and methane tests showed no indication of carbon formation on the turbine simulator.

COMBUSTION GAS TEMPERATURE

Combustion gas temperatures during these tests at gas generator operating conditions were measured with a gas thermocouple rake immersed in the combustion gas stream 6.12 cm (2.41 in.) upstream of the turbine simulator tubes. Figure 16 gives the circumferential locations and immersion depths of the gas thermocouples. Figure 17 shows that the combustion gas temperatures increased with increasing mixture ratio for both the LNG and methane tests. For comparison, the previous Carbon Deposition data (Ref. 1) and data from NASA-MSFC LO_2/LNG tests (Ref. 2) are also plotted on this figure. All sets of data show gas temperatures 30% lower than the ODE predicted gas temperatures at mixture ratios less than 0.3. The gas temperatures gradually improve to within 10% of the ODE prediction at mixture ratios greater than 0.4. One high mixture ratio (0.81) methane test exhibited an unexplainably high gas temperature of 1394 K (2050°F) with a large temperature variation, which may have been due to reaching the thermocouple range limit at 1367 K (2000°F). The measurement uncertainty of this test is somewhat academic in that the gas temperature is greatly in excess of the operating temperatures that current turbine materials can withstand.

C* PERFORMANCE

The C* performance data for the LNG and methane tests are plotted in Figure 18 alongside the previous Carbon Deposition methane tests (Ref. 1) and the MSFC test data (Ref. 2). This figure indicates the C* performance increases from 90% of ODE prediction at low mixture ratios to 96% at higher mixture ratios. This trend supports the results observed in the gas temperature data which shows that as mixture ratio increases the gas temperature deviation from theoretical values decreases. Figure 18 also reinforces the conclusion obtained in previous Carbon Deposition testing (Ref. 1) that changing chamber pressure has little effect on C* performance in the 5.17 to 13.8 MPa (750 to 2000 psia) test range.

CONCLUSIONS

The Carbon Deposition program has extended its existing gas generator data base to include LNG testing at low injection densities and pure methane testing at high injection densities.

Liquified Natural Gas was tested with the existing fine pattern triplet injector to examine the effect of low purity methane on carbon deposition. Chamber pressure ranges were 840 to 1370 psia (5.8 to 9.4 MPa) and mixture ratio ranges were 0.24 to 0.58. A total of seven tests were conducted at 200 second test durations. No appreciable carbon buildup was observed on the turbine simulator.

Another objective of the program was to examine the effect of methane injection densities representative of full scale hardware on carbon deposition. A coarse pattern triplet injector, which was tested at approximately ten times the flowrate of the fine pattern triplet injector, and at chamber pressure ranges 6.4 to 15.2 MPa (925 to 2210 psia), and mixture ratio ranges 0.23 to 0.81. A total of nine tests were conducted, and no appreciable carbon build-up was detected.

Based on the results of these test series, low purity methane (~92% CH_4) will not produce carbon deposition in the 5.51 to 9.65 MPa (800 to 1400 psia) chamber pressure range for gas generator conditions. The results also show that carbon formation and deposition is not dependent upon injection density over the range tested. Figure 19 summarizes the results of the carbon deposition as a function of mixture ratio for the two propellant combinations tested. The figure shows that operation with impure methane or operation with full scale injection densities is unrestricted over the desired gas generator operating range.

RECOMMENDATIONS

The carbon deposition program has provided considerable data concerning the generation and deposition of carbon in gas generators/preburners. However, additional areas of investigation should be pursued. A systematic study of the interaction of fluid dynamics and soot formation and deposition in gas generators/preburners should be initiated. The effects of injector element type (coax, doublet, etc.) can effect carbon formation and deposition and should be investigated.

REFERENCES

1. Hernandez, R. and Mercer, S.D, "Carbon Deposition Characteristics of LO_2/HC Propellants", Paper AIAA-87-1855, 23rd Joint Propulsion Conference, San Diego, CA, June 29-July 2, 1987.
2. Bailey, C.R., "High Pressure LOX/Natural Gas Staged Combustion Technology" presented at the 1984 JANNAF Propulsion Meeting, New Orleans, LA, 8 February 1984.

ACKNOWLEDGMENT

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Table 1. Comparison of LNG and High Flow Rate Methane Test Hardware

Component	LNG Testing	High Flow Rate Methane Testing
Injector	Fine Element, Low Flow	Coarse Element, High Flow
Resonator/Fuel Film Cooling Ring	Same	Same
30.5 cm (12 in.) Calorimetric Barrel Section	Same	Same
Uncooled Turbulence Ring	3.8 cm (1.5 in.) Diameter	5.08 cm (2.0 in.) Diameter
20.3 cm (8 in.) Calorimetric Barrel Section		
Upstream Barrel Section	Thermocouple Instrumentation	Thermocouple Instrumentation
Turbine Simulator	6 Tubes, INCONEL 600 0.952 cm (0.375 in.) Diameter	7 Tubes; INCONEL 600 0.635 cm (0.25 in.) Diameter
Downstream Barrel Section	Pressure Tap Section	
Exit Nozzle	1.27 cm (0.5 in.) Diameter Throat	2.54 cm (1.0 in.) Diameter Throat

Table 2. Carbon Deposition Gas Generator Test Program Summary

Propellant Combination	Injector Type	Number of Valid Tests	Pc Range Mpa (psia)	Mixture Ratio Range	Combustion Gas Temp. Range, K (°F)	Total Test Duration (sec)	Total Mass Burned, kg (lbm)
LO_2/LNG	Fine Patrn. Triplet	7	5.79-9.45 (840-1370)	.24-.58	555-1138 (540-1590)	1400	9336 (20,564)
LO_2/LCH_4	Coarse Ptrn. Triplet	9	6.38-15.24 (925-2210)	.23-.81	633-1372 (680-2010)	321.6	59,044 (26,806)

TABLE 3. 1988 LNG Composition, Mole Percent

Methane	92.803%
Ethane	5.554%
Propane	0.925%
Oxygen	0.252%
Nitrogen	0.227%
Butanes	0.207%
CO_2	0.031%

