ESL-TR-89-33

Feasibility of Reburning for Controlling NO_x Emissions from Air Force Jet Engine Test Cells

STEPHEN A. JOHNSON
CHARLES B. KATZ

PSI TECHNOLOGY COMPANY
20 NEW ENGLAND BUSINESS CENTER
ANDOVER, MA 01810

JUNE 1989

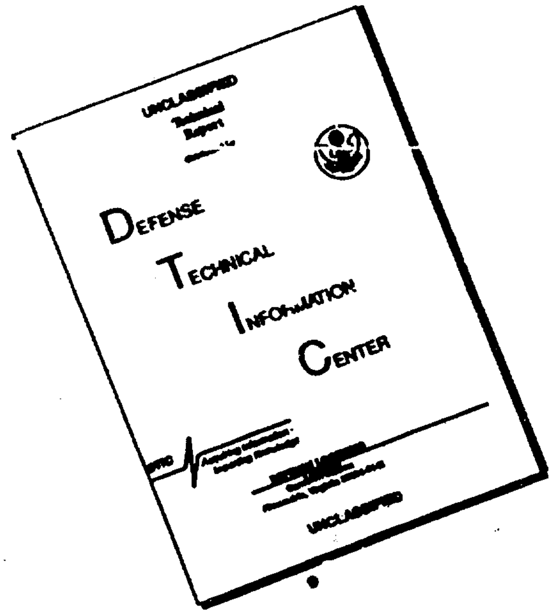
FINAL REPORT
OCTOBER 1988 - APRIL 1989

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

AIR FORCE ENGINEERING AND SERVICES CENTER

AFESC

ENGINEERING & SERVICES LABORATORY
AIR FORCE ENGINEERING & SERVICES CENTER
TYNDALL AIR FORCE BASE, FLORIDA 32403


DEFENSE
TECHNICAL
INFORMATION
CENTER

NOTICE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release. Distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) PSI-2075-TR-939	5. MONITORING ORGANIZATION REPORT NUMBER(S) ESL-TR-89-33
6a. NAME OF PERFORMING ORGANIZATION PSI Technology Company 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Engineering and Services Center
6c. ADDRESS (City, State, and ZIP Code) 20 New England Business Center Andover, MA 01810	7b. ADDRESS (City, State, and ZIP Code) Hq. AFESC/RDVS Tyndall Air Force Base, FL 32403
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. F08635-89-C-0064
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO | WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Feasibility of Reburning for Controlling NO_x Emissions from Air Force Jet Engine Test Cells

12. PERSONAL AUTHOR(S)
Stephen A. Johnson and Charles B. Katz

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM Oct 88 TO Apr 89	June 1989	81

16. SUPPLEMENTARY NOTATION
Availability of this report is specified on reverse of front cover.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Nitrogen oxides; Jet engine test cells; Emission control; Economics

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this study was to determine the technical and economic feasibility of reburning as a NO_x control technique for Air Force jet engine test cells. Work included laboratory-scale testing of a prototype reburner, a preliminary reburn system design, and an estimate of capital and operating costs for a hypothetical JETC rated at 600 lb air/second. The study shows that 60 percent NO_x reduction on a mass basis (80 percent on a lb/MBtu basis) can be achieved, but large NO_x reductions require excessive amounts of reburning fuel (natural gas). Pressure loss across the reburner did not exceed 0.1 in. of water. Laboratory results suggested a full-scale reburner design rated at

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Captain Wayne Chepren	22b. TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

150 million Btu/hr. Four reburners located in a separate combustion chamber downstream of the augmenter tube would be required for the hypothetical JETC. Capital cost for the retrofit was estimated to be $3 million; operating costs were $2 million/year based on 800 hours of testing per year at a constant reburning fuel flow rate (to minimize hydrocarbon as well as NO_x emissions). Operating the reburner only at military and afterburner engine modes (NO_x control only) could cut the operating cost by 50 percent. Reburner developments to minimize fuel usage would make the technology more attractive.

PREFACE

This report was prepared by PSI Technology Company under Air Force Contract No. F08635-89-C-00641, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida 32403-6001. Captain Wayne Chepren was the government technical manager. This report summarizes work done between 5 October 1988 and 4 April 1989.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

PAUL KOTANCHIK, GS-11
Project Officer

WAYNE P. CHEPREN, Capt, USAF
Chief, Environmental Compliance R&D

NEIL J. LAMB, Lt Col, USAF, BSC
Chief, Environics Division

FRANK P. GALLAGHER III, Colonel, USAF
Director, Engineering and Services Laboratory

(The reverse of this page is blank.)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONCLUDED)

LIST OF TABLES

SECTION I

INTRODUCTION

A. OBJECTIVES

The environmental impact of military activities is undergoing increased public and regulatory scrutiny. Because of their large size large exhaust flows, and high concentrations of nitrogen oxides (NO_x) Air Force jet engine test cells (JETCs) are becoming prime targets for environmental assessments and emission controls. NO_x, a U.S. EPA-regulated priority pollutant detrimental to human health, is also a key agent in the formation of acid rain and ground-level ozone. This research program was initiated to determine the feasibility of reburning as a means of controlling NO_x emissions from JETCs.

B. BACKGROUND

The U.S. Air Force operates approximately 250 JETCs which are considered stationary sources by the EPA and therefore fall under local, state, and federal emission regulations. The current federal NO_x emission limit for stationary sources firing liquid fuels is 0.3 lb/MBtu, roughly equivalent to 5.6 g NO_2/kg fuel.

The purpose of a JETC is to perform controlled testing of jet engines after maintenance or overhaul to assure proper operation before returning them to service. Engines are operated over their full range of thrust, representative of typical operational modes (startup, taxi, runway roll, climbout, maneuvering, approach, and landing). Total test times can vary from 2 to 8 hours.

JETC design varies from base to base, but the most common indoor configuration is pictured in Figure 1. The engine to be tested is securely mounted in the horizontal portion of a long U or L-shaped enclosure constructed of steel and concrete. Air is drawn into the enclosure through sound-deadening

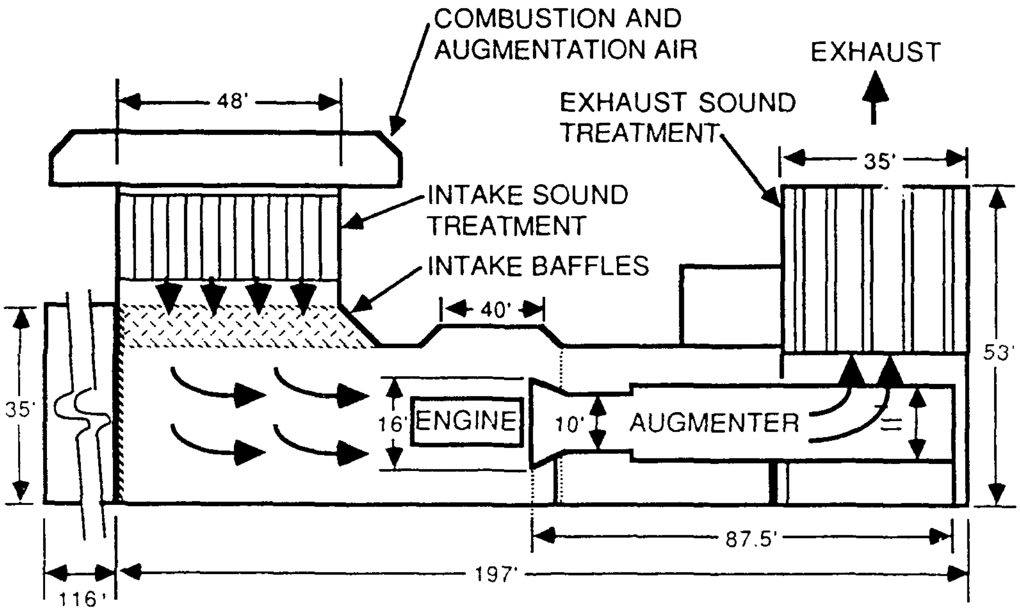


Figure 1. Tinker AFB JETC 4 Facility Dimensions.

ports and baffles. The resultant unequal flow distributions are corrected by turning vanes designed to provide an undistorted airflow to the engine inlet at a velocity not to exceed 50 ft/s (Reference 1).

The jet engine exhaust gases are blown into a large, long tube (typically 10 feet in diameter by 100 feet long) with a convergent entrance section. This JETC component, called an augmenter, serves three purposes (Reference 2):

1. The entrance to the augmenter is venturi-shaped, similar to an ejector pump, to draw air into the test cell and ensure equal air pressure at the inlet and outlet of the engine.

2. The augmenter draws a portion of the air around the engine housing to provide cooling similar to that experienced by the engine in flight.

3. The air drawn into the augmenter dilutes and cools the engine exhaust gas, which is necessary to prevent damage to the JETC construction materials.

The amount of air drawn into the cell depends on the placement of the engine relative to the augmenter throat. In practical operation, the ratio of bypass airflow to engine exhaust gas flow (augmentation ratio) varies from about 0.5 to 2.5 on a mass basis (Reference 3).

The augmented gas temperature can vary between 400 and 2000°F (200 to 1100°C) depending on engine firing rate and augmentation ratio. Some augmenter tubes are equipped with cooling water sprays to further quench the exhaust gas temperature below 600°F (315°C), thus allowing the use of inexpensive construction materials. The gases exit the augmenter tube through a perforated basket to help dissipate the momentum of the jet as well as some of the acoustic energy. In some cells, this basket is surrounded by a movable sleeve that can be used to adjust the back pressure on the engine (Reference 1).

The exhaust gas leaving the augmenter tube fills the blast room before exiting the JETC through the stack. The cooled exhaust is vented to atmosphere through multiple channels in the exhaust stack designed to minimize the noise created during a test run. The stack has an exit area that ranges from 200 to 900 ft^2, and the flow distribution among the channels is observed to be very irregular (Reference 3).

These JETCs process an enormous amount of gas. Material balances for a "typical" engine test at full military and afterburner loads (600 lb-air/s) are given in Tables 1 through 4, taken from Reference 4.

Another unique feature of JETC operation is a highly variable test cycle. Figure 2 shows an example of how engine load may be varied with time during a test at Tinker AFB (Reference 5). We note that each load condition is seldom maintained for more than five minutes, and that transient exhaust conditions undoubtedly occur.

As expected, NO_x emission from a JETC is a strong function of engine load (i.e., peak flame temperature). Figure 3 shows NO_x emissions as a function of

TABLE 1. FLOW CHARACTERISTICS FOR A J-79 ENGINE TEST AT MILITARY POWER SETTING AND A TEST CELL AUGMENTATION RATIO OF 0.6 TO 1

						Stack Gas at 600°F		Stack Gas at 150°F	
	1	2	3	4	5	6	7	6	7
Flow Characteristic	Fuel	Engine Air	Augmentation Air	Exhaust Gas	Augmented Gas	Quench Water	Stack Gas	Quench Water	Stack Gas
C in lb/hr	8,570	-	-	-	-	-	-	-	-
H_2 in lb/hr	1,430	-	-	-	-	-	-	-	-
O_2 in lb/hr	-	136,000	81,600	101,720	183,320	-	183,320	-	183,320
N_2 in lb/hr	-	512,000	307,200	512,000	819,200	-	819,200	-	819,200
H_2O in lb/hr	-	7,120	4,280	20,000	24,280	38,340	62,620	168,000	192,280
CO_2 in lb/hr	-	-	-	31,400	31,400	-	31,400	-	31,400
Total in lb/hr	10,000	655,120	393,080	665,120	1,058,200	38,340	1,096,540	168,000	1,226,200
Temperature	80	80	80	1,175	770	140	600	140	150
SCFM	-	145,220	87,150	147,500	234,650	-	248,000	-	294,000
ACFM	0	150,590	90,250	463,080	554,500	-	505,000	-	344,000
Dewpoint °F	-	-	-	-	-	-	111	-	145
Stack Velocity (ft/s)	-	-	-	-	-	-	21	-	14

TABLE 2. FLOW CHARACTERISTICS FOR A J-79 ENGINE TEST AT MILITARY POWER SETTING AND A TEST CELL AUGMENTATION RATIO OF 2 TO 1

						Stack Gas at 600°F		Stack Gas at 150°F	
	1	2	3	4	5	6	7	6	7
Flow Characteristic	Fuel	Engine Air	Augmentation Air	Exhaust Gas	Augmented Gas	Quench Water	Stack Gas	Quench Water	Stack Gas
C in lb/hr	8,570	-	-	-	-	-	-	-	-
H_2 in lb/hr	1,430	-	-	-	-	-	-	-	-
O_2 in lb/hr	-	136,000	272,000	101,720	373,720	-	373,720	-	373,720
N_2 in lb/hr	-	512,000	1,024,000	512,000	1,536,000	-	1,536,000	-	1,536,000
H_2O in lb/hr	-	7,120	14,240	20,000	34,240	-	34,240	168,000	185,240
CO_2 in lb/hr	-	-	-	31,400	31,400	-	31,400	-	31,400
Total in lb/hr	10,000	655,120	1,310,240	665,120	1,975,360	None	1,975,360	168,000	2,126,360
Temperature	80	80	80	1,175	450	-	450	140	150
SCFM	-	145,220	290,440	147,500	437,940	-	437,940	-	491,090
ACFM	0	150,590	301,180	463,080	765,300	-	765,300	-	575,090
Dewpoint °F	-	-	-	-	-	-	73	-	125
Stack Velocity (ft/s)	-	-	-	-	-	-	32	-	24

TABLE 3. FLOW CHARACTERISTICS FOR A J-79 ENGINE TEST AT AFTERBURN POWER SETTING AND A TEST CELL AUGMENTATION RATIO OF 0.6 TO 1

						Stack Gas at 600°F		Stack Gas at 150°F	
	1	2	3	4	5	6	7	6	7
Flow Characteristic	Fuel	Engine Air	Augmentation Air	Exhaust Gas	Augmented Gas	Quench Water	Stack Gas	Quench Water	Stack Gas
C in lb/hr	30,000	-	-	-	-	-	-	-	-
H_2 in lb/hr	5,000	-	-	-	-	-	-	-	-
O_2 in lb/hr	-	136,000	81,600	16,000	97,600	-	97,600	-	97,600
N_2 in lb/hr	-	512,000	307,200	512,000	819,200	-	819,200	-	819,200
H_2O in lb/hr	-	7,120	4,280	52,120	56,400	336,000	392,400	528,000	584,400
CO_2 in lb/hr	-	-	-	110,000	110,000	-	110,000	-	110,000
Total in lb/hr	35,000	655,120	393,080	690,120	1,083,200	336,000	1,419,200	528,000	1,611,200
Temperature	80	80	80	3,175	2,060	140	600	140	150
SCFM	-	145,220	87,150	153,000	240,150	-	358,500	-	426,000
ACFM	-	150,590	90,250	1,069,000	1,160,000	-	729,000	-	499,000
Dewpoint °F	-	-	-	-	-	-	167	-	177
Stack Velocity (ft/s)	-	-	-	-	-	-	30	-	21

TABLE 4. FLOW CHARACTERISTICS FOR A J-79 ENGINE TEST AT AFTERBURN POWER SETTING AND A TEST CELL AUGMENTATION RATIO OF 2 TO 1

						Stack Gas at 600°F		Stack Gas at 150°F	
	1	2	3	4	5	6	7	6	7
Flow Characteristic	Fuel	Engine Air	Augmentation Air	Exhaust Gas	Augmented Gas	Quench Water	Stack Gas	Quench Water	Stack Gas
C in lb/hr	30,000	-	-	-	-	-	-	-	-
H_2 in lb/hr	5,000	-	-	-	-	-	-	-	-
O_2 in lb/hr	-	136,000	272,000	16,000	288,000	-	288,000	-	288,000
N_2 in lb/hr	-	512,000	1,024,000	512,000	1,536,000	-	1,536,000	-	1,536,000
H_2O in lb/hr	-	7,120	14,260	52,120	66,380	223,000	299,380	511,000	577,380
CO_2 in lb/hr	-	-	-	110,000	110,000	-	110,000	-	110,000
Total in lb/hr	35,000	655,120	1,310,240	690,120	2,000,380	223,000	2,333,380	511,000	2,511,380
Temperature	80	80	80	3,175	1,150	140	600	140	150
SCFM	-	145,220	290,440	153,000	443,440	-	526,000	-	623,000
ACFM	-	150,590	301,180	1,069,000	1,371,000	-	1,069,000	-	730,000
Dewpoint °F	-	-	-	-	-	-	141	-	161
Stack Velocity (ft/s)	-	-	-	-	-	-	46	-	30

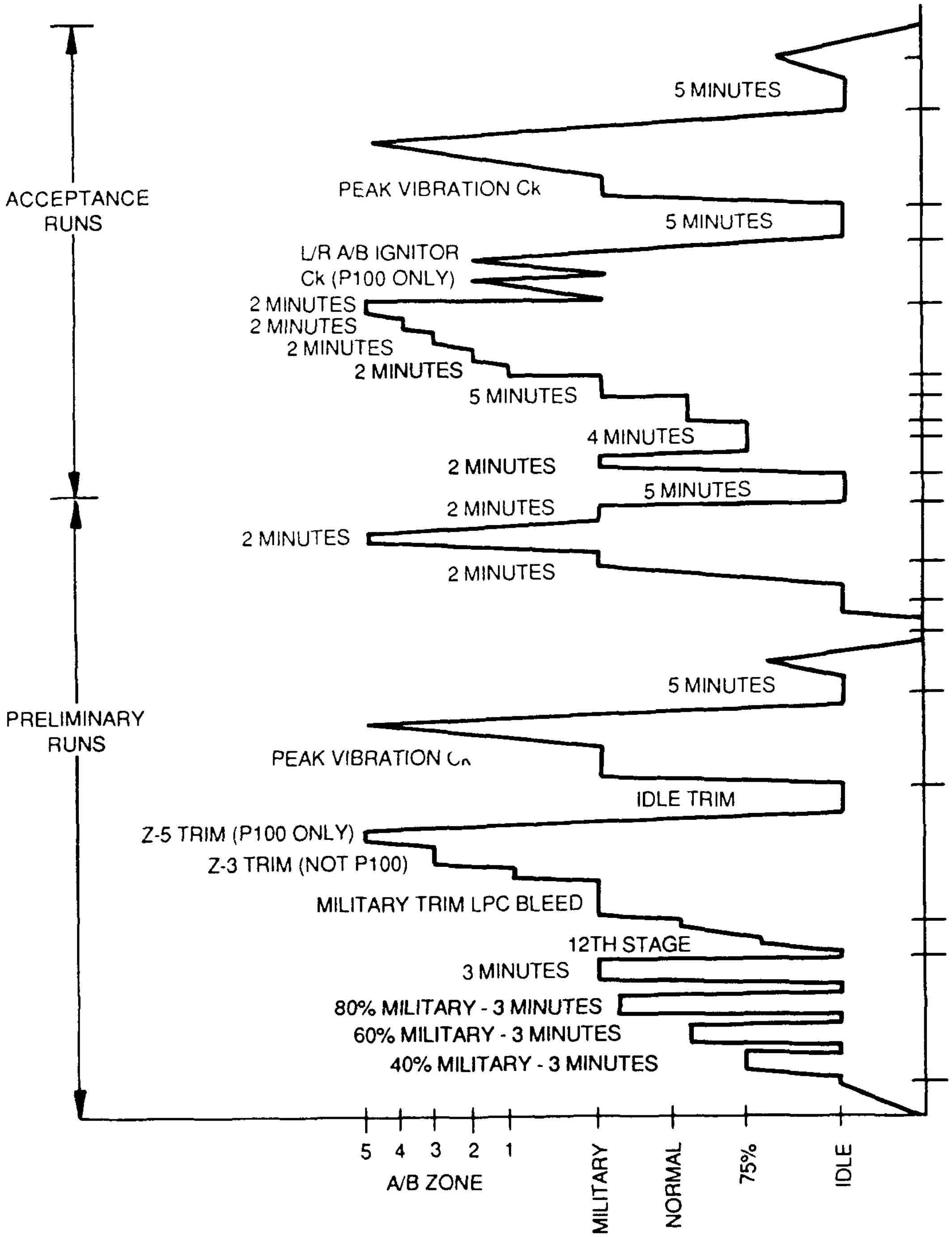


Figure 2. A Typical TF30 Run Schedule at Tinker AFB (Reference 5).