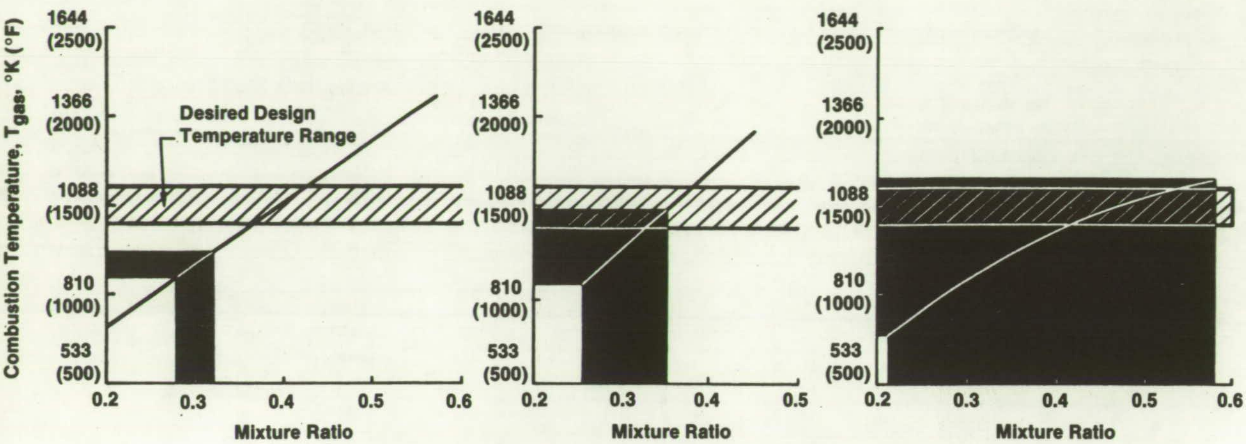

Figure 1. Gas Generator Operating Limits

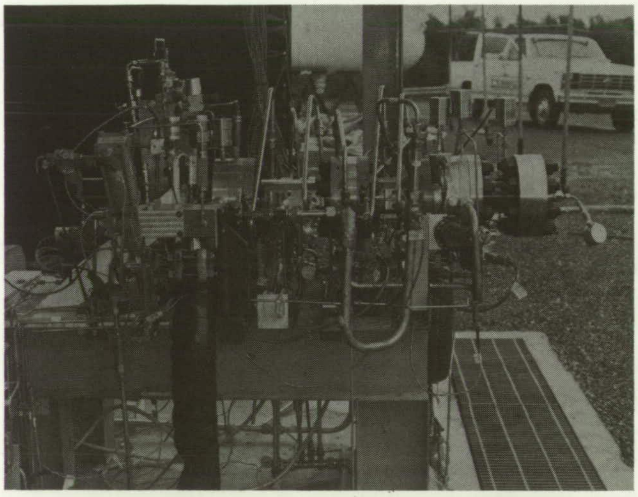

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Fig. 2a. Carbon Deposition Test Apparatus

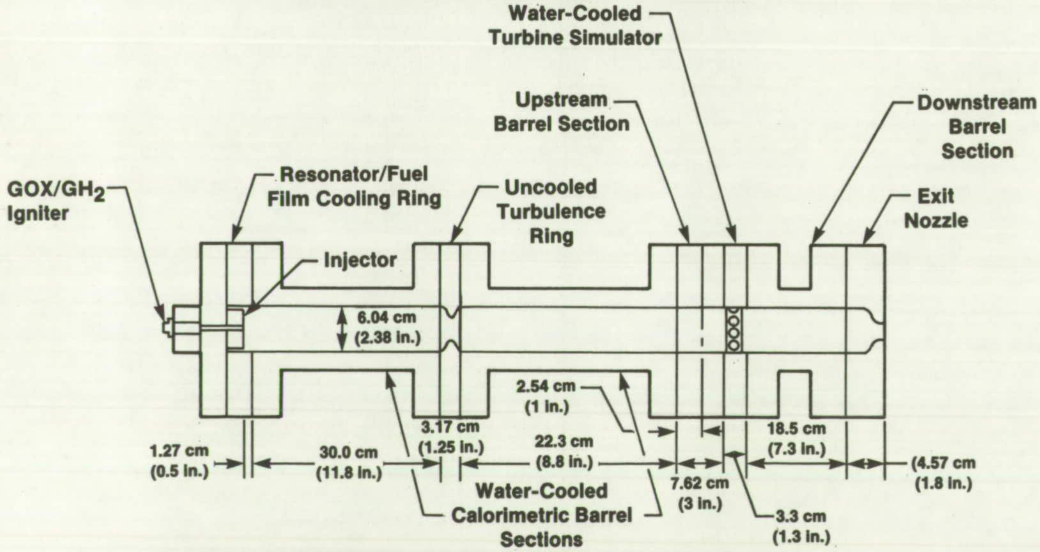


Fig. 2b. Gas Generator Assembly Schematic

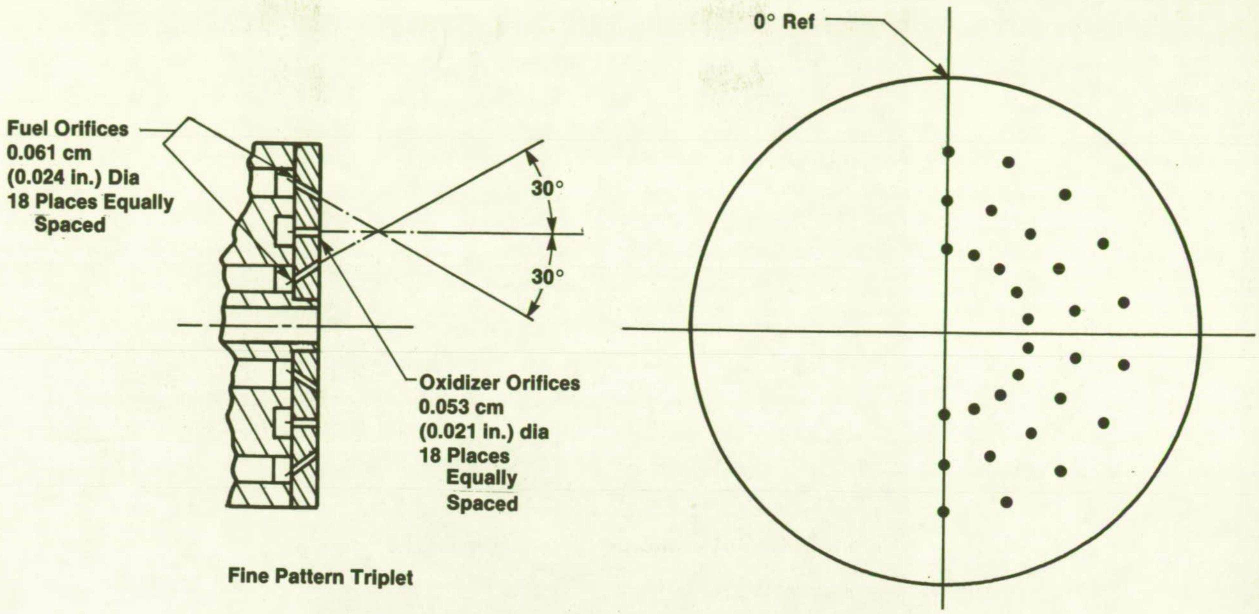


Fig. 3a. Schematic of the Fine Pattern Triplet Injector

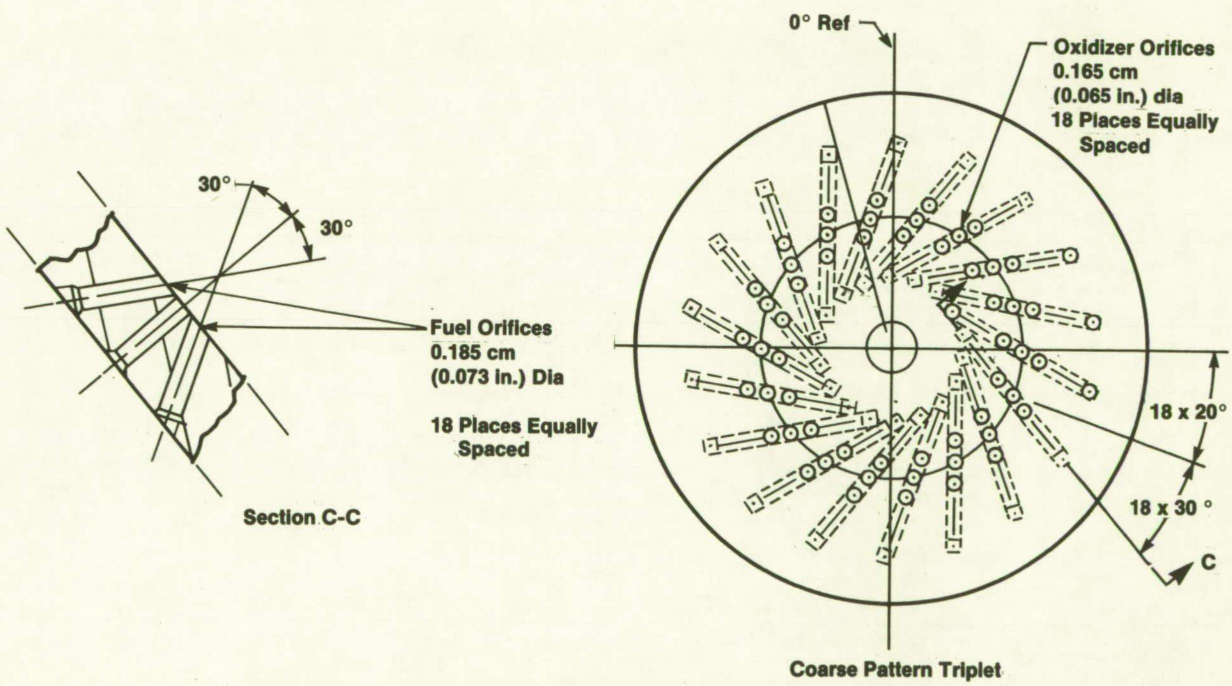


Fig. 3b. Schematic of the Coarse Pattern Triplet Injector

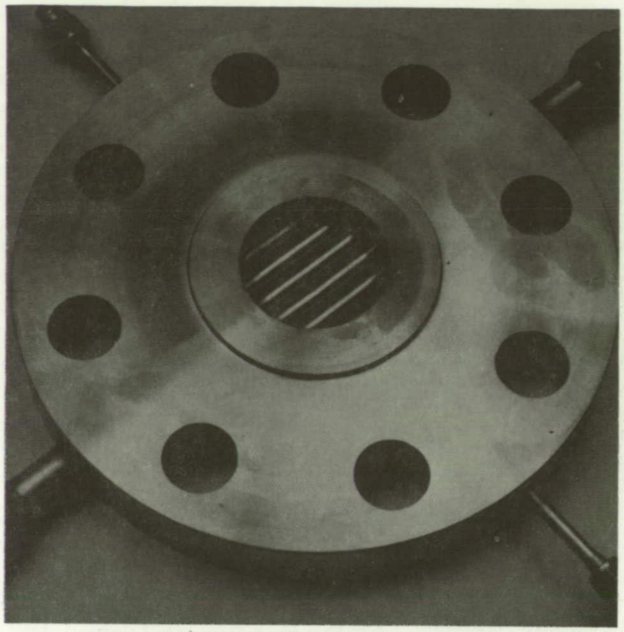


Fig. 4. Turbine Simulator Used for LO_2/LNG Testing

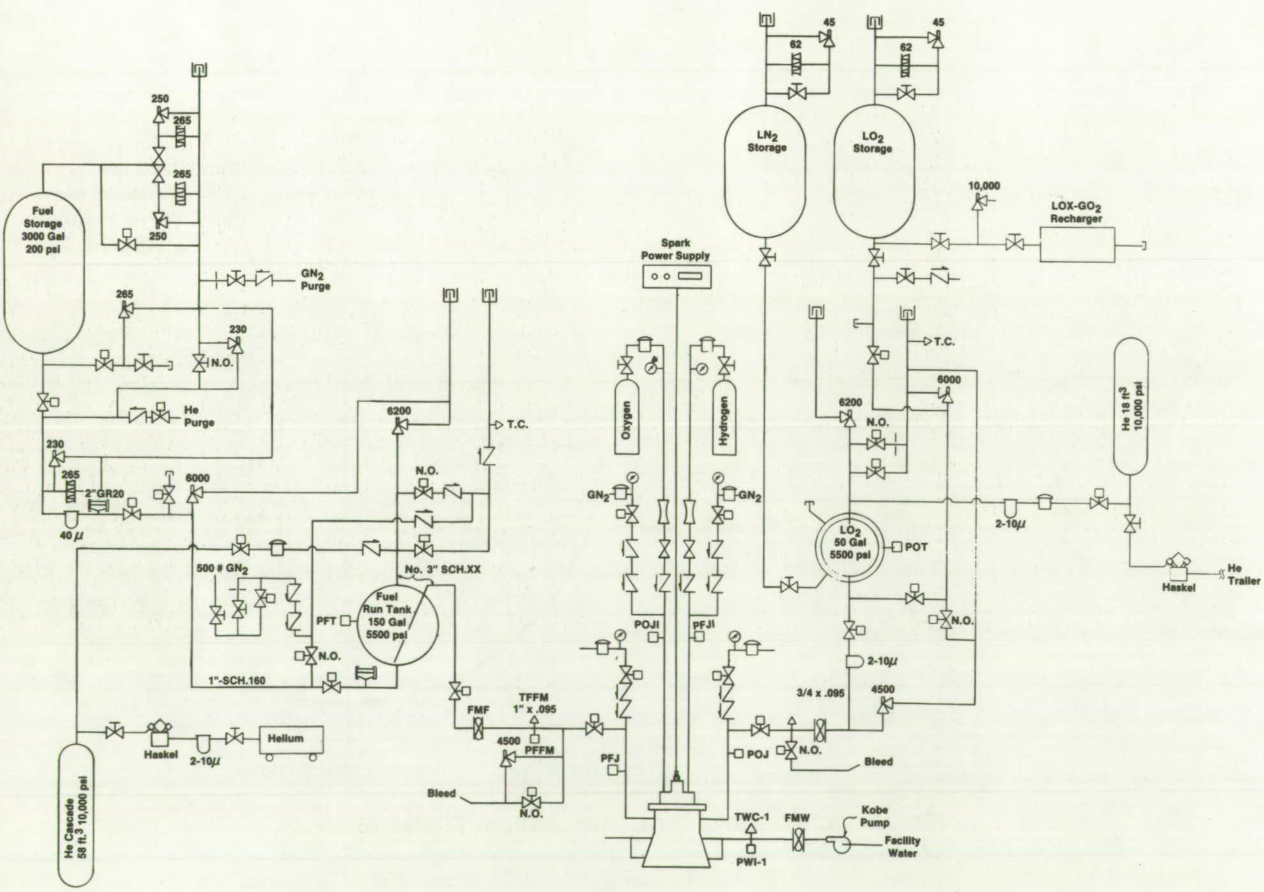


Fig. 5. Test Apparatus Schematic