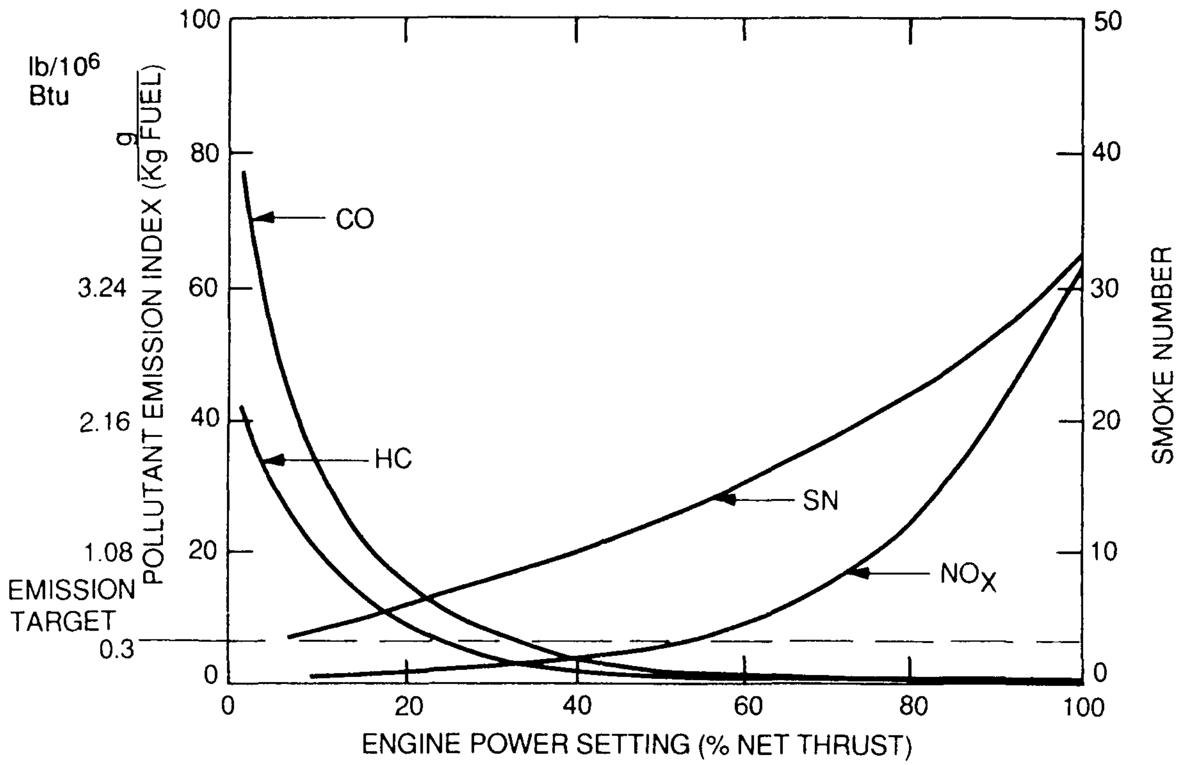


Figure 3. Typical Nonafterburning Turbine Engine Emission Trends (Reference 6).

load for one J-79 engine (Reference 6). If we accept a NO_x emission goal of 0.3 lb/MBtu (the current EPA limit for liquid-fueled stationary sources) without supplemental NO_x reduction equipment, this particular engine meets the emission goal at loads below 50 percent thrust. Therefore, it may be feasible to implement the NO_x reduction process only at loads greater than 50 percent. In this manner, the emission control process need remain effective over a much narrower range of exhaust temperatures and exhaust gas velocities. An additional potential benefit of reburner operation is the consumption of carbonaceous smoke particles, which are produced in large quantities during periods of high engine load.

The approximate gas composition derived from the JETC operating data in Tables 1 through 4 is given in Table 5. Augmented gas temperatures (before water sprays) extracted from the same tables are plotted on Figure 4.

TABLE 5. EXHAUST GAS COMPOSITION

Component	Concentration	
	100% Thrust	Afterburner (140% Thrust)
NO_x, ppmV	150	350
O_2, %	15	8
CO_2, %	3	6
CO, ppmV	50	50
H/C, ppmV	4	1
H_2O, %	4	26 (after quench)
N_2, % (by difference)	78	60

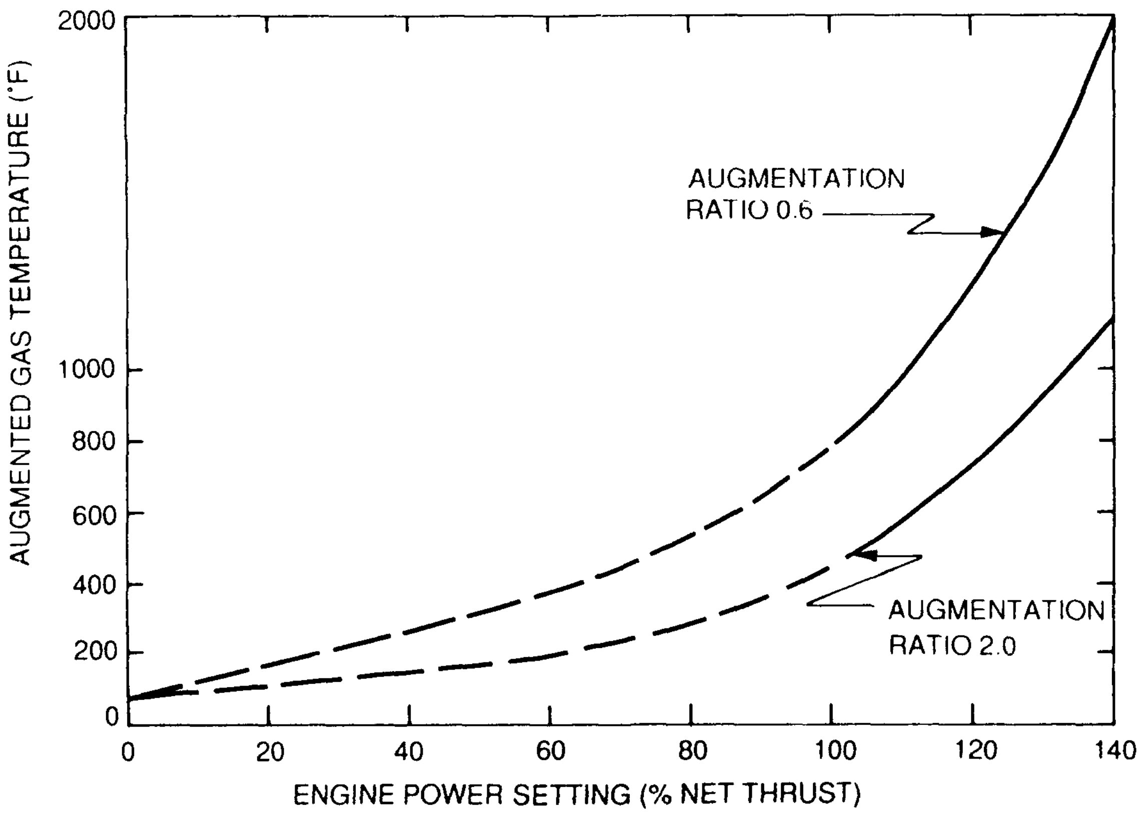


Figure 4. Temperature of Diluted Exhaust from J-79 Engine.

Temperature range and range of exhaust gas O_2 concentration are important to the reburning system design.

C. SCOPE OF PHASE I WORK

The overall goal of the program is to apply PSI Technology Company's considerable experience in developing reburning systems for utility boilers and diesel engines to the design of a system to control NO_x emissions from Air Force incinerators and JETCs. The emphasis in Phase I is on the JETC application. Specific technical objectives of the proposed Phase I effort are listed below:

1. To design a reburning system capable of at least 50 percent NO_x reduction when applied to JETCs (Task 1).

2. To quantify the effects of gas temperatures, NO_x and O_2 concentration, and reburning fuel flow on NO_x emissions (Task 2).

3. To determine the technical and economic feasibility of these reburning system applications (Task 3).

Meeting these objectives will require answers to the following key technical questions:

- What are the effects of jet engine operating conditions on NO_x emissions, as well as other potential exhaust gas contaminants?

- Under what operating conditions (temperature, gas composition, flow rate) will reburning be effective in removing NO_x from this exhaust gas?

- What are the capital and operating costs associated with applying the technology to each combustion source?

- What are the technical issues and problems that must be addressed in a Phase II development program before reburning can be prudently applied to jet engine test cells?

SECTION II

APPLICATION OF REBURNING TO JETCs

A. REBURNING BACKGROUND

It has long been known that NO_x can be reduced to N_2 by reaction with hydrocarbon radicals produced when fuel is injected downstream of the primary combustion zone. Wendt (Reference 7) in 1973 called this process reburning because a second flame zone was required to achieve both reduced NO_x and burnout of the additional fuel.

Although conceptually simple, the reburning reaction mechanism is quite complex, as shown in Figure 5. The NO_x reduction efficiency in the reburn zone is influenced by both NO_x formation and reduction processes; the key to success is to establish conditions of temperature and mixing where the reduction mechanisms dominate.

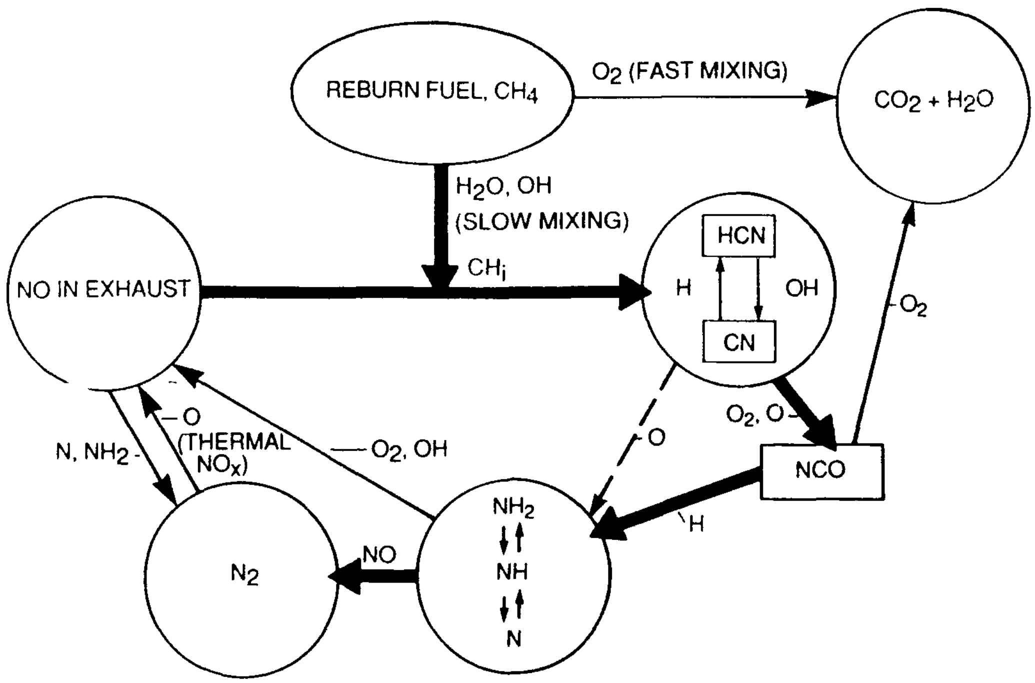


Figure 5. NO_x Formation and Destruction Pathways During Natural Gas Reburning.

Following the figure, hydrocarbon radicals formed from the reburning fuel react with NO to produce cyanogen/hydrogen cyanide. These species react further with free radicals to form NH_i species that rapidly react with more NO to form N_2. Thus, NO_x will be destroyed in the flame. The level of NO_x reduction depends on the rates of hydrocarbon radical production (as well as on the competing hydrocarbon oxidation reactions) and the flame temperature. High temperatures favor free radical formation and the reaction of NO with hydrocarbons; low temperatures favor the reaction of NO with NH_i species. Laboratory tests have shown that the NO + NH_i destruction reaction is the most important reaction in practical systems.(8) Additional air may be injected downstream of the reburning zone to complete combustion of the reburning fuel.

Much of the research on reburning technology has focused on boiler applications, where exhaust gas oxygen levels are relatively low and temperatures entering the reburn zone are relatively high. Figure 6 shows NO_x emissions

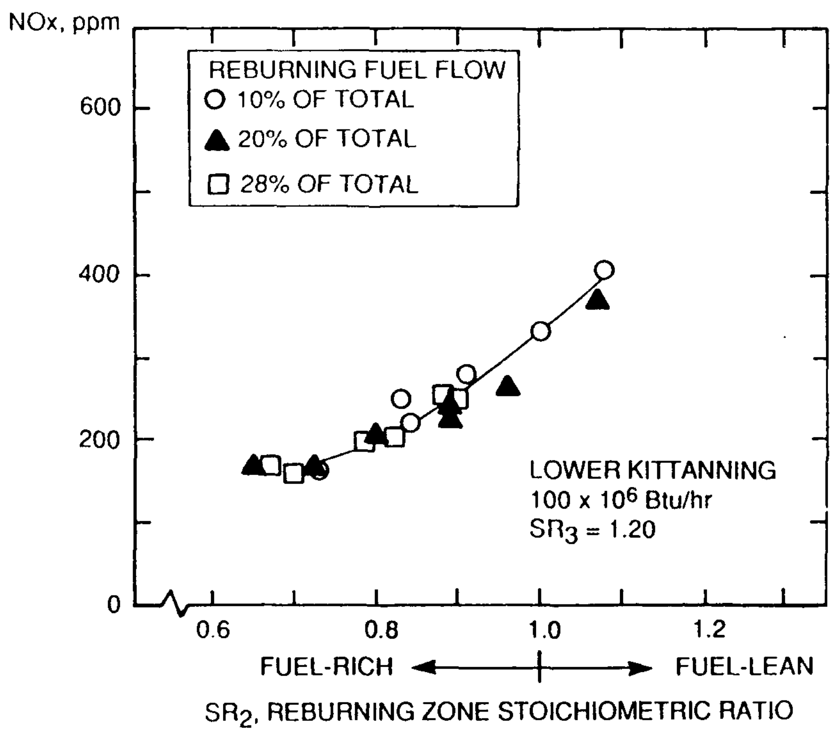


Figure 6. Fuel-Staged Emissions as a Function of Reburning Zone Stoichiometry (Reference 9).

reported by Lisauskas and Johnson (Reference 9) for a coal-fired system having a baseline emission of about 800 ppm. The NO_x reduction is maximized when the reburning zone is maintained under reducing conditions. The large amounts of oxygen in the exhaust from JETCs, make it impractical to add enough fuel to consume all the O_2.

Fortunately, local reducing conditions can still be achieved even if the overall mixture remains oxidizing. If the mixing rate of fuel and exhaust gas is slow enough, fuel-rich pockets of gas will exist in the flame. In these regions, hydrocarbon radicals can still react to destroy NO. Yang et al. (Reference 10) investigated reburning for application to industrial process heaters that also operate with high amounts of excess air. His results are summarized in Figure 7. Without creating a condition where an entire zone of the furnace was fuel-rich, he was able to reduce NO_x by 40 to 55 percent, depending on the amount of reburning fuel added.

The hypothesis of fuel-lean reburning is also consistent with emission tests of gas turbine combined-cycle power plants in the 1970s. Under some conditions, it was noted that NO_x formed in the gas turbine primary combustion zone could be destroyed by the duct burner, which was installed to raise exhaust gas temperatures and improve heat recovery in the bottoming-cycle steam generator (Reference 11).