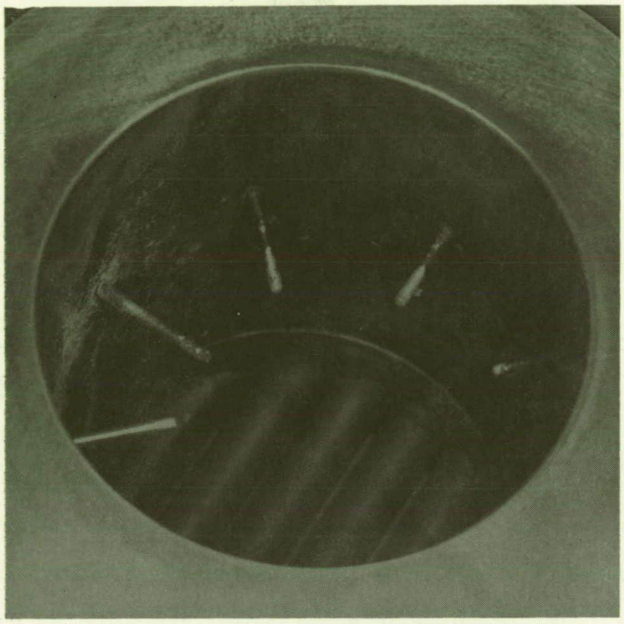


Fig. 6. Condition of Turbine Simulator After Testing With LO_2/LNG

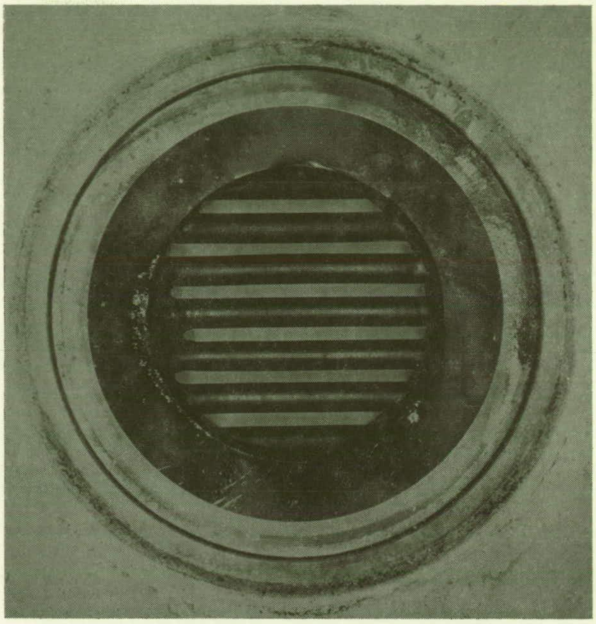


Fig. 7. Condition of Turbine Simulator After Testing With LO_2/Methane

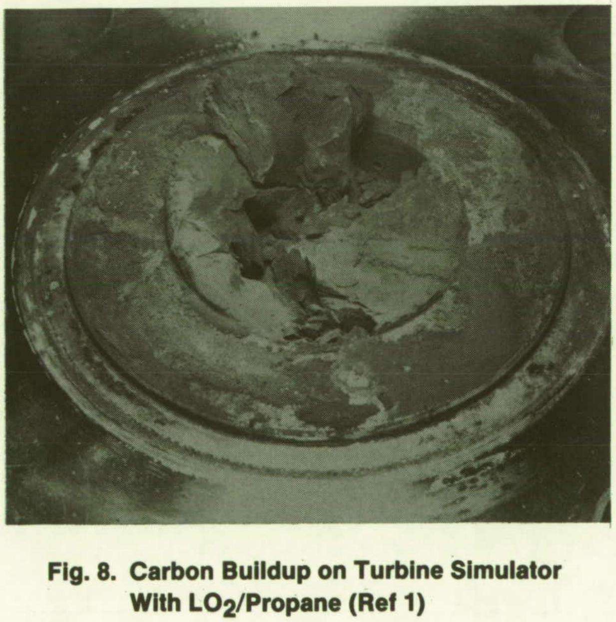
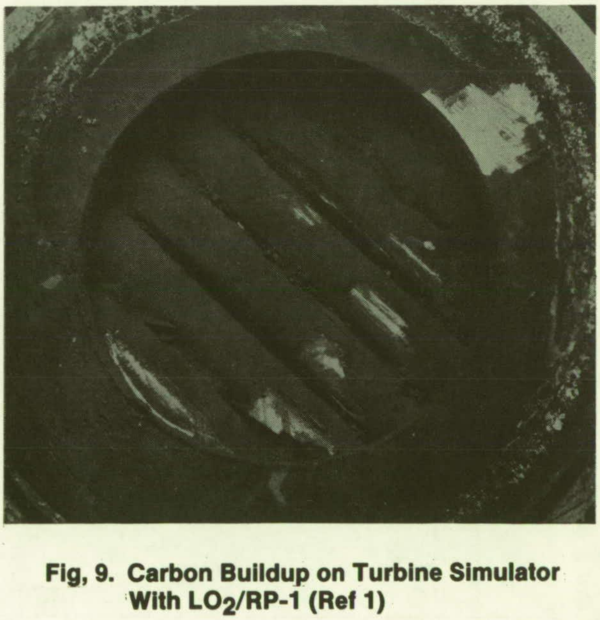


Fig. 8. Carbon Buildup on Turbine Simulator With LO_2/Propane (Ref 1)



Fig, 9. Carbon Buildup on Turbine Simulator With LO_2/RP-1 (Ref 1)

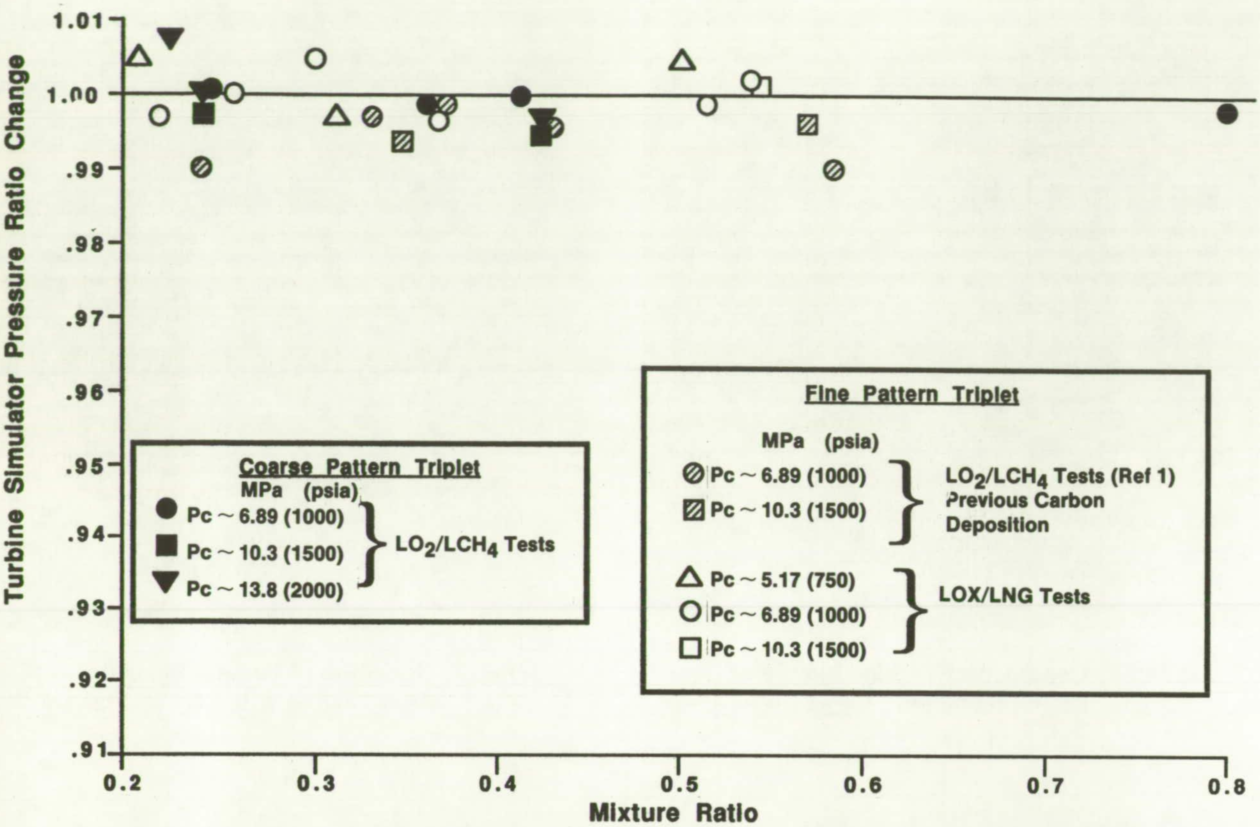


Fig. 10. Turbine Simulator Pressure Ratio Change for the LO_2/LCH_4 and LO_2/LNG Tests

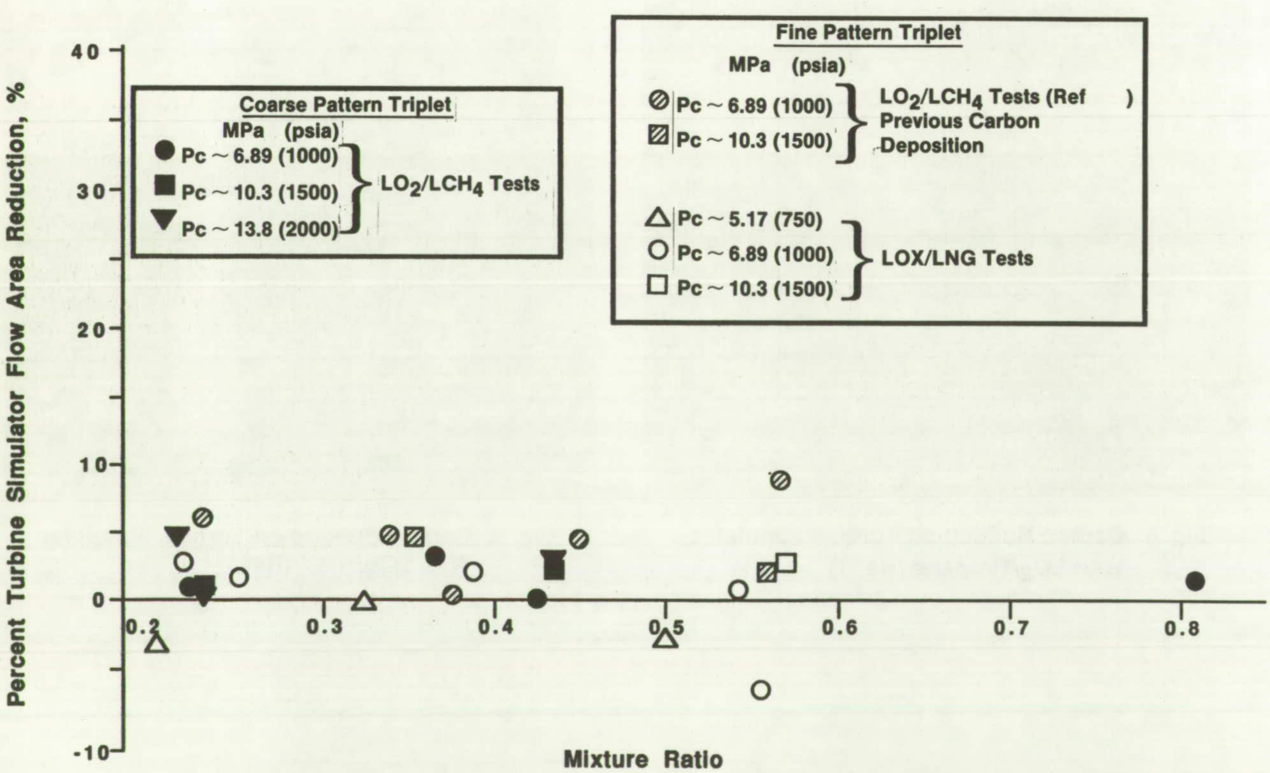


Fig. 11. Turbine Simulator Flow Area Reduction for the LO_2/LNG and LO_2/LCH_4 Tests