In other combined cycle applications where the oxygen-containing turbine exhaust gas was used as the oxidant in a separately fired steam generator, NO_x reductions greater than 50 percent were achieved when some of the burners were fired fuel-rich (References 12, 13). More recently, Brown and Kirby (Reference 14) investigated the application of reburning to diesel engines. Their conclusion is that reburning is impractical in O_2-rich exhaust steams because enormous amounts of reburning fuel are required to achieve substantial destruction of NO_x. Their tests, however, may not have achieved the slow mixing rates that would be required to maintain free radical concentrations long enough to destroy NO_x in such a system.

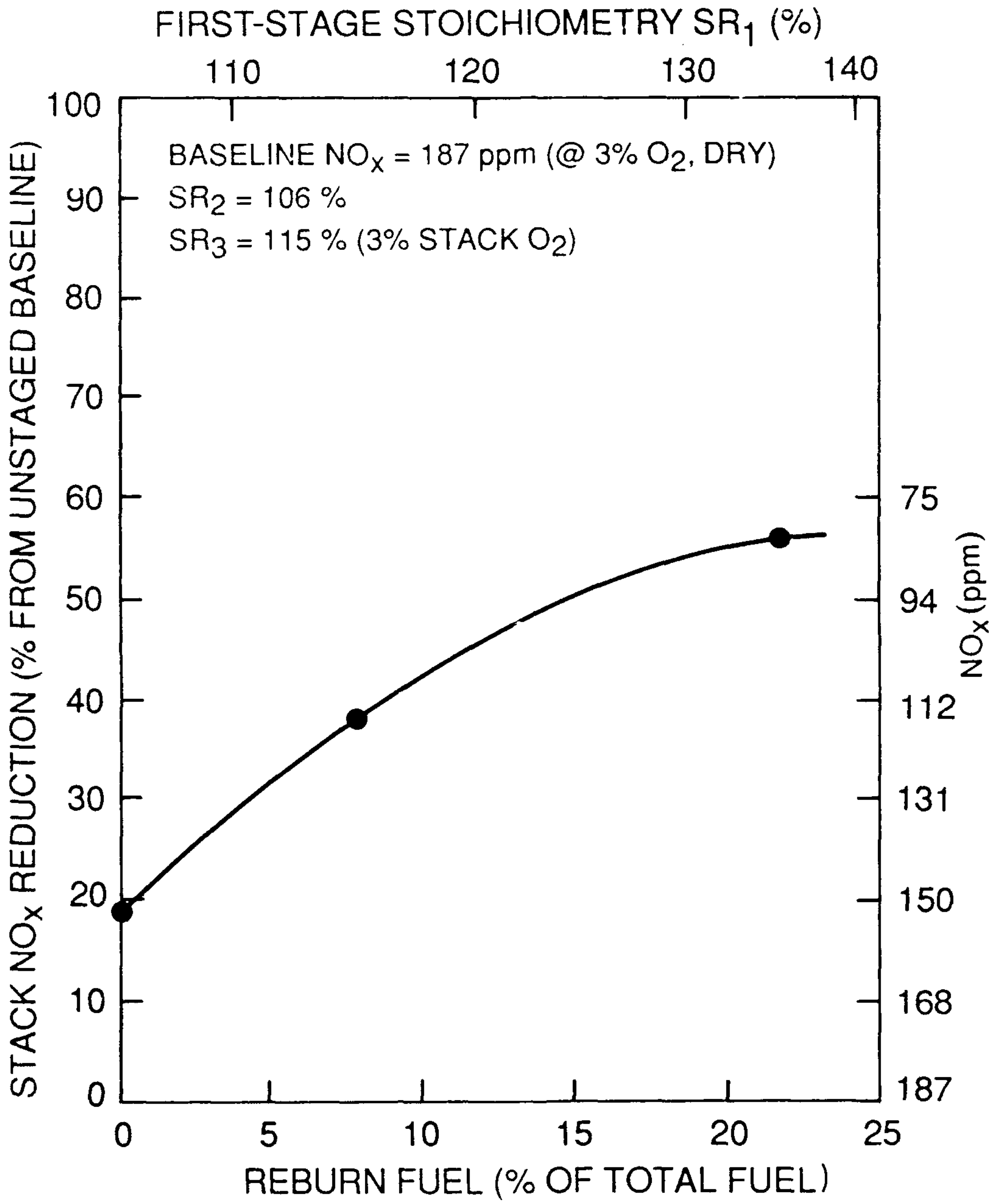


Figure 7. All Fuel-Lean Industrial Furnace NO_x Reduction (Reference 10).

B. RATIONALE FOR THE JETC REBURNING APPLICATION

A generalized schematic of reburning to remove NO_x from an oxygen-rich exhaust stream is shown in Figure 8. In order to achieve at least 50 percent NO_x reduction, the system must provide the following conditions:

- slow, but nearly complete mixing of reburn fuel with the exhaust stream;
- temperatures high enough to promote and sustain free radicals in the shear layers of the resulting diffusion flame;
- some premixing of exhaust with reburning fuel to assure contact of a significant fraction of the NO with hydrocarbon radicals in the fuel-rich flame region;
- O_2 concentration in the exhaust high enough to stabilize the reburning flame.

The temperature and O_2 concentration of the JETC exhaust vary with engine thrust and degree of dilution by augmenter air. However, they are not

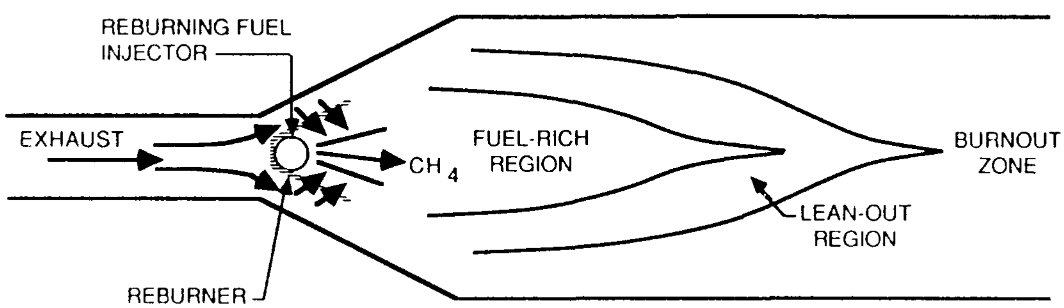


Figure 8. Reburn Schematic - Plan View.

independent of each other. Figure 9 shows this relationship based on the data of Tables 1 through 4 for military/afterburner thrusts and a range of augmentation ratios. The total gas mass flow was approximately the same for each data point. Based on this relationship it can be concluded that augmenter ratio can be used to control both temperature and O_2 concentration over a wide range. It should be possible to obtain temperatures higher than 800°F and O_2 concentrations above 12 percent, which would be conducive to both free radical formation and stable reburner flames.

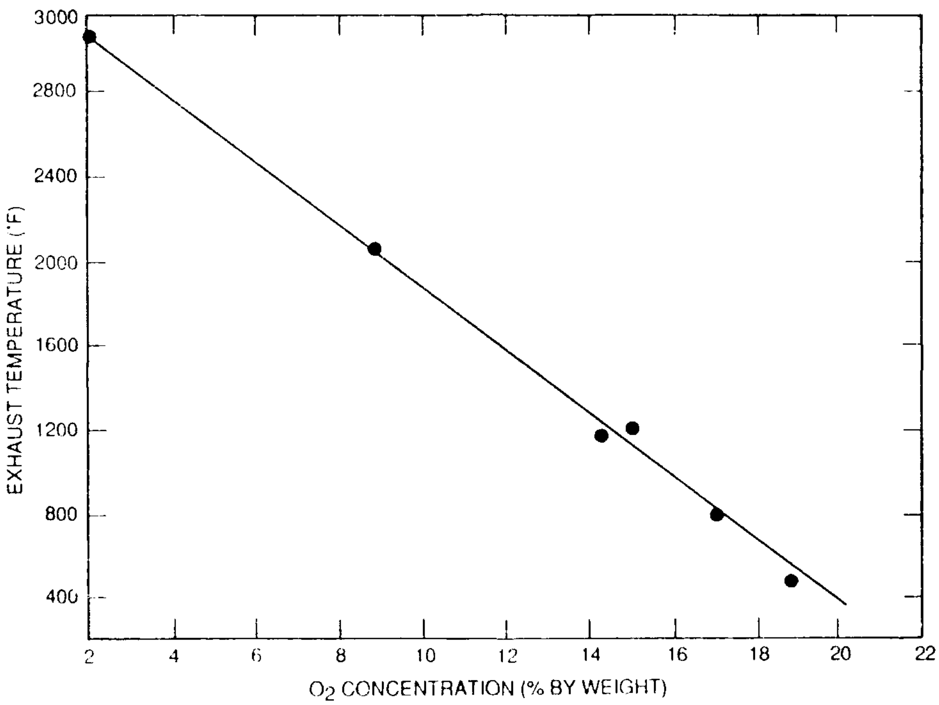


Figure 9. Relationship Between Exhaust Temperature and O_2 Concentration on a JETC.

Other potential advantages of reburning NO_x control processes include the following:

- low pressure drop (< 5 inches of water) so that engine operation will not be affected by the NO_x control process;

- simple operation and control;
- low capital cost relative to selective catalytic NO_x reduction;
- opportunity to recover heat from the engine exhaust during testing, depending on site-specific JETC designs and energy needs of the Air Force bases where they are located.

The sections that follow describe the preliminary design of a JETC reburning system and the feasibility of fulfilling these potential advantages.

SECTION III

PRELIMINARY REBURNING SYSTEM DESIGN

A. DESIGN BASIS

A jet engine test cell located at Tinker Air Force Base has been chosen as the basis for the preliminary reburning system design. Physical dimensions and mass flow rates for this JETC are given in Reference 1.

The system is designed for NO_x emissions not to exceed 0.3 lb NO_2/MBtu, equivalent to the current EPA standard for new stationary sources burning liquid fuels. Uncontrolled NO_x emissions at full military thrust may range from 0.4 to 1.6 lb/MBtu (Reference 15). Therefore, the emission target represents about a 25 to 80 percent NO_x reduction on a lb/MBtu basis. For this study, we have assumed that a 50 percent average reduction of NO_x will be sufficient. For the purpose of simplifying reburner control, it is proposed that the reburner be operated at a constant firing rate during the entire test period. At high engine loads (> 50 percent), the reburner will provide the NO_x reduction required to meet emissions regulations. Operation of the reburner at lower engine loads, while not necessary for NO_x reduction purposes, will offer the additional benefit of reducing JETC hydrocarbon/CO emissions (via their combustion in the reburner flame) which are particularly problematic during the low load conditions. The system will be designed such that the exhaust stream oxygen concentration will not fall below 3 percent at any engine load.

PSIT and the Air Force Technical Project Officer agreed that, for the purposes of this study, the materials of construction for each JETC component may be changed if required by the NO_x control process. However, no changes will be made if the operation of the test engine would be affected in any way. It was assumed that existing means of controlling exhaust gas temperature (i.e., augmentation ratio or spray water flow) could be utilized to optimize the NO_x removal process.

To estimate operating costs associated with the reburner system, it was also necessary to make assumptions concerning the JETC operating schedule. For this study, we have stipulated that the subject JETC will average 4 hours of operation per day, for 200 days per year. Thus the total yearly operation will be about 800 hours, producing approximately 300 tons per year of uncontrolled NO_x.

B. DESIGN ALTERNATIVES

Two alternative locations for the reburner system were considered in this study:

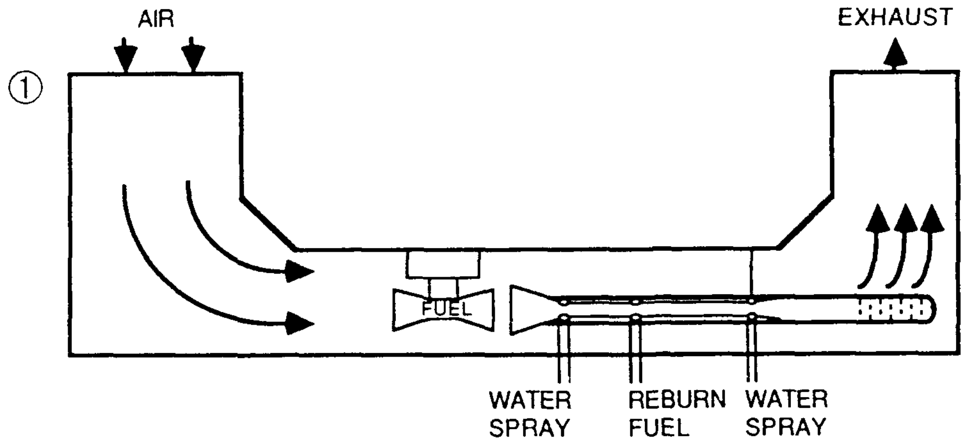
1. in the augmenter tube; or

2. in a separate reburning chamber downstream of the augmenter tube (external to the existing JETC).

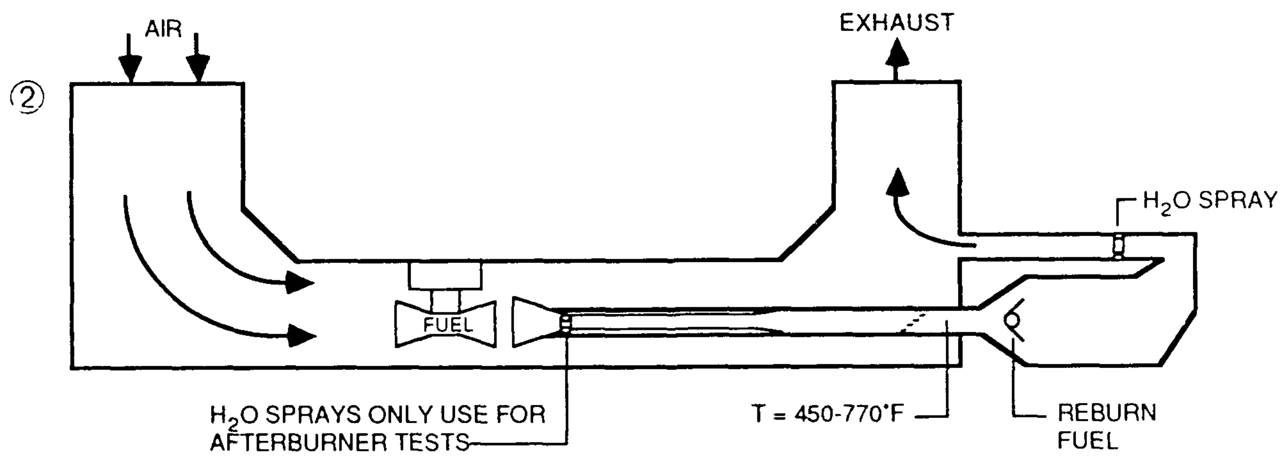
These alternatives are shown schematically in Figure 10.

Option 1 has the advantage of minimizing capital cost by utilizing existing equipment, although it is expected that the reburner will generate temperatures in excess of 1200°F (650°C). Therefore, the reburning retrofit may include replacing the augmenter tube with a more expensive alloy, or lining the tube with insulating refractory to allow operation in this temperature range.

Another concern with Option 1 is the gas velocity in the augmenter tube. We estimate the average gas velocity to vary from about 50 ft/s to over 200 ft/s for engine operation ranging from 50 percent thrust to afterburner thrust. The velocity field at the entrance to the augmenter, however, is surely nonuniform and highly turbulent as engine exhaust (supersonic velocity) mixes with dilution air. Since fuel-lean reburning requires slow mixing of reburning fuel and exhaust gas to achieve NO_x reduction, the reburner should be located in a region of uniform flow. The desired exhaust gas velocity is less



- INCORPORATE REBURNING INTO AUGMENTER
- MAY REQUIRE REPLACING AUGMENTER WITH HIGH-TEMPERATURE ALLOY
- WORRY ABOUT VELOCITY/TURBULENCE



- INCORPORATE H_2O SPRAYS TO QUENCH VERY HIGH EXHAUST TEMPERATURES IN AUGMENTER
- BUILD EXTERNAL REBURN CHAMBER DOWNSTREAM OF EXISTING AUGMENTER TUBE
- ADJUST/CONTROL OF BACKPRESSURE?

Figure 10. Reburning Options.

than 100 ft/s. Also, the mean bulk-gas residence time in the augmenter could be as low as 0.4 s. If the reburner is located 6 to 8 duct diameters downstream of the augmenter entrance (a location where flow may be more uniform), there may be less than 0.2 s of residence time to achieve NO_x reduction and burnout of reburning fuel. This residence time may be insufficient.

Option 2, building a separate reburning reactor external to the JETC, provides more flexibility to optimize the reburning temperature, velocity and residence time. Therefore, it is likely that maximum NO_x reduction can be achieved with this option, but there are still a few concerns. High temperature gases directly from the augmenter may be required to minimize the use of reburning fuel. This suggests minimal usage of water sprays in the augmenter. Even with this option, it may be prudent to consider modifying the augmenter to withstand temperatures above 1000°F (540°C). Also, we are concerned with integrating the reburn reactor with the shrouded basket at the exit of the augmenter. The design should still allow regulation of augmenter back-pressure and dissipate the acoustic energy of the exhaust. Therefore, we recommend that the duct to the reburn reactor be an annulus surrounding the augmenter basket, as shown in Figure 11.