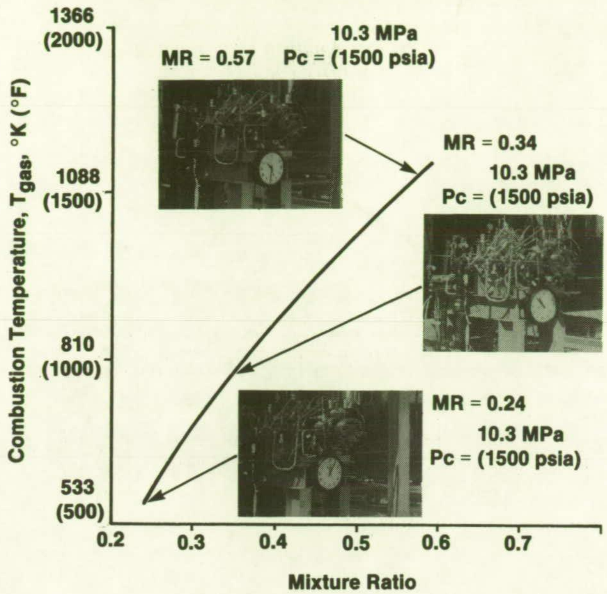


Fig. 12. Exhaust Plumes for LO_2/LNG

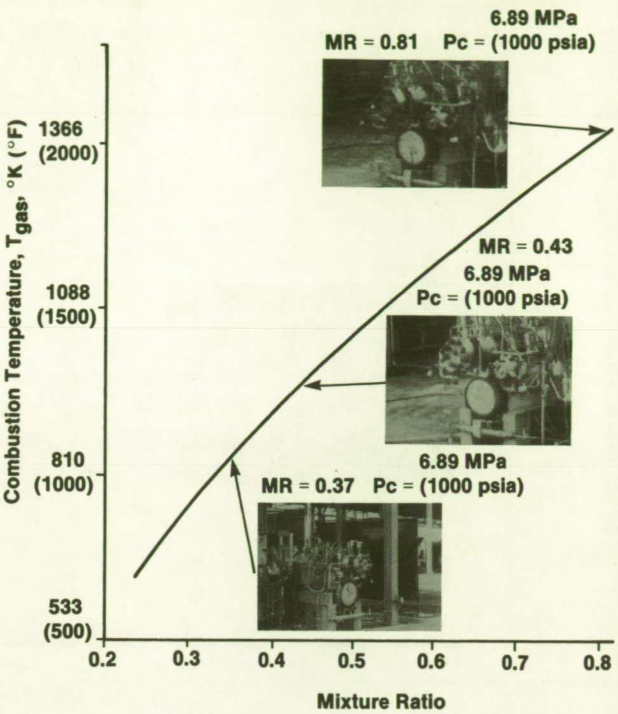


Fig. 13. Exhaust Plumes for LO_2/Methane

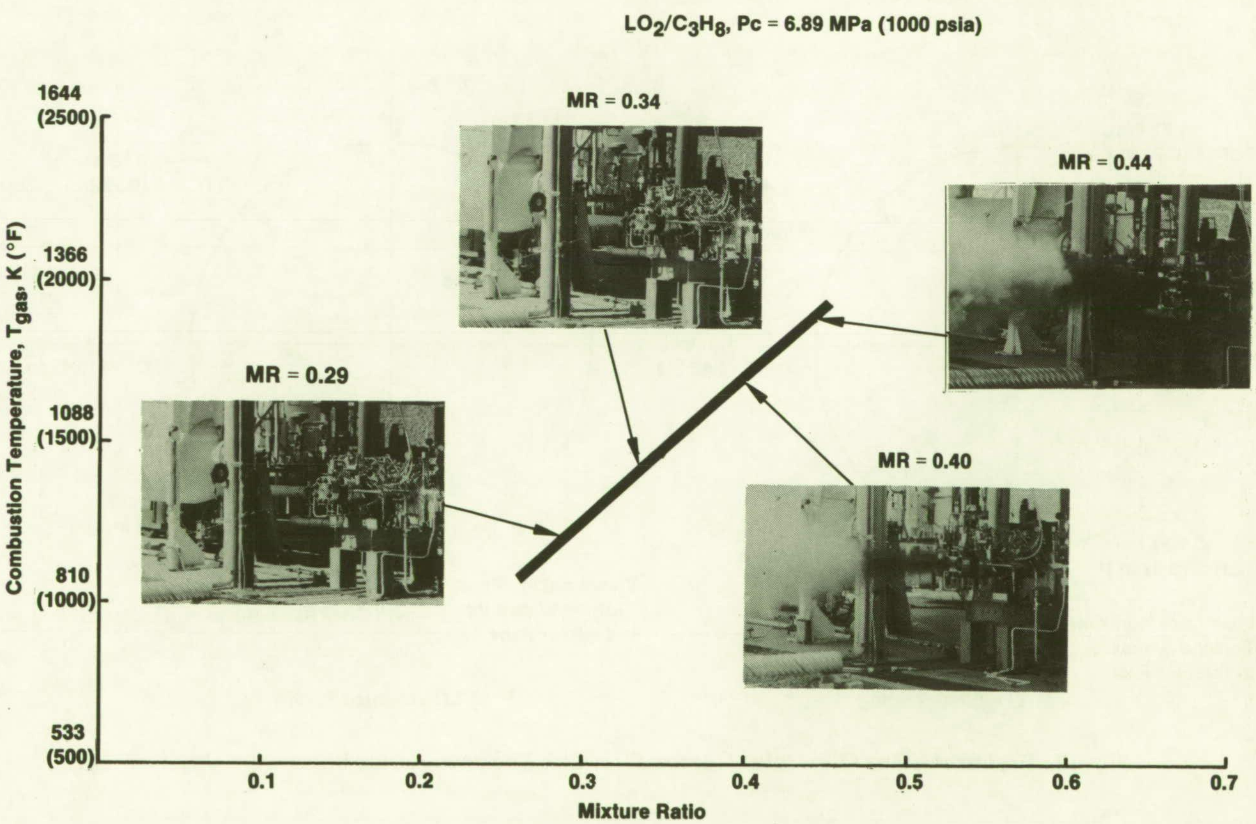


Fig. 14. Exhaust Plumes for LO_2/Propane (Ref. 1)