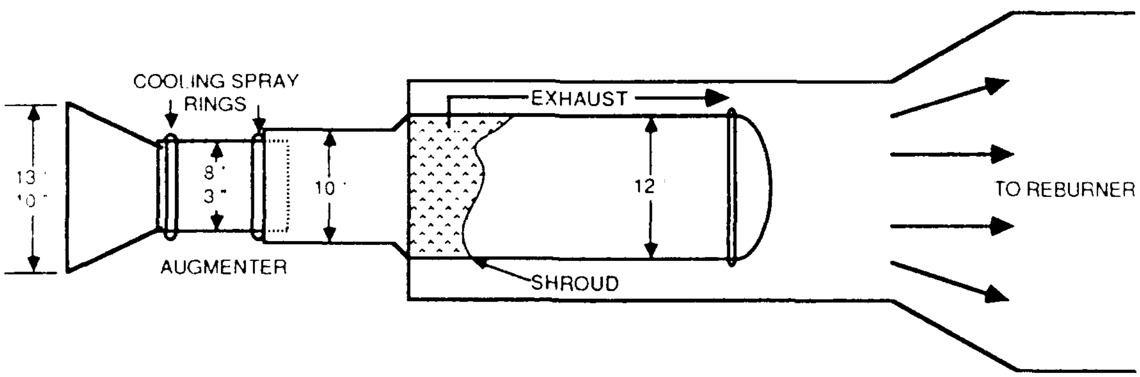
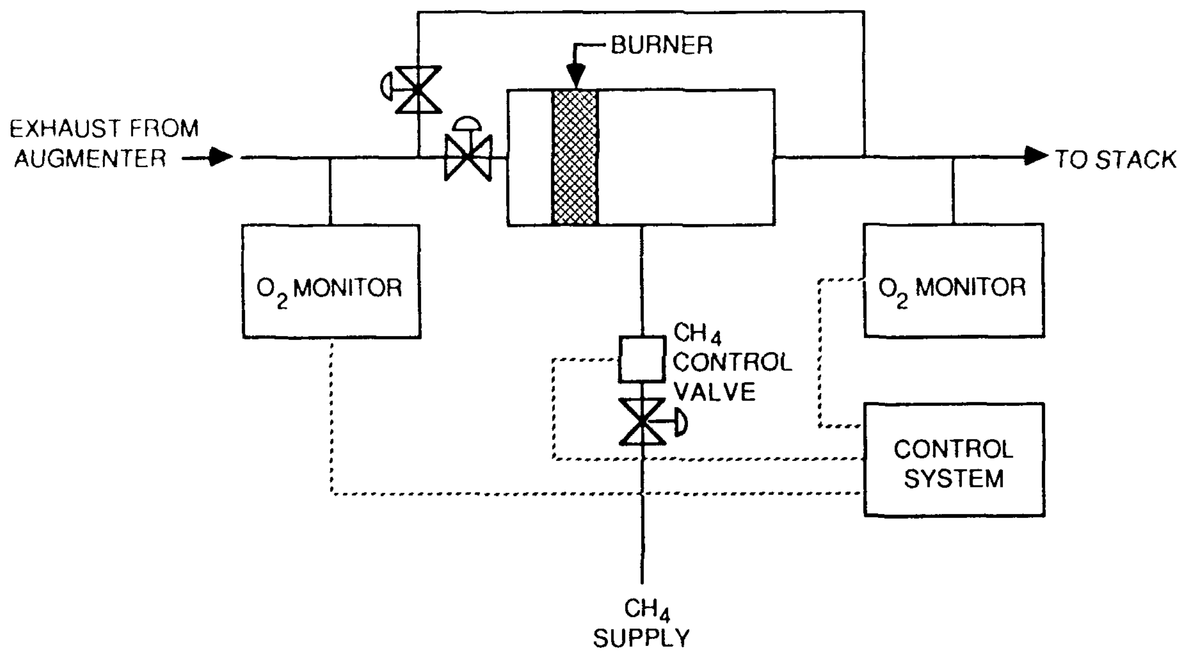


Figure 11. Connection Between Augmenter and Reburner.

C. REBURNING SYSTEM COMPONENTS

A general schematic showing all the components of the proposed reburning system is given as Figure 12. Preliminary specifications for each component are discussed below. Where specifications changed as a result of the experimental task, these changes are noted, although a complete explanation will be saved for Section IV.



Equipment:

- Duct Burner
- Combustion chamber
- O_2 Monitor (inlet and outlet)
- CH_4 Supply Piping
- CH_4 Flow Control System
- Valves and Piping
- Miscellaneous Ductwork

Figure 12. Reburning Components.

1. Duct Burner

A single duct burner rated at 160 MBtu/hr was originally specified (four reburners rated at 150 MBtu/hr were later shown to be required based on the laboratory tests). A single burner would provide a ratio of exhaust gas flow to reburner fuel flow of 280 on a mass basis. The burner will consist of a shrouded gas ring containing eight gas-injection spuds, mounted on a flange that bolts into a duct coming from the augmenter. The burner will be equipped with a spark igniter and optical flame scanner. The burner is expected to provide 4 to 1 turndown, achieve a pressure loss of less than 2 inches of water, and operate stably at exhaust gas oxygen concentrations greater than 12 percent.

2. Combustion Chamber

The duct extension from the augmenter consists of a 12-ft inner diameter cylinder constructed of Type 304 stainless steel (operating metal temperature up to 1400°F). The combustion chamber opens to a 20-ft inner diameter through a conical transition piece tapered at a 30-deg angle. It will also be constructed of 304 stainless and lined with refractory firebrick to prevent overheating of the metal and to minimize heat loss. The transition piece will be lined with refractory tile. The overall length of the combustion chamber is 60 ft.

3. Exhaust Ductwork

The exhaust leaving the combustion chamber will be ducted back to the blast room of the JETC. The exact layout of this ductwork will depend on the availability of space surrounding the JETC, but it is assumed that 70 ft of duct, 15 ft in diameter will suffice. The ductwork will consist of carbon steel. Water sprays will be located at the exit of the combustion chamber to quench gas temperatures below 500°F (260°C).

Since the temperature of the reburner exhaust is expected to be 1200° to 1600°F (650° to 870°C), it may be economical to cool the exhaust gases using a heat recovery boiler. The heat of the exhaust gas is sufficient to generate 200,000 lb/hr of saturated steam at 250 psia or 400,000 lb/hr of steam superheated to 650°F. Otherwise, the 500,000 lb/hr of quench water flow already designed for this unit could be used to ensure that the stack temperature will not exceed 500°F.

4. Oxygen Monitoring System

The O_2 concentration of the engine exhaust entering and leaving the reburn combustion chamber should be monitored. Outlet O_2 levels approaching the inlet O_2 concentration while the natural gas is flowing indicate a flame-out. In this event, the natural gas should be shut off while the system is purged of unreacted methane. If the exit O_2 concentration falls below a critical value (about 3 percent based on our laboratory experiments), emissions of hydrocarbons and CO may become excessive, and the natural gas flow should be reduced.

5. Control System

Signals from the O_2 meters are processed by a feed-forward controller, which actuates the main natural gas control valve. The controller also receives a signal from the flame scanner attached to the reburner. Either signal may initiate a shutoff, purge, relight cycle.

6. Natural Gas Supply Piping

It has been assumed that the reburning system will have access to pipelined natural gas. A nominal 100 feet of piping has been included in this preliminary design.

D. MASS BALANCE FOR REBURNING SYSTEM

Before the start of the experimental work, a mass balance was performed using a target value for the amount of reburning fuel required. Determination of this value was the key objective of the testing, but the exercise was valuable to establish the technical issues relative to the design of a reburner to process the huge volumes of gas exhausted by a typical JETC.

In a boiler reburning system, the flowrate of reburning fuel is approximately one percent of the total flue gas mass flow. Therefore, this same number was chosen as the starting point for the preliminary system design for JETCs. The resulting reburner fuel flow rate is approximately 20,000 lb/hr (400 to 450 MBtu/hr).

Mass balances were calculated for three JETC conditions:

- military thrust, augmentation ratio of 2.0
- military thrust, augmentation ratio of 0.6
- afterburner thrust, augmentation ratio of 2.0.

Low load operational data were not available for the subject JETC, but the total gas flow is expected to be influenced more by the augmentation ratio than by the fuel flow rate to the test engine.

Figures 13 to 15 illustrate these mass balances. All inlet conditions were taken from Tables 1, 2 and 4; NO_x concentrations were taken from Figure 3 for the military power level and extrapolated for afterburner conditions.

The reburning system has two positive effects toward meeting an EPA NO_x limit of 0.3 lb NO_2 per million Btu fuel input:

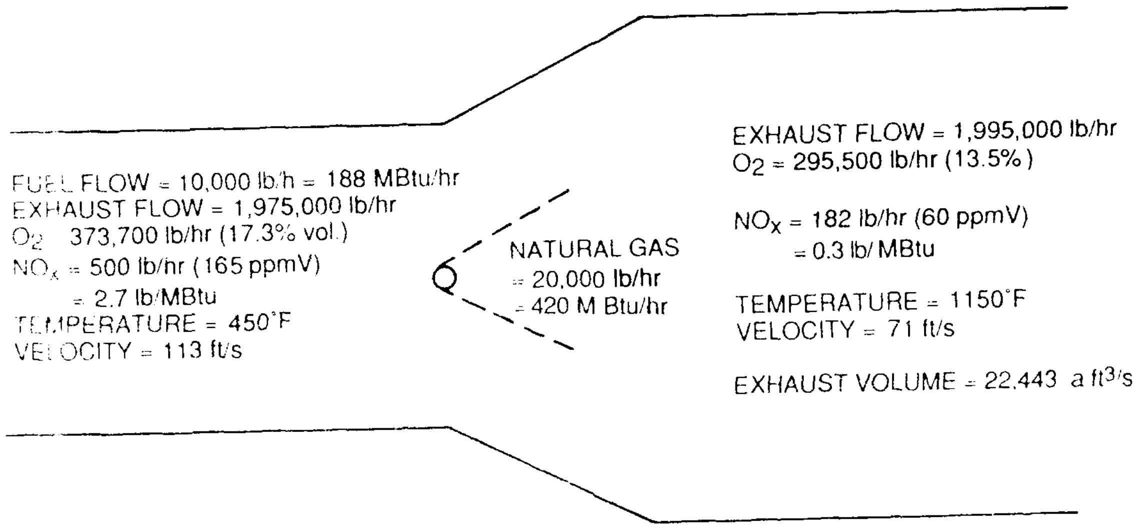


Figure 13. Reburn System Mass Balance Calculated at Military Thrust, Augmentation Ratio of 2.0.

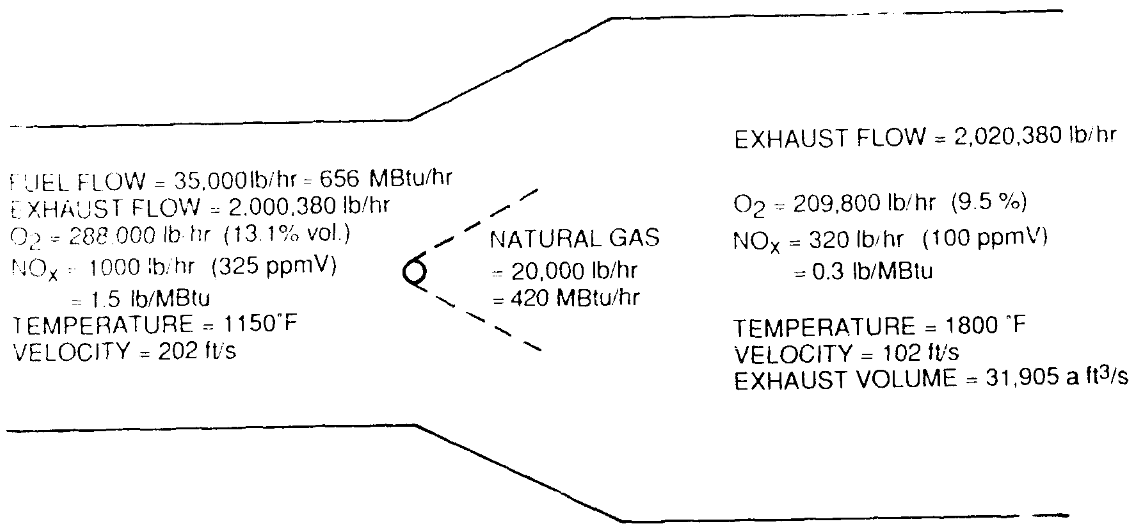


Figure 14. Reburn System Mass Balance Calculated at Afterburner Thrust, Augmentation Ratio of 2.0.

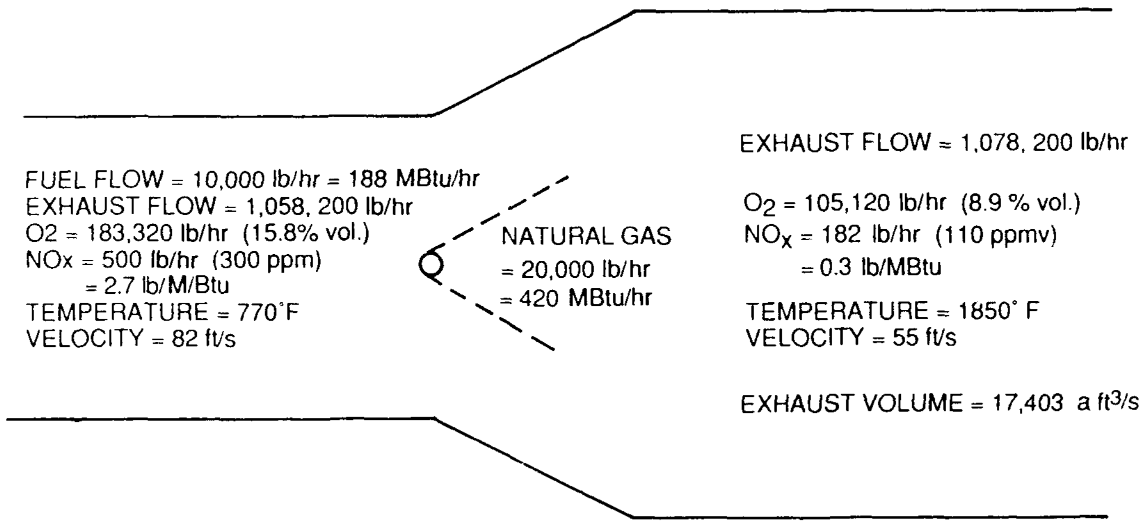


Figure 15. Reburn System Mass Balance Calculated at Military Thrust, Augmentation Ratio of 0.6.

1. Reburning reduces the pounds of NO_x in the exhaust stream via reaction of the incoming NO_x with flame radicals; no additional NO_x is produced.

2. Reburning increases the total heat input to the JETC system.

Therefore, when calculating the emission rate of the system according to EPA methodology, the process decreases the numerator (lb/hr of NO_x) and increases the denominator (Btu/hr of fuel). For the cases shown, the NO_x reduction in ppm (hypothetical, not experimental) would be 62 to 69 percent but the reduction in lb/MBtu would be 80 to 90 percent. For the current program goal of 50 percent NO_x reduction, the reduction in lb NO_2/MBtu would be 70 to 85 percent.

Other germane observations from the mass and energy balances are outlined below:

- The reburning process will cause a temperature rise of 650° to 700°F at an augmentation ratio of 2.0, and about 1100°F at an augmentation ratio of 0.6 (assuming no heat loss to the system).

- Maximum average gas velocity in the combustion chamber is expected to be about 102 ft/s based on the bulk average volumetric flow rate and expected temperature.

- Augmentation ratios can be adjusted to keep inlet O_2 concentrations above 13 percent to prevent reburner flameout.

E. SUMMARY OF KEY ISSUES

The preliminary reburn system design study identified several key issues to be resolved before reburning can be used to control NO_x and hydrocarbon emissions from jet engine test cells. Many of these issues have been mentioned in the preceding discussion; all issues are summarized below:

- How much reburn fuel is required to achieve at least a 50 percent reduction in NO_x concentration?

- How effective is a low-NO_x reburner in destroying soot or hydrocarbons that may also contaminate the exhaust gas?

- Can we simultaneously achieve high NO_x reduction and complete burnout of reburn fuel?

- What reburner turndown must be achieved to assure flame stability and complete combustion during idle and low load JETC conditions?

- What is the minimum O_2 concentration in the engine exhaust at which the reburner flame can be stabilized? Can the augmenter ratio be set to avoid low O_2 and subsequent reburner flameout?

- Will the pressure drop across the reburner be less than 5 inches of water for all possible operating conditions?

- Is heat recovery from the reburner exhaust practical?

- What key parameters should be considered when scaling the reburner design to the size required for a full-sized JETC?

Investigation of these issues formed the basis of the experimental portion of this program (described in Section IV) and were evaluated further in the feasibility study discussed in Section V.

SECTION IV
EXPERIMENTAL RESULTS

The primary objective of the laboratory-scale experiments was to assess the effectiveness of reburning as a means of NO_x reduction at conditions representative of JETC operation and, consequently, to generate specific design requirements for the proposed full-scale application. The technical issues that have been explored are summarized as follows:

1. The relationship of NO_x reduction to reburner stoichiometry (relative amounts of fuel and oxidizer).

2. The influence of reburner inlet gas conditions (temperature and NO_x concentration) and flow parameters (total flow rate and shroud configuration) on the reburning process.

3. The effect of adding gaseous ammonia (source of additional NH_i radicals) to the reburning fuel.

The experimental parameters and the range over which they were varied are listed in Table 6. Subject to the constraints of the apparatus and the limited scope of the program, efforts were made to approximate typical JETC exhaust conditions as much as possible. The following subsections present the experimental results and discuss the relationships between test parameters and reburner performance.

A. APPARATUS

The dedicated reburning test reactor used for the laboratory-scale experiments is depicted schematically in Figure 16. The reactor is composed of three sections: a methane/air/oxygen-fired primary burner, a variable-surface-area gas-to-liquid heat exchanger, and the test section, in which the reburner unit is located. The primary burner (maximum firing rate: 25,000 Btu/hr)

TABLE 6. TEST PARAMETERS

Parameter	Range
Reburner fuel flow	0 to 4.0 slpm
Inlet O_2 concentration	14 to 19 percent
Inlet NO_x concentration	500 to 1000 ppm
Inlet temperature	570° to 900°F
Total exhaust flow rate	64 to 130 slpm
Shroud open area	0 to 100 percent
Ammonia/NO molar ratio	0 to 2

supplies a flow of hot combustion gas of controllable composition. Independent control of total combustion gas flow and oxygen concentration is achieved by adjusting the relative flow rates of air and oxygen to the burner. At the burner exit, the gas stream is doped with pure NO to bring the overall gas NO_x concentration to the desired level. Gases leaving the burner pass through the heat exchanger, which serves to reduce gas temperature entering the test section. The heat exchanger section consists of water-cooled stainless steel tubes inserted perpendicular to the gas flow. The gas exit temperature is regulated by varying the number of tubes in the exhaust gas flow. Exit temperatures in the range of 500° to 1000°F were attainable using this technique.

The test section incorporates the reburner assembly and several thermocouple and gas sampling ports. The reburner, which will be discussed shortly in more detail, is a jet-diffusion type and is located near the entrance of the test section. Gas temperature downstream of the reburner is measured at several locations along the length of the test section with type K thermocouples. To minimize heat loss to ambient, the test section is insulated both internally (with a fibrous alumina cylindrical liner) and externally. However, because of the very large differential between gas and ambient temperatures, some temperature drop along the flow axis does occur. Figure 17 shows test section centerline temperature profiles (900°F inlet temperature) for three

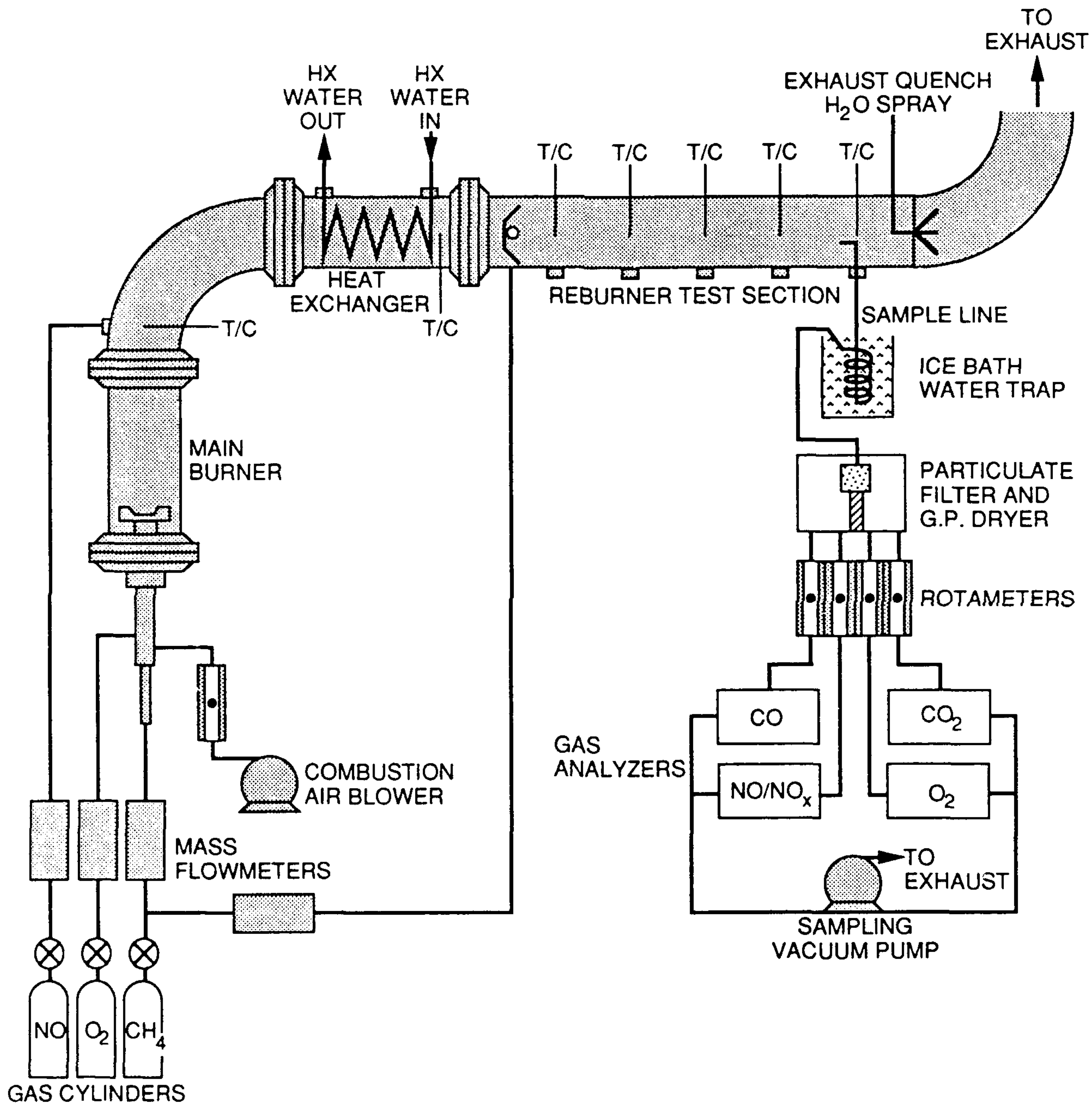


Figure 16. Reburner Test Apparatus.

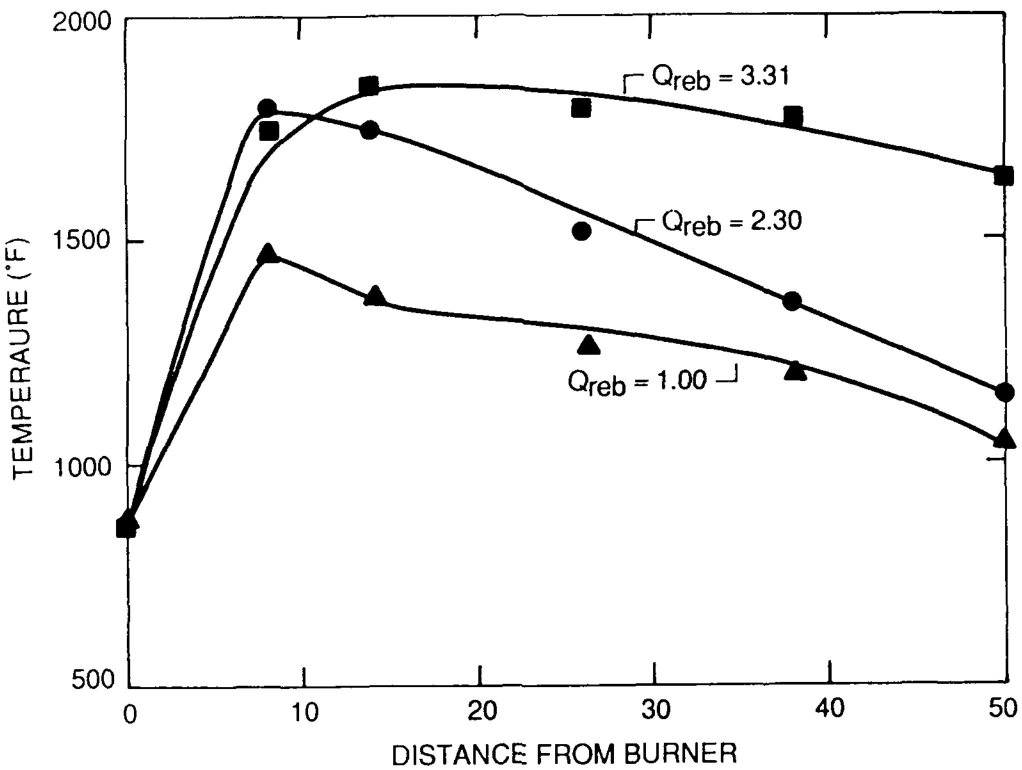


Figure 17. Axial Centerline Temperature Profiles.

different methane flows. As would be expected, reburner exhaust gas temperature increases substantially with increases in fuel flow. In addition, the shape of the temperature profile varies according to fuel flow rates. The relatively small axial temperature gradient of the high fuel flow case is attributable to the extended length of the combustion zone.

To determine gas composition, sampled gases were withdrawn from the reactor by means of a water-jacketed stainless steel probe at a port approximately 50 inches (127 cm) downstream of the reburner. This location corresponds to a nominal postreburning gas residence time (depending on temperature and gas flow rate) of 200 to 700 ms. The sampled gases, cooled rapidly by convection to the cold tube walls, were passed sequentially through an ice-bath water trap, particulate filter, and gas permeation membrane drier (which removed any residual water vapor) before being directed to a battery of on-line continuous gas analyzers. The measured gas components included the following: CO and CO_2 (Beckman Model 864 nondispersive infrared meters), O_2 (Teledyne Model 320A detector) and NO/NO_x (ThermoElectron Model 10AR chemiluminescent analyzer). The gas analyzers were calibrated with the appropriate certified gas standards before the start of each series of experiments. To limit reactions of the components of interest (specifically NO/NO_x) within the sampling lines, all surfaces contacting the gas stream were fabricated from Teflon TM or passivated stainless steel.

The laboratory-scale reburner employed for these experiments (shown in Figure 18) is modeled on a commercially available shrouded duct burner used for heating gas streams in industrial processes. This burner design is believed to be well suited to the reburning application because it provides for staged mixing of fuel and oxidizer and, hence, promotes the presence of locally fuel-rich

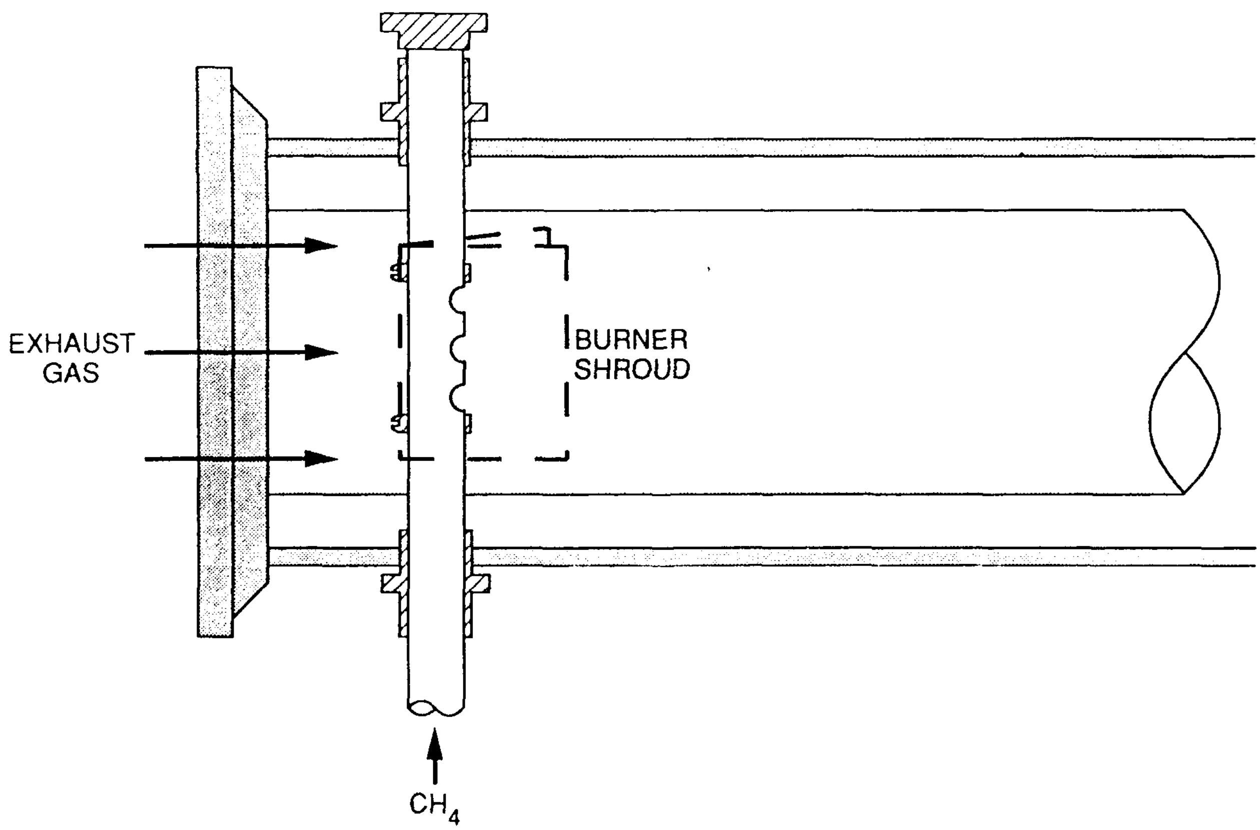


Figure 18. Laboratory-Scale Reburner Schematic.

regions, which are critical for the reduction of NO by flame radicals. The mixing rate of the fuel and oxidizer can be adjusted by varying the shroud open area. For most of the experiments discussed herein, a shroud fabricated from perforated stainless steel with 36 percent open area was used. As will be discussed later, the influence of the shroud open area on NO_x reduction was assessed by conducting experiments with a solid shroud (0 percent open area) in place and with the shroud removed (100 percent open area). The shroud angle (formed by shroud "wings" and axis of gas flow) was set arbitrarily at 45 degrees. The projected area of the shroud is 1.56 inch^2, or about 50 percent of the duct cross-sectional area. The reburner methane is injected coaxially with the gas flow through three holes, spaced by 5/16 inch, drilled radially in the 1/4 inch stainless steel gas tube. The shroud, which is attached to the gas tube with retaining rings, is centered in the duct. Measurements of differential pressure across the burner indicated undetectable (< 0.1 in W.G.) pressure drop, even at the maximum gas flow rate. A photograph of the prototype reburner is shown in Figure 19.

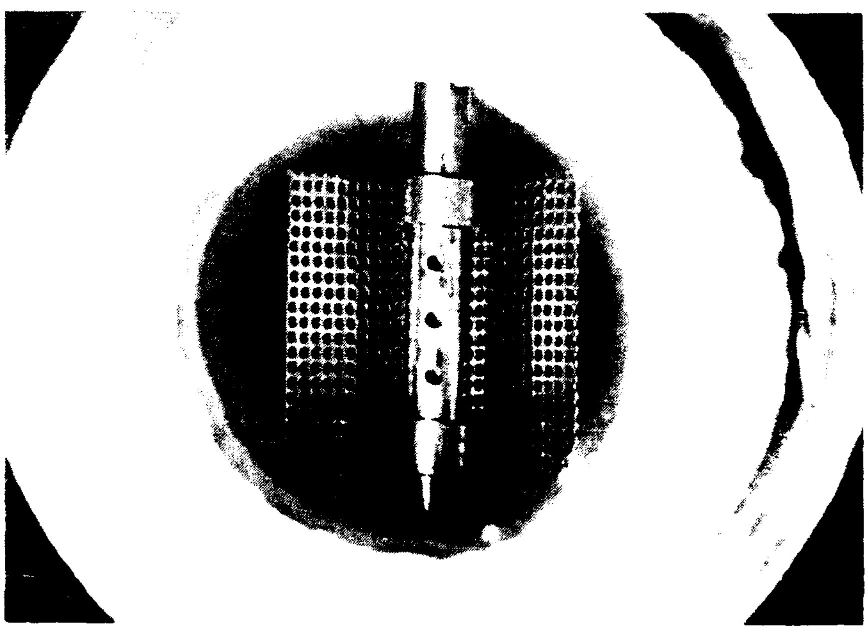


Figure 19. Photograph of Laboratory-Scale Reburner.

The range of operation over which a stable reburning flame can be obtained is particularly significant because the NO_x reduction process is predicted upon a stable flame being present. Initial testing of the shrouded reburner at typical experimental conditions (900°F inlet temperature) revealed that the onset of flame instability occurred when the inlet oxygen concentration was reduced below 14 percent. Operation at lower oxygen concentrations can be achieved by employing an auxiliary ignition source (such as an electrically heated surface or a shielded premixed pilot flame) to maintain flame stability. Vendors of commercial duct burners guarantee flame stability down to 12 percent O_2. Larger-scale tests are expected to yield stable flames over a wider range of exhaust conditions.

B. TEST RESULTS

1. Effect of Stoichiometry

The goal of the first set of experiments was to investigate the relationship between reburner stoichiometry and the NO_x reduction. This parameter is of primary importance, since it establishes the amount of reburner fuel necessary (at a given inlet oxygen concentration) to achieve the required NO_x reductions. Measurements of postreburning NO_x concentration were made at three inlet oxygen levels (14, 15, and 19 percent) and several reburner methane flows (varied between 0.5 and 4.0 standard liters per minute). To isolate the effect of stoichiometry on NO_x reduction, inlet NO_x concentration (1000 ppmV), inlet temperature (900°F), and total inlet gas flow (65 slpm) were kept constant for all runs in this series.

To facilitate interpretation of the experimental data, the principal quantity of interest is the percentage of NO_x removed from the incoming gas stream by the reburning process. The equation used to calculate the NO_x reduction percentages from the measured quantities is given as follows:

$$\%\ NO_x\ \text{reduction} = \left(1 - \frac{[NO_x]_{\text{outlet, dry basis}}}{[NO_x]_{\text{inlet, dry basis}}} \cdot \frac{1 + X_{H_2O,\ \text{inlet}}}{1 + X_{H_2O,\ \text{outlet}}} \cdot \frac{Q_{\text{total, outlet}}}{Q_{\text{total, inlet}}}\right) \times 100$$

This expression corrects the measured outlet NO_x concentration for dilution by reburner CH_4 and for increased water vapor content. The NO_x concentrations are measured on a dry basis by the on-line analyzer. Inlet and outlet total gas flow rates and water vapor concentrations are calculated from the metered gas flows with the assumption that all the reburner methane reacts to form CO_2 and water. The ratio of nitric oxide (NO) to total NO_x remained nearly constant for all measurements (0.90 to 0.95), thus, it is not necessary to distinguish between NO and NO_x reduction behavior.