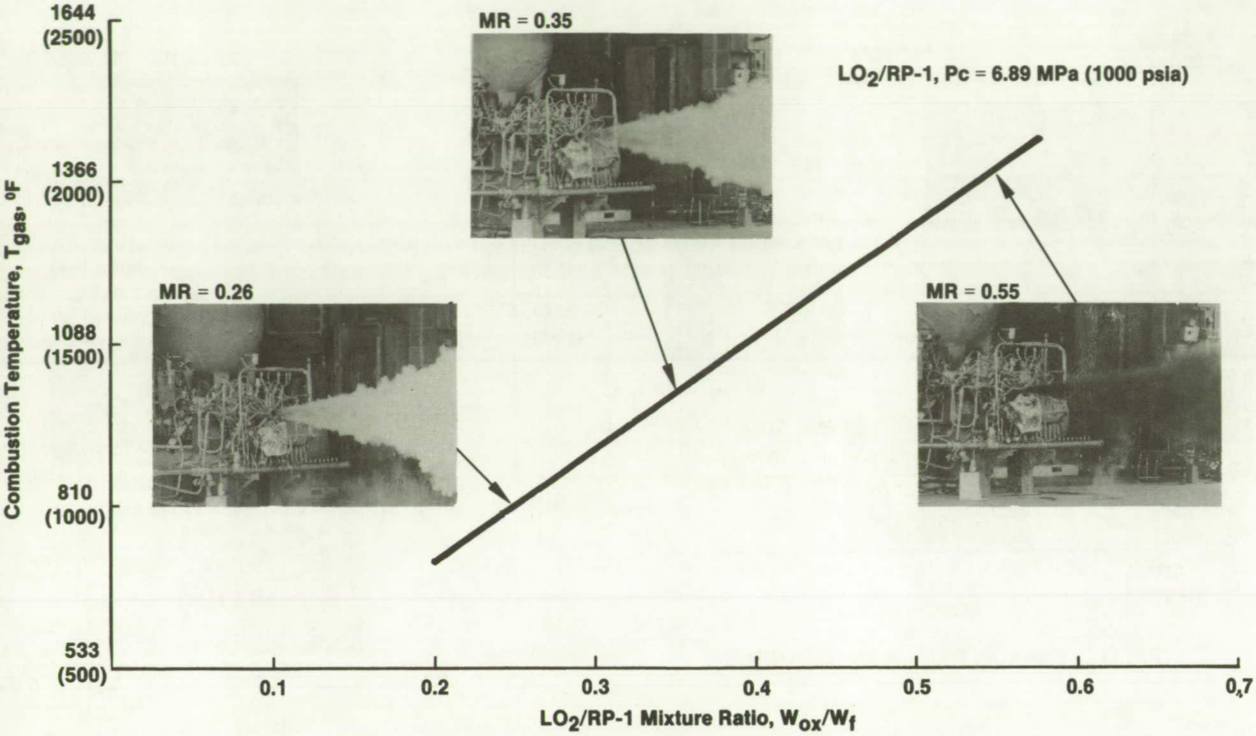


Fig. 15. Exhaust Plumes for LO_2/RP-1 (Ref 1)