Experimentally determined values of NO_x reduction varied from a minimum of zero to a maximum of 60 percent. In Figure 20 the data have been plotted as a function of reburner fractional heat input, and in Figure 21 as a function of reburner fuel equivalence ratio. These parameters differ in that the fractional heat input $[Q_{CH_4,reburn}/(Q_{CH_4,reb} + Q_{CH_4,pri})]$ is a function of fuel flows only, whereas the fuel equivalence ratio indicates relative quantities of fuel and oxidizer in the reburner zone. Inspection of the first

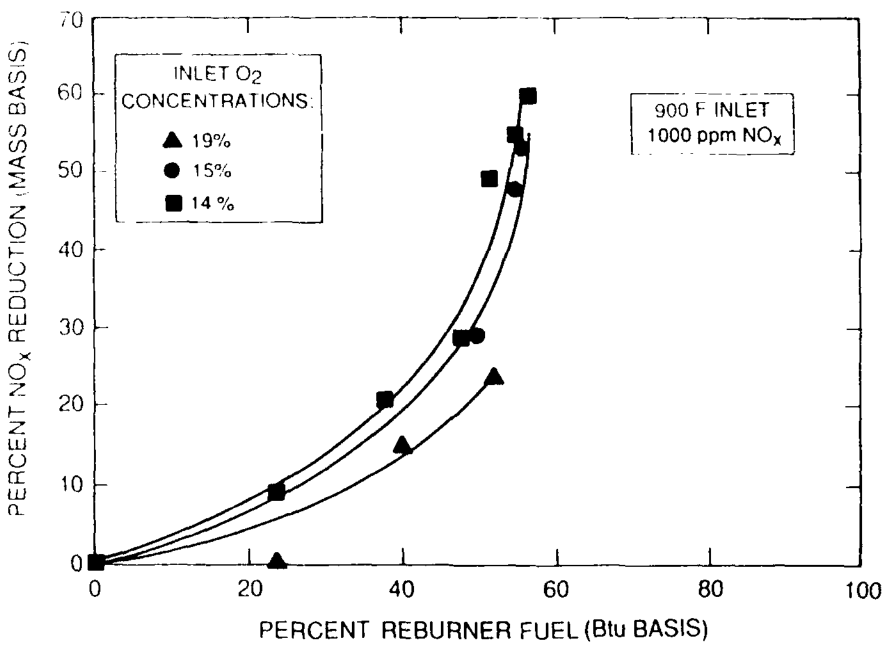


Figure 20. NO_x Reduction as a Function of Reburn Fuel Flow Rate.

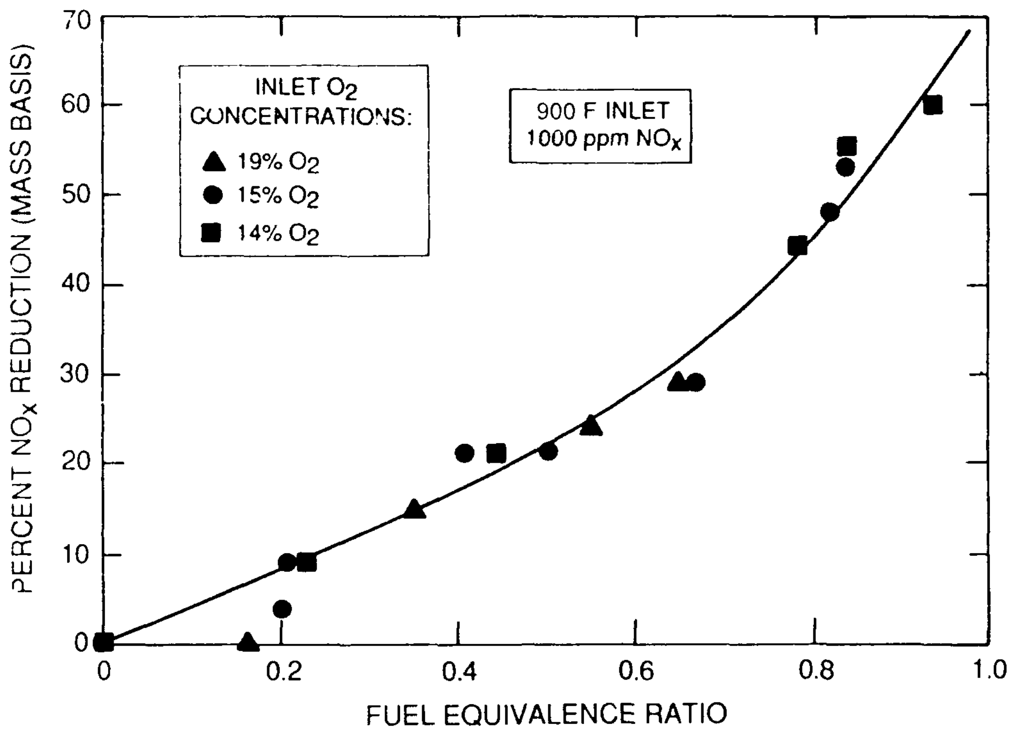


Figure 21. NO_x Reduction as a Function of Fuel Equivalence Ratio.

graph demonstrates that the NO_x reduction is related both to the fractional heat input and to the inlet oxygen concentration, i.e., distinct trends of NO_x reduction versus fractional heat input can be assigned to each of the three values of oxygen concentration. As the inlet oxygen concentration is increased from 14 to 19 percent, the percentage of NO_x removed at a given reburner heat input progressively decreases. Even at the most favorable condition (14 percent oxygen), substantial NO_x reductions (> 30 percent) are not achieved until the fuel fractional input approaches 50 percent, which corresponds to equal rates of jet engine and reburner fuel flow.

In Figure 21 the variation in NO_x reduction is shown as a function of the calculated fuel equivalence ratio. The fuel equivalence ratio (ϕ_F) is defined as the ratio of fuel to oxygen divided by the stoichiometric ratio of fuel to oxygen. On this scale, values less than unity represent fuel-lean conditions (zero corresponding to no reburner fuel flow) whereas values greater than unity signify a fuel rich environment. All testing in the present study was conducted at fuel equivalence ratios less than unity. In this case, a single curve approximates the data for all three oxygen concentrations. In this manner, the NO_x reduction can be shown to be a simple function of the equivalence ratio. At values of the equivalence ratio less than about 0.7 (4.5 percent O_2 exiting the reburner at an inlet O_2 concentration of 15 percent), the curve rises relatively gradually, while at higher values the curve becomes considerably steeper, indicating that locally fuel-rich conditions persist long enough to reduce NO_x. The target value of 50 percent reduction is attained at an equivalence ratio of about 0.87 (2 percent excess O_2 starting from 15 percent O_2).

The results from this series of tests suggest that at the temperatures and flows present in the reactor, only small amounts of NO_x reduction are possible when the overall reburner stoichiometry is fuel-lean. When enough fuel is added to bring conditions close to stoichiometric (and that amount depends on the concentration of oxygen in the exhaust gas), much more efficient NO_x removal is observed.

2. Effect of Inlet NO_x Concentration

It is anticipated that engine NO_x emissions will vary widely according to jet engine type, load, and fuel content. In addition, the reburner inlet NO_x concentration in the proposed JETC application would depend on the degree of dilution of the engine exhaust by the augmenter air. For this reason, it is important to examine the effect of inlet NO_x concentration on achieved reduction. Figure 22 shows the variation of NO_x reduction with reburner fuel equivalence ratio for two different inlet NO_x concentrations (550 and 1000 ppm). For these experiments, inlet oxygen concentration and temperature were maintained at constant values of 15 percent and 900°F, respectively. The graph demonstrates that for a given fuel equivalence ratio, substantially greater percentages of NO_x reduction occur for the higher value of inlet NO_x concentration (1000 ppm). For example, at a fuel equivalence ratio of 0.82,

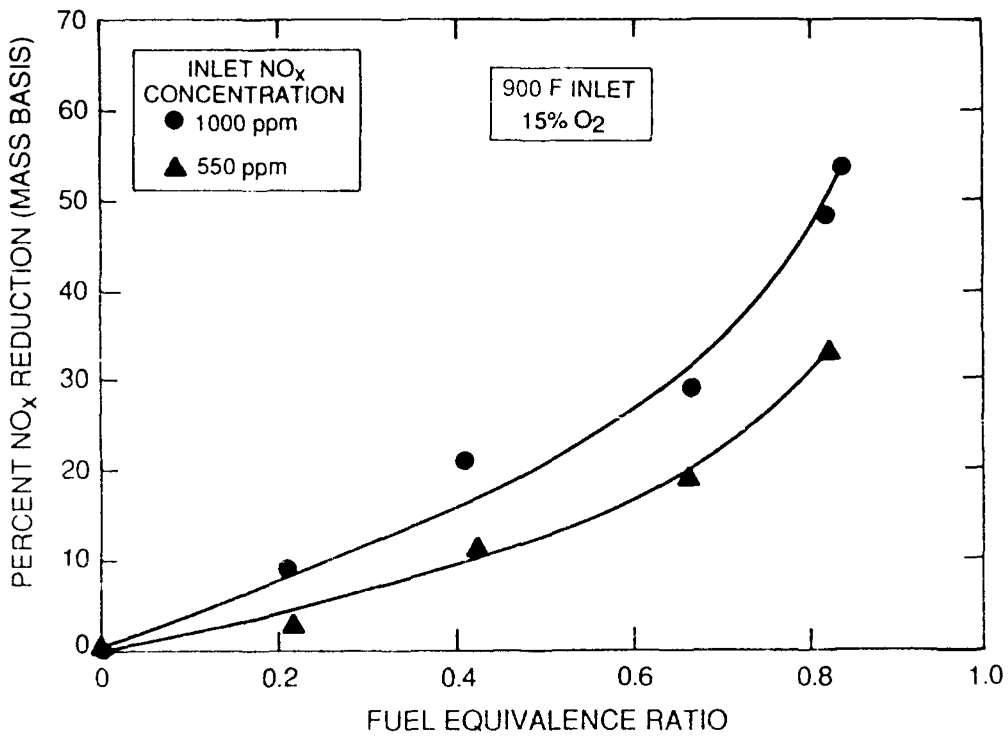


Figure 22. Effect of NO_x Concentration on Reburning NO_x Reduction.

reburning produces 48 percent NO_x reduction at the higher inlet concentration, while only 33 percent is removed at the lower concentration.

A further reduction in NO_x inlet concentration could be expected to lead to an additional decrease in NO_x removal efficiency. This result suggests that achieving optimal reburning conditions in the JETC application requires that the augmentation ratio be kept to a minimum. Increased dilution of the jet engine exhaust with bypass air, although not affecting NO_x emissions on a lb/MBtu basis, would increase oxygen concentrations and decrease NO_x concentrations in the mixed gas stream, both of which are unfavorable for efficient reburner NO_x removal. Therefore, the augmentation ratio should be set at the minimum value for stable operation of the reburner.

3. Effect of Inlet Temperature

In the JETC application, the reburner inlet temperature is expected to vary over a large range. While constraints of the experimental apparatus precluded testing of the model reburner over the full temperature range typical of the JETC, a series of tests was conducted at inlet temperatures of 570°, 720° and 900°F, which represent a partial span of the expected operating conditions of a JETC. The resulting trends of NO_x reduction as a function of fuel equivalence ratio are displayed in Figure 23. At relatively small values of the fuel equivalence ratio (< 0.7), diminished NO_x reduction is exhibited at the lowest temperature. No difference can be discerned between the curves representing the two higher temperature cases. As the fuel equivalence ratio is increased, the discrepancy in NO_x reduction between the high and low temperature runs becomes progressively smaller. Further testing is necessary to determine whether similar trends are seen at still lower temperatures.

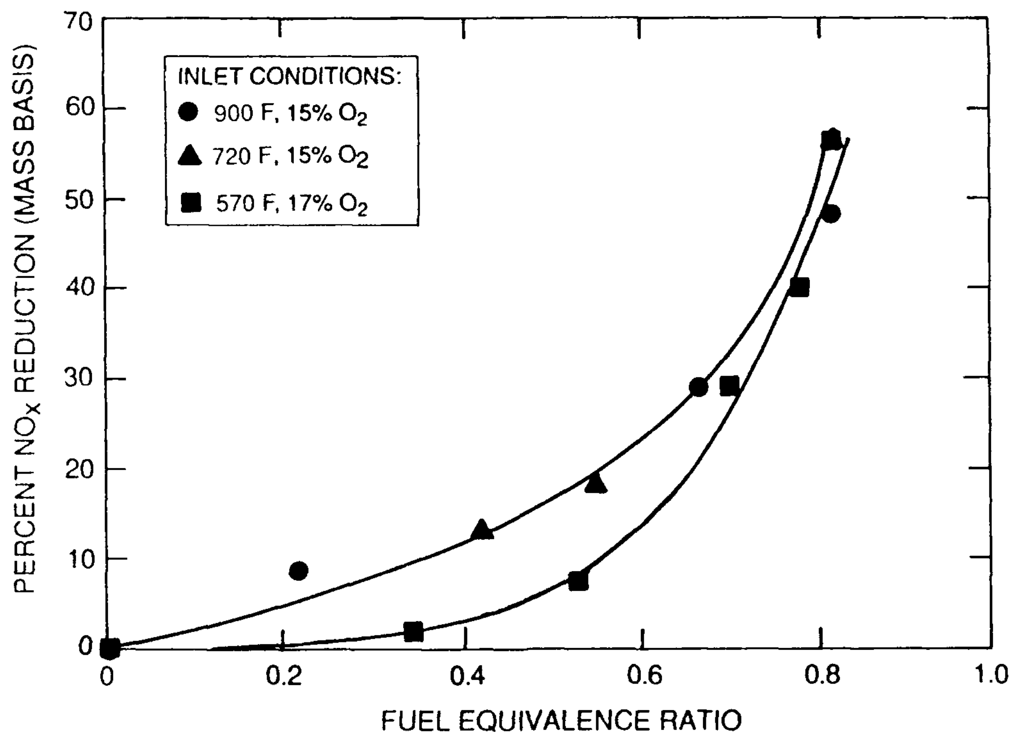


Figure 23. Effect of Inlet Exhaust Temperature on Reburner NO_x Reduction.

From these data, it is not expected that JETC exhaust temperature would have a strong effect on reburner performance.

4. Effect of Total Gas Flow Rate

The total gas flow rate at the reburner inlet represents another significant process parameter that varies over a large range in the JETC application. To study the effect of changing exhaust gas flow rate, runs were performed in the reburning test reactor at flows of 65, 91 and 130 slpm. For this series of experiments, inlet gas temperatures were maintained at a constant value of 900°F. At the two lower flow rates, an inlet oxygen concentration of 15 percent was used; however, a minimum inlet oxygen concentration of 18 percent was required to ensure flame stability at the highest flow rate.

Results for the three sets of data are plotted in Figure 24. It is clear that the total flow rate has an important effect on the reburner

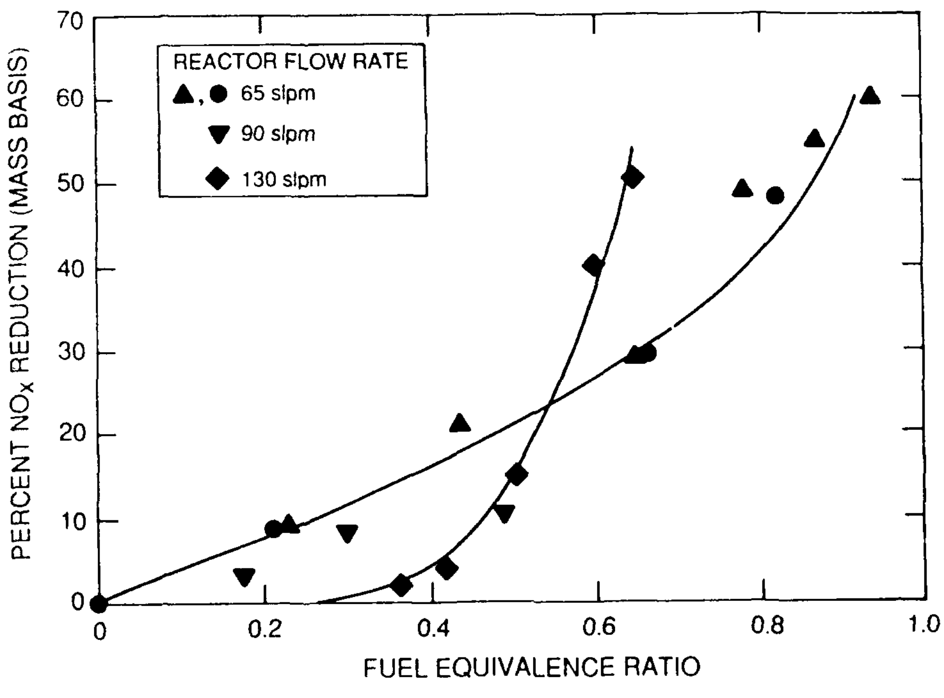


Figure 24. Effect of Exhaust Gas Inlet Flow Rate on Reburner NO_x Reduction.

performance. Data taken at the lowest flow rate show that the amount of NO_x reduction appears to increase relatively gradually with increases in equivalence ratio. At the higher flow rates, NO_x reduction remains near zero until a threshold value of equivalence ratio is approached (approximately 0.5) at which point the NO_x reduction begins to increase dramatically. At values of the equivalence ratio greater than 0.6, the NO_x reduction obtained at the higher flow rates is substantially greater than that observed in the low flow rate case.

Two important effects of increasing flow rate on the reburning process can be identified. First, reburner outlet temperature is increased by the higher rates of heat release. The second effect is the change in mixing characteristics caused by the increases in gas velocity. It should be noted that the flow conditions (velocity profiles, turbulence, acoustically induced gas flows) that are present in a JETC are vastly different from those in the small scale laboratory apparatus in which these experiments were conducted. It is therefore possible that reburner NO_x removal effectiveness could be considerably better (or worse) in the JETC environment than was observed on a laboratory scale, as long as flame instability does not result from these same mixing conditions.