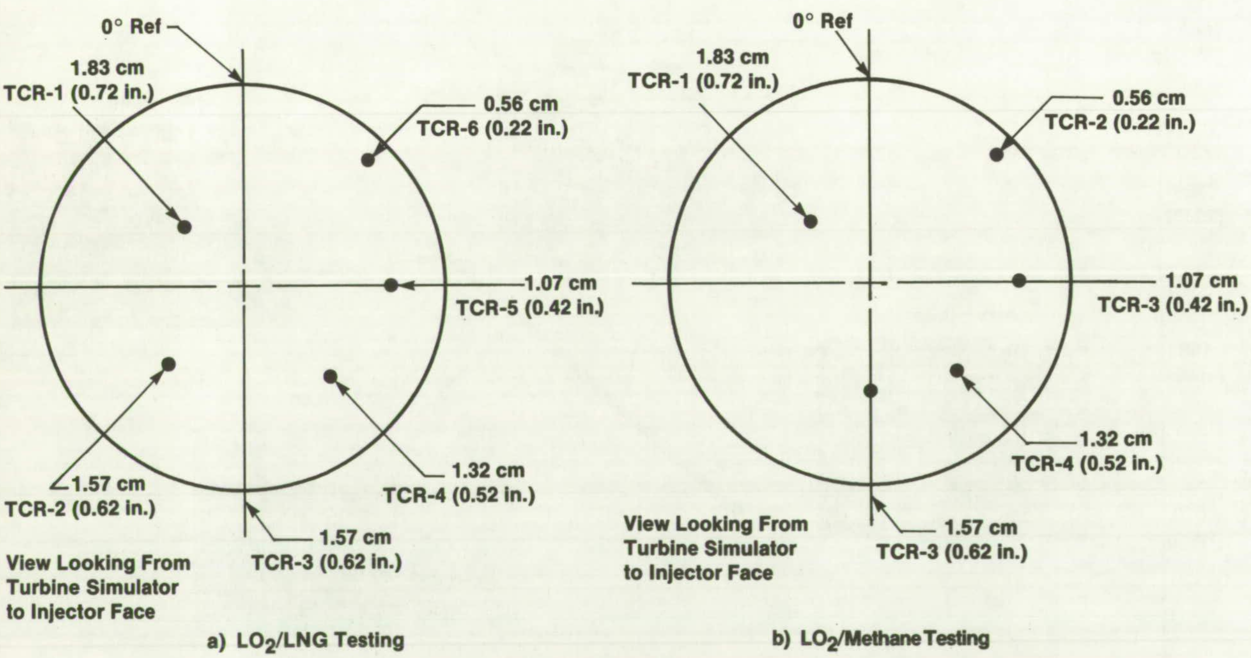


Fig. 16. Preburner/Gas Generator Combustion Gas Thermocouples Immersion Depths

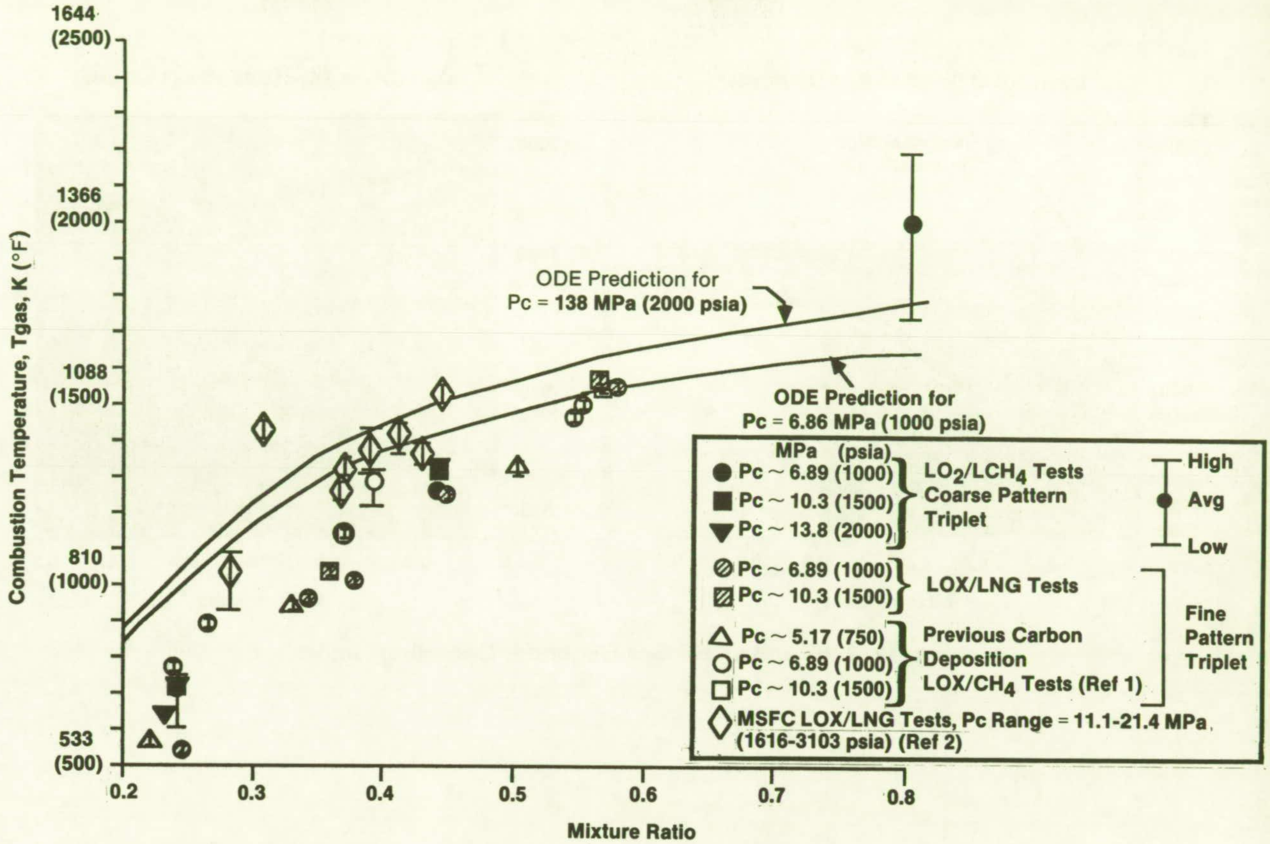


Fig. 17. Combustion Gas Temperatures for LOX/LNG and LOX/LCH_4 Tests

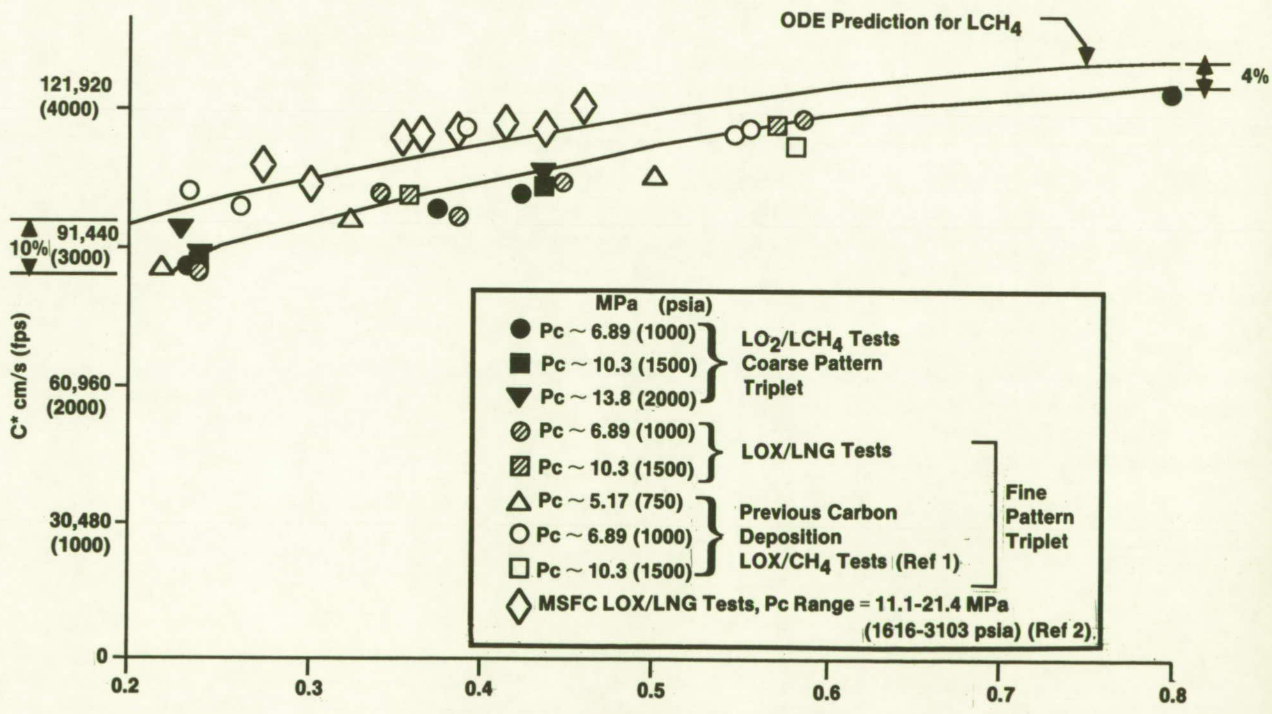


Fig. 18. C* Performance for LO_2/LNG and LO_2/LCH_4 Tests

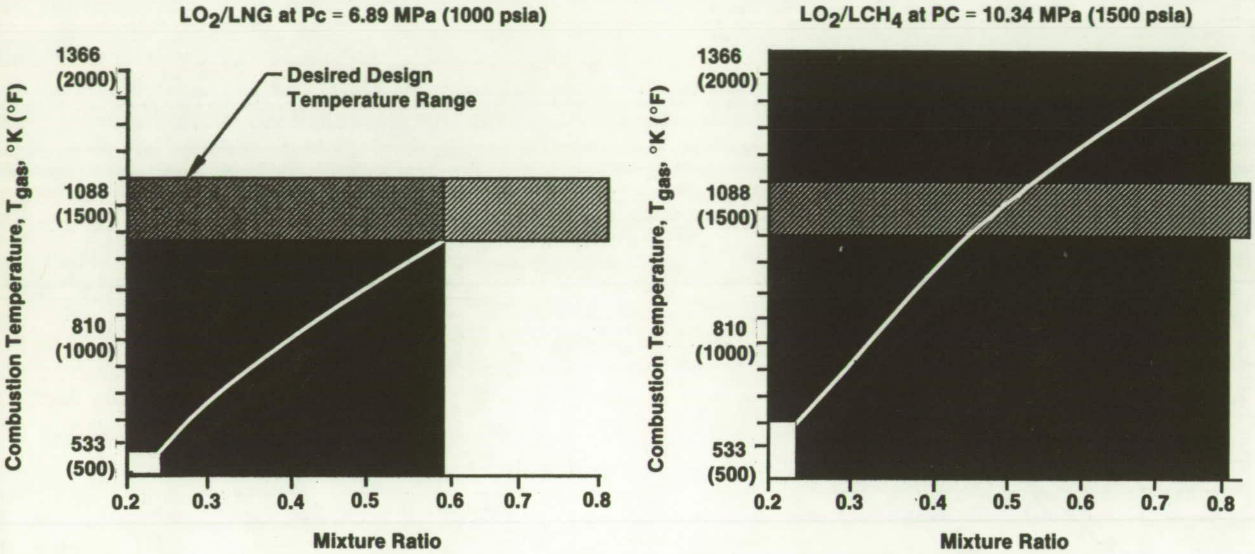


Fig. 19. LNG and LCH4 Gas Generator Operating Limits