5. Effects of Burner Configuration

As discussed previously, the presence of the burner shroud serves to control the rate at which mixing of fuel and oxygen occurs. The reburning process is known to be sensitive to mixing rate, and thus it might be anticipated that the amount of NO_x reduction achieved by reburning is affected by the shroud configuration or, more specifically, the percentage of shroud open area. To assess the effect of shroud open area on NO_x reduction, experiments were conducted with the burner shroud removed, and also with a solid burner shroud fabricated from stainless-steel shim plate in place. The results of these experiments were compared with those previously obtained using the shroud fabricated from perforated stainless-steel sheet with 36 percent open area.

Figure 25 shows NO_x reduction plotted against fuel equivalence ratio for each of the three shroud configurations. All runs were conducted at the relatively high inlet O_2 concentration of 19 percent; this much O_2 was required to sustain combustion in the shroudless burner. Examination of the curve shows that, although some scatter is evident, no systematic variation of NO_x reduction with shroud open area can be discerned. This result suggests that, within the range of conditions necessary to establish a stable reburning flame, the reburning process NO_x reduction is not as sensitive to moderate variations in fuel/gas mixing rate as might have been expected; however, this could be an artifact caused by flame instabilities inherent to the small scale of the experiment.

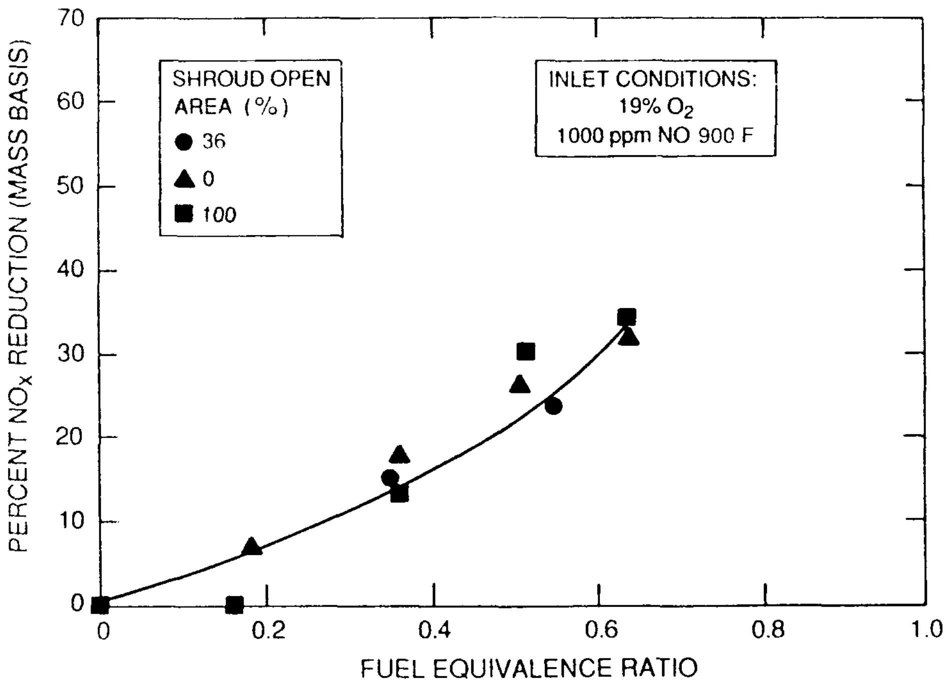


Figure 25. Effect of Reburner Shroud Configuration on NO_x Reduction.

6. Effect of Ammonia Addition

It is known that, at the appropriate temperatures (1750° to 1900°F), ammonia will react selectively with NO_x, producing molecular nitrogen and water vapor. To explore the prospect of enhancing reburner performance through addition of a small amount of ammonia to the fuel, a series of experiments was conducted in which varying amounts of gaseous ammonia were mixed with the reburner methane. The ammonia flows were set to give molar ratios of NH_3/NO in the range of 0 to 2. Measurements were taken at two different methane flows: inlet temperatures and oxygen concentrations were kept constant for each run.

The results are displayed in Figure 26. At the lower fuel flow rate, ammonia addition has a small negative effect on NO_x reduction, which becomes more pronounced with increases in ammonia flow. At the higher fuel flow rate, very little effect is evident. It is clear that, rather than enhancing reburning NO_x reduction, the ammonia can act as an agent for NO_x production, similar in effect to fuel nitrogen. Thus, ammonia addition is not considered appropriate for improving NO_x reduction by reburning. In addition, the fact that ammonia oxidizes under the reburning conditions indicates that oxidizing conditions dominate the flow field produced by the experimental reburner and that optimal reburning conditions were not achieved.

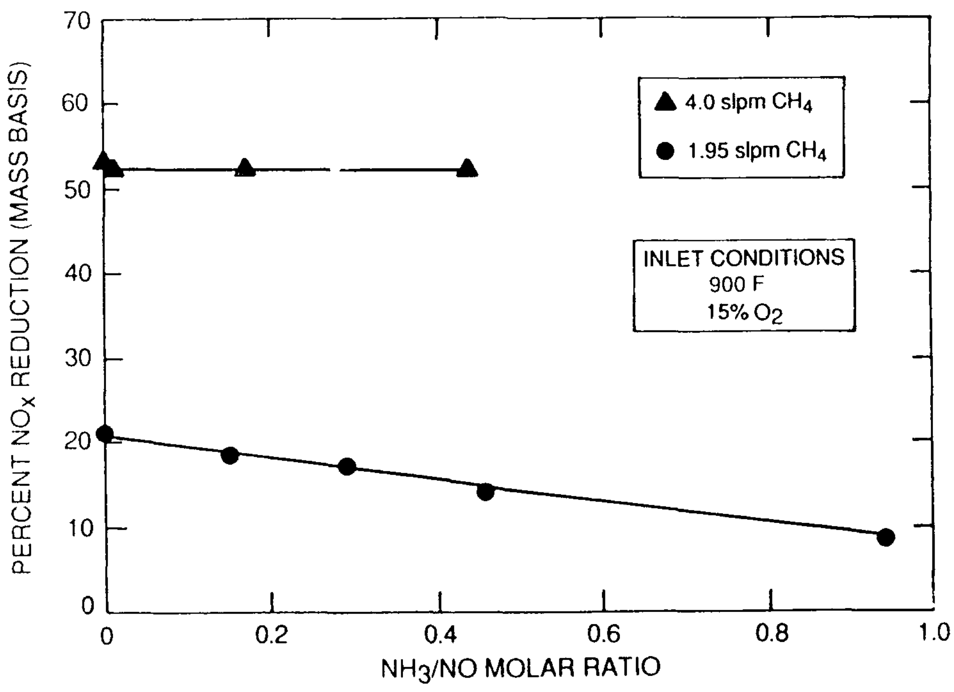


Figure 26. Effect of Ammonia Addition to Reburning Process.

7. System NO_x Reduction

Current EPA NO_x emission regulations are based not on an exhaust gas ppm level, but on a mass basis referenced to the heat input from the fuel. Typical units for NO_x emissions include lb NO_2/million Btu input from the fuel, or grams NO_2/kilogram of fuel. Consistent with this convention, NO_x emissions from a JETC should be referenced to heat input from the fuel, including reburning fuel.

Figure 27 shows NO_x emissions in lb/MBtu plotted as a function of reburn/engine fuel ratio (Btu basis). Data for inlet NO_x concentrations of 1000 ppm (2.4 lb/MBtu) and 550 ppm (1.3 lb/MBtu), are plotted. Since the design study assumed an inlet NO_x level of 0.6 lb/MBtu (250 ppm of NO_x at 11 percent O_2), a third curve extrapolated from the data is also shown. Note

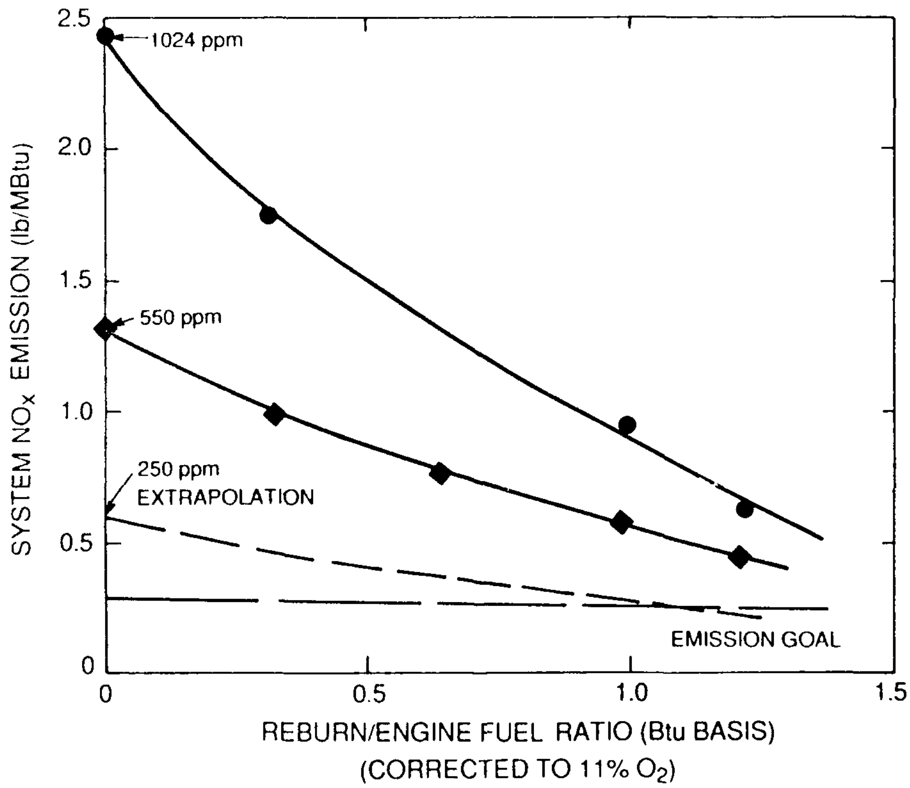


Figure 27. Reburn System NO_x Reduction Inlet T = 890°F.

that the NO_x emission goal changes with the amount of reburning fuel under this scenario because the EPA NO_x limit for gas-fired stationary sources is 0.2 lb/MBtu. For a combined liquid/gas-fired system, the emission limit is based on the percentage of each fuel fired (Btu basis):

$$\text{emission limit} = (0.3)\ (\text{fraction of liquid fuel}) + (0.2)\ (\text{fraction of gas fuel}) \quad .$$

Expressed in this way, the potential system reburning NO_x reduction is greater, but the emission goal is also a moving target. Note that the emission goal is met when the heat input from the reburn fuel is approximately equal to the engine fuel heat input. Thus the implementation of reburning will be more expensive than originally anticipated. Although improvements in reburning fuel consumption are probable based on limited tests at higher exhaust flow velocities, our best guess right now is that a reburn/engine fuel ratio of at least 0.6 will be required at military or afterburner thrust conditions.

8. Summary

The noteworthy findings of the laboratory-scale reburning tests can be summarized as follows:

1. Reburning NO_x reduction effectiveness was determined to be primarily a function of the overall fuel/oxygen stoichiometry. It was found that at very fuel-lean conditions (fuel equivalence ratio < 0.5), only small NO_x reductions (< 20 percent) were observed. When reburner fuel flow was increased to produce a smaller excess of oxygen, more substantial NO_x reductions occurred. A maximum NO_x reduction of 60 percent was achieved at an equivalence ratio of 0.94, which is still in the fuel-lean regime.

2. Inlet NO_x concentration and temperature were both determined to affect reburner performance. Reducing inlet NO_x resulted in a

decrease in the percentage of NO_x removed by reburning at a given reburner fuel flow. Reducing temperature from 900° to 570°F had a small detrimental effect on NO_x removal at lower reburner fuel flows; at higher flows, no variation with inlet temperature was detected.

3. Reburner performance was found to be invariant with respect to the burner shroud open area. However, increasing total exhaust flow rate had a beneficial effect in terms of improving NO_x removal efficiencies at higher values of the equivalence ratio.

4. The addition of ammonia to the reburner fuel at low flow rates (comparable to the NO flow rate) had a small negative effect on reburner performance which became more pronounced as ammonia flow was increased.

SECTION V

TECHNICAL AND ECONOMIC FEASIBILITY

Based on the test results, the preliminary reburning system has been revised and a "ballpark" estimate of capital and operating costs has been performed for the large JETC at Tinker Air Force Base. The only change to the reburning system is the number of reburner units. Instead of utilizing one reburner, we have now specified four reburners, each rated at 150 MBtu/hr input. This change will have nominal impact on capital costs, but a significant effect on operating costs as described below.

A. COST ESTIMATE METHODOLOGY

The method used to arrive at capital and operating costs in this study is based on the methodology recommended by Electric Power Research Institute (EPRI) (Reference 15). Appendix A (extracted from this reference) provides an outline of the cost components considered and an example of the format that is discussed here.

The Total Capital Investment (TCI) is one of the most important results of the economic analysis. The TCI represents the sum of the Total Plant Cost (TPC), royalties (where applicable), preproduction costs, inventory capital, and initial catalyst and chemical charge. The cost of land is not included here since this is a retrofit application on existing land. A royalty allowance equal to 0.5 percent of the process capital is used on proprietary processes. Process Capital is defined as the total cost of each unit, including equipment and all installation costs (labor and materials). The preproduction costs consist of the following: 1 month of fixed operating costs, 1 month of variable operating costs at full capacity, and 2 percent of TPC. The last charge covers modification to the equipment needed during startup. The inventory capital is equal to 60 days of variable operating costs, excluding power, steam, process water, and disposal costs. The initial supplies and materials cost accounts for supplies needed to start up the unit. In the case of process requiring a catalyst, the equipment cost does not include the catalyst cost. Instead, the initial catalyst is accounted for in the startup costs. For process chemicals, a 15-day supply is assumed as an initial charge.

The TPC is the sum of Process Capital, General Facilities Cost, Engineering and Home Office Fees, and Project Contingency Cost. The Process Contingency used in the EPRI Methodology accounts for the effect of the status of process development on the design and cost of commercial-scale equipment. We do not apply a process contingency to the capital cost; instead we use the probability of technical success as a separate measure of the status of process development. In addition, the EPRI Methodology includes an allowance for escalation of constiuction costs over the construction period, which is not used in this analysis because the construction period for the JETC modification is expected to be short. The General Facilities charge and the Engineering and Home Office Fees are assessed at 5 and 10 percent of the Process Capital, respectively. The Project Contingency Cost is computed as 20 percent of the sum of the Process Capital and General Facilities costs as appropriate for a preliminary design. The Process Capital (sometimes referred to as the installed equipment cost) is the total constructed cost of all equipment, including direct and indirect construction costs. Fees for freight and sales tax are included in the equipment cost. Direct installation costs account for the labor and materials costs of installation, including costs for site preparation and buildings. Indirect installation costs consist of the following: engineering and supervision labor, construction and field labor, any construction fees, and a small contingency fee.

The Operating and Maintenance Cost is the sum of operating labor, maintenance (labor and materials), and overhead labor. The annual maintenance costs are estimated as a percentage of the process capital cost. The EPRI methodology suggests maintenance cost factors for different technologies. The maintenance cost is broken down as 40 percent labor and 60 percent materials. The overhead charge is computed as 30 percent of the operating and maintenance labor and is a charge for administrative and support labor.

Following the EPRI methodology, the Operating and Maintenance Cost is broken down into a fixed component and a variable component. The fixed Operating ad Maintenance cost is the product of the capacity factor (or the utilization) and the annual Operating and Maintenance Costs; the balance of the cost is assumed to be variable. The Variable Operating cost has two components: consumables (power, chemicals, etc.) and operating and maintenance, as described above.

The total annual operating cost is the sum of the fixed Operating and Maintenance cost, the Variable Operating cost, and the cost of capital. The cost of capital is based on a 12-year depreciation period at 10 percent interest. The yearly charge for the cost of capital is 15 percent of the total capital investment. The operating cost is expressed in millions of dollars per year. The total operating time of the facility has been assumed to be 800 hr/yr.

B. COST ESTIMATE FOR A 600 lb/s JETC

Capital cost estimates for the JETC reburning application have been extrapolated from similar studies performed for EPRI by PSIT,[12] as well as from vendor quotations for the gas analyzers. This type of estimate has a probable accuracy of ±30 to 50 percent.

The capital costs are summarized in Table 7. The reburner design was discussed informally with Babcock & Wilcox Company (B&W), a potential Phase III partner. The cost of each 150 MBtu/hr reburner is based on their installed cost for a similar-sized natural gas burner plus a 25 percent premium for custom design and fabrication. The combustion chamber cost was based on total weight of steel contained in a cylinder 20 feet in diameter, 50 feet long, and 1 inch thick. The delivered cost of steel was taken as about $1 per pound. B&W K-28 refractory brick was included as insulation for the combustion chamber. Foundations, ductwork, damper, and control costs, as well as all installation costs were scaled from the aforementioned EPRI study. The gas-monitoring

TABLE 7. CAPITAL COST SUMMARY

	Delivered Cost ($)	Field Labor ($)	Field Materials ($)	Total ($)
Reburners (4 x 150 MBtu/hr)	150,000	150,000	20,000	320,000
Combustion chamber (20 ft diam x 50 ft long)	160,000	288,000	50,000	495,000
Foundations & support steel	120,000	150,000	20,000	290,000
Exhaust duct & bypass	175,000	20,000	5,000	200,000
Two exhaust dampers	90,000	10,000	--	100,000
Control system (controller, valves, electronics)	50,000	25,000	--	75,000
Insulation & lagging	100,000	400,000	10,000	510,000
O_2 monitors (2)	5,000	--	--	5,000
NO_x monitor	15,000	--	--	15,000
Natural gas piping	50,000	150,000	10,000	210,000
Process Capital	915,000	1,193,000	115,000	2,223,000
Engineering/Home Office Fee (10%)				222,300
Facilities (5%)				111,100
Contingency (20%)				444,600
Total Plant Cost				3,001,000

equipment costs are based on vendor quotes and include sampling probes and conditioning equipment. Readouts for the NO_x and O_2 instruments are included in the control system costs. It was assumed that a natural gas pipeline is available to the airbase; the cost of natural gas piping assumed that 100 feet of pipe would be required to tie the reburner into the main pipeline.

The total Process Capital cost is estimated to be about $2.2 million. Other costs include engineering at 10 percent of the process capital, general facilities at 5 percent of process capital, and a project contingency at 20 percent of process capital. The total plant cost is approximately $3 million.

Other costs often included in the EPRI methodology have been neglected in this study. Preproduction costs are intended to cover lost power generation and inefficient fuel use due to operator training and equipment shakedown. Since the JETC facility does not produce power, this cost factor has been ignored. Similarly, since the Air Force is funding the process development effort, there would be no royalty payments for a commercial application. Inventory capital, the investment in fuel prior to startup, is not included because we have assumed that a natural gas source already exists on site.

Operating costs for the 600 lb/s JETC are presented in Table 8. Fixed operating and maintenance costs (the sum of the first four numbers in Table 8) associated with the test facility are expected to increase by about $120,000 per year if a reburning system were added. This is based on an assumption that one extra facility operator will be required, and that maintenance will cost roughly $89,000 (4 percent of process capital costs). This estimate, based on industrial experience, is probably conservative when applied to a military test facility.

By far the most significant operating cost is the cost of the natural gas reburning fuel. Based on 800 hr of operation at an average gas flow rate of 600,000 standard cubic feet per hour, the natural gas cost alone will represent

TABLE 8. OPERATING COST SUMMARY*

Operating labor (1 person at $21/hr for 800 hr)	$ 16,800/yr
Maintenance labor } 4% of process capital	35,600/yr
Mainatenance materials } 4% of process capital	53,400/yr
Administrative and support labor	15,700/yr
Total fixed operating costs	$ 121,500/yr
Variable oeprating costs:	
Reburn fuel at $3/1000 ft^3	1,440,000/yr
Quench water at $0.65/1000 gal**	31,200/yr
Cost of capital (15%/yr)	$ 450,000/yr
Total annual operating cost =	$2,042,700/yr

*Based on 800 hr/yr operation

**Water cost would be zero if facility has 1000 gpm capacity already

$1.44 million per year. This is the major drawback of the system. For comparison, a more selective NO_x reducing agent (methylamine, investigated in a parallel PSIT project for the Air Force) would cost only $200,000 per year (400,000 lb/yr at a delivered price of $0.50 per lb) for the same amount of NO_x reduction.

The other significant operating cost is the cost of financing the capital investment. Based on 15 percent per year of total plant cost, the Air Force would be paying $450,000/yr in finance charges during a 12-year depreciation period at 10 percent interest.

C. OPERATING COST SENSITIVITY

The total yearly operating cost for reburning is slightly greater than $2 million. If the reburning fuel requirement were decreased by a factor of three by means of additional reburner development work (certainly an ambitious goal), the total operating cost could be reduced to about $1 million per year. This would still be one-third higher than the projected total operating costs for the monomethyl amine injection process. Another solution could be to minimize reburning fuel by operating only at peak NO_x emissions, but with operation would not reduce hydrocarbon emissions common to low load.

One means by which to evaluate the comparative economic promise of NO_x control processes is by calculation of the cost-benefit in terms of dollars per ton of removed NO_x. In utility boiler applications, candidate processes which possess values less than $1000 per ton are considered viable. For the JETC reburning application, the cost-benefit is about $10,000 per ton of NO_x removed. Hydrocarbon and smoke emissions from JETC facilities are highly variable (ranging from 1 to 100 lb/1000 lb fuel according to References 15 and 17), but if we assume that an equal amount of these pollutants can be destroyed by reburning, the cost-benefit is still on order of $5,000 per ton pollutants removed. Therefore, although reburning appears to be technically feasible, it is economically unattractive for the JETC application.

SECTION VI
CONCLUSIONS AND RECOMMENDATIONS

In summary, NO_x reductions greater than 50 percent can be achieved using a natural gas reburning system. Although not included as part of the experimental program, it is expected that at least a 70 percent reduction of smoke and hydrocarbon emissions can also be achieved; however, experimental results suggest that conditions that maximize NOx reduction may increase the level of carbon monoxide in the exhaust gases.

The main problem with the reburning process with respect to the JETC application is the very high fuel requirement. Our work shows that lower exhaust oxygen levels and higher exhaust temperatures decrease reburning fuel requirements, but wide variations in these parameters occur during most JETC test cycles. In the design study, we have assumed a constant flow rate of reburning fuel. With this scheme, we would achieve maximum NO_x reduction during afterburner operation and maximum hydrocarbon/carbon monoxide reduction during low-load operation. The fuel cost for this mode of operation would be about $1800/hr of JETC operation ($1440K/yr).

The following steps could be taken to reduce fuel consumption and thus improve the economic attractiveness of the reburning process:

1. Operate the reburner only at loads greater than 50 percent thrust (intermediate, military, and afterburner engine modes). This procedure would reduce fuel consumption by a factor of 2 to 4, but eliminate the benefit of hydrocarbon/carbon monoxide control since these emissions are only significant during engine idle and approach modes where the NO_x concentration is low. This intermittent reburning scheme would require sophisticated on-off control similar to a home heating furnace.

2. Optimize NO_x reduction performance by means of testing and modification of reburner design, with special attention given to controlling the fuel-exhaust mixing. Such tests would require the use of a pilot-scale facility to more closely duplicate the flow conditions present in the JETC environment.

Therefore, Phase II work could consist of three major thrusts:

- Reburner Development Tests
- Reburner Operation and Control Tests
- Detailed Engineering and Application Study.

At this time, however, reburning looks less attractive than the direct injection of methylamine (MMA) for achieving significant destruction of NO_x. Therefore, PSIT recommends that the MMA process be pursued immediately; the reburning Phase II scope should only be initiated if the MMA work falls short of expectations.

REFERENCES

1. F.L. Robson, A.S., Keston, and R.D., Lessard, Analysis of Jet Engine Test Cell Pollution Abatement Methods, AFWL-TR-73-18, Kirtland AFB NM, May 1973.

2. J.R. Geiger and P.S. Daley, The Feasibility of Controlling Turbine Engine Test Cell Particulate Emissions with a Baghouse, CEEDO-TR-78-24, Civil and Environmental Engineering Development Office, Tyndall AFB FL, September 1978.

3. R.L. Drake, Comparative Evaluation of Technologies for Reduction of NO_x Effluents from Incineration of Hazardous Wastes, Subtask 9.37 report: SETA Contract No. F08635-85-C-0057. Tyndall AFB FL, February 1988.

4. G.F. Davies and R.H. Crow, Turbojet Aircraft Engine Test Cell Pollution Abatement Study, CR 34.001, Naval Civil Engineering Laboratory, Port Hueneme CA, June 1973.

5. Oklahoma City Air Logistics Center Automated Jet Engine Test Facility and Engine Test Capabilities, U.S. Air Force, Test Production Engineering Section, Production Engineering Branch, Propulsion Division, Directorate of Maintenance, Tinker AFB, Oklahoma City OK, 1980.

6. R.W. Boubel and J.A. Martone, USAF Aircraft Engine Emission Goals: A Critical REview, ESL-TR-79-30, Engineering and Services Laboratory, Tyndall AFB FL, September 1979.

7. J.O.L. Wendt, C.V. Sternling, and M.A. Matovich, "Reduction of Sulfur Trioxide and Nitrogen Oxides by Secondary Fuel Injection," 14th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh PA, 1973.

8. R.A. Lisauskas, S.A. Johnson, and R.J. Snodgrass, "Results of Fuel-Staged Combustion Tests," presented to EPA Technical Review Committee for In Furnace NO_x Reduction," Salt Lake City UT, 1984.

9. R.A. Lisauskas, R.J. Snodgrass, and S.A. Johnson, "Experimental Investigation of Retrofit Low-NO_x Combustion Systems," Proceedings of the Joint EPA/EPRI Symposium on Stationary Combustion NO_x Control," Boston MA, 1985.

10. R.J. Yang, J.K. Arand, and F.J. Garcia, "Laboratory Evaluation of In-furnace-NO_x-Reduction for Industrial Combustion Applications," ASME Paper 84-JPGC FU 12, New York NY, October 1984.

11. S.A. Johnson and A.H. Rawdon, "Control of NO_x Emissions from Power Boilers," The Institute of Fuel, Adelaide, Australia, November 1974.

12. J.K. Arand and L.J. Muzio, "Oklahoma Gas and Electric Combined Cycle NO_x Reduction Laboratory Tests," KVB, Irvine CA, 1977.

13. M.W. McElroy, Oklahoma Gas and Electric Full-Scale Demonstration of NO_x Destruction in Fuel-Rich Burners, EPRI Program RP-782, Palo Alto CA, 1977.

14. R.A. Brown and W.C. Kirby, "Application of Reburning for NO_x Control in Cogeneration," *1985 Joint EPA/EPRI Symposium on Stationary Combustion NO_x Control*, Boston MA, May 1985.

15. Electric Power Research Institute, Technical Assessment Guide, EPRI Report No. P-2410-SR, 1982.

16. E.J. Hausknecht and E.L. Douglas, Air Pollution Emission Compliance of U.S. Navy Test Facilities for Gas Turbine Engines," AESO Report No. 2-85, Aircraft Environmental Support Office, Naval Air Rework Facility, North Island, San Diego CA, May 1985.

17. R.A. Lisauskas, R.J. Snodgrass, and S.A. Johnson, "Engineering and Economic Analysis of Retrofit Low-NO_x Combustion Systems," Proceedings of the 1987 Joint EPA/EPRI Symposium on Stationary Combustion NO_x Control, New Orleans LA, March 1987.

18. G.D. Seitchek, Aircraft Engine Emissions Estimator, ESL-TR-85-14, Air Force Engineering and Services Center, Tyndall AFB FL, November 1985.

(The reverse of this page is blank.)

APPENDIX A

EXAMPLE FORMAT FOR CAPITAL INVESTMENT AND REVENUE REQUIREMENT SUMMARY TABLES

TITLE

PLANT CAPACITY, FUEL TYPE, ETC.

Capital Investment	$/kW
Process Capital[a]	A
General facilities	B
Engineering and home office fees	C
Project continency	D
Process contingency	E
Sales tax[b]	F
Total plant cost (December 1982 dollars)	TPC = A+B+C+D+E+F
Total plant investment (January 1983 startup)	TPI = TPC x (Adj. factor)
Royalty allowance	G
Proproduction costs	H
Inventory capital	I
Initial catalyst and chemicals	J
Land	K
Total capital requirement (January 1983 startup)	TCR = TPI+G+H+I+J+K

Operating and Maintenance Costs (First Year - December 1982 dollars)	$/kW-yr
Operating labor	L
Maintenance labor	M
Maintenance materials	N
Administrative and support labor	P = 0.3 (L+M)
Total O&M first year	CM = L+M+N+P
Fixed O&M first year	CF x CM = FOM ($/kW-yr)

$$\text{Variable O\&M first year} = \frac{\text{OM} \times (1\text{-CF}) \times 1000 \text{ mills/\$}}{8760 \times \text{CF}} = \text{VOM (mills/kWh)}$$

a) Detailed breakdown of the process capital by plant section should be presented in a separate table with field labor, field materials, and factory materials shown separately

b) Show sales tax here f not already included in A and/or B.

Consumables Operating Costs Excluding Fuel (First Year - December 1982 dollars)	Mills/kWh
Water	Q
Chemicals	R
Other consumables	S
Waste disposal	T
Total consumables (excluding fuel)	CM = Q+R+S+T
By-Product Credits (First Year - December 1982 dollars)	(V)
Fuel Cost (First Year - December 1982 dollars)	W
30-Year Levelized O&M Costs (Period 1981-2010)	**Equations**
30-year levelized fixed O&M	LFCM = 2.314 x (FOM) $/kW-yr
30-year levelized variable O&M	LVOM = 2.314 x (VOM) mills/kWh
30 year levelized consumables O&M (excluding fuel)	LCM = 2.314 x (CM) mills/kWh
30-year levelized by-product credit	LB = Z* x V mills/kWh
30-year levelized fuel	LFU = Y* x W mills/kwH
30-Year Levelized Fixed Charges (Capital)	LFC = 0.161 x (TCR) $/kW-yr

30-Year Levelized Busbar Cost of Power at Levelized-Capacity Factor (CF) for Period 1983 - 2012

$$\text{Power Cost} = \frac{(\text{LFC} + \text{LFOM}) \times (1000\ \text{mills/\$})}{(\text{CF}) \times (8760\ \text{hr/year})} + \text{LCOM} + \text{LCM} - \text{LB} + \text{LFU mills/kWh}$$

*Y is the 30-year levelization factor for fuel. Z is the 30-year levelization factor for by-products.

APPENDIX B

SUMMARY OF TEST DATA

(The reverse of this page is blank.)

Run Number	Burner Air (scfm)	Reactor Gas Flows: Burner CH_4 (slpm)	Oxygen (slpm)	Reburner CH_4 (slpm)	Reburner NH_3 (sccm)	Reburner Inlet Total Flow (slpm)	Reburner Outlet Total Flow (slpm)	Reburner Fuel Equivalence Ratio	Reburner Heat Input Fraction
1	2.0	3.2	4.0	1.01	0	63.9	64.9	0.21	0.24
2	2.0	3.2	4.0	3.19	0	63.9	67.1	0.67	0.50
3	2.0	3.2	4.0	3.91	0	63.9	67.8	0.82	0.58
4	2.0	3.2	4.0	1.03	0	63.9	64.9	0.22	0.24
5	2.0	3.2	4.0	2.04	0	63.9	65.9	0.43	0.39
6	2.0	3.2	4.0	3.14	0	63.9	67.0	0.66	0.50
7	2.0	3.2	4.0	3.88	0	63.9	67.7	0.82	0.55
8	2.0	3.3	7.4	1.03	0	67.4	68.4	0.16	0.24
9	2.0	3.3	7.4	2.22	0	67.4	69.6	0.35	0.40
10	2.0	3.3	7.4	3.51	0	67.4	70.9	0.55	0.52
11	2.0	3.2	3.5	1.02	0	63.4	64.4	0.23	0.24
12	2.0	3.2	3.5	1.99	0	63.4	65.4	0.44	0.38
13	2.0	3.2	3.5	2.92	0	63.4	66.3	0.65	0.48
14	2.0	3.2	3.5	3.92	0	63.4	67.3	0.87	0.55
15	2.0	3.2	3.5	3.52	0	63.4	66.9	0.78	0.52
16	2.0	3.2	3.5	4.25	0	63.4	67.6	0.94	0.57
17	2.0	3.2	4.0	2.02	0	63.9	65.9	0.43	0.39
18	2.0	3.2	4.0	2.90	0	63.9	66.8	0.61	0.48
19	2.0	3.2	4.0	3.89	0	63.9	67.8	0.82	0.55
20	2.0	3.3	7.4	1.13	0	67.4	68.5	0.18	0.26
21	2.0	3.3	7.4	2.00	0	67.4	69.4	0.31	0.38
22	2.0	3.3	7.4	3.23	0	67.4	70.6	0.51	0.49
23	2.0	3.3	7.4	4.06	0	67.4	71.4	0.64	0.55
24	2.0	3.2	4.0	1.95	27	63.9	65.8	0.41	0.38
25	2.0	3.2	4.0	1.95	17	63.9	65.8	0.41	0.38
26	2.0	3.2	4.0	1.95	55	63.9	65.8	0.41	0.38
27	2.0	3.2	4.0	1.95	9	63.9	65.8	0.41	0.38
28	2.0	3.2	4.0	1.95	0	63.9	65.8	0.41	0.38
29	2.0	3.2	4.0	4.00	0	63.9	67.9	0.84	0.56
30	2.0	3.2	4.0	4.00	26	63.9	67.9	0.84	0.56
31	2.0	3.2	4.0	4.00	10	63.9	67.9	0.84	0.56
32	2.0	3.2	4.0	4.00	4	63.9	67.9	0.84	0.56
33	2.0	3.3	7.4	1.00	0	67.4	68.4	0.16	0.23
33	2.0	3.3	7.4	1.00	0	67.4	68.4	0.16	0.23
34	2.0	3.2	7.4	2.30	0	67.3	69.6	0.36	0.41
35	2.0	3.3	7.4	3.31	0	67.4	70.7	0.52	0.50
36	2.0	3.3	7.4	9.05	0	67.4	71.4	0.64	0.55
37	4.0	5.75	11.0	2.11	0	130.1	132.2	0.18	0.27
38	4.0	5.7	11.2	3.52	0	130.2	133.7	0.30	0.38
39	2.8	4.6	6.5	4.18	0	90.4	94.6	0.60	0.48
40	2.8	4.6	6.5	4.54	0	90.4	95.0	0.65	0.50
41	2.8	4.6	6.5	2.50	0	90.4	92.9	0.36	0.35
42	2.8	4.6	6.5	2.91	0	90.4	93.3	0.42	0.39
43	2.8	4.6	6.5	3.50	0	90.4	93.9	0.50	0.43
44	3.5	5.6	8.6	4.49	0	113.4	117.8	0.49	0.44
45	2.0	3.2	6.0	1.96	0	65.9	67.8	0.34	0.38
46	2.0	3.2	6.0	3.05	0	65.9	68.9	0.53	0.49
47	2.0	3.2	6.0	4.02	0	65.9	69.9	0.70	0.56
48	2.0	3.2	6.0	4.42	0	65.9	70.3	0.77	0.58

Run Number	Shroud Open Area (%)	NH_3/NO Molar Ratio	Measured [CO] Output (ppm)	Temperatures Reburner Inlet (°F)	Port A (°F)	Port B (°F)	Port C (°F)	Port D (°F)	Port E (°F)
1	36	0	0	893	1476	1370	1260	1199	1048
2	36	0	0	881	1790	1822	1708	1666	1377
3	36	0	0	-	-	-	-	-	-
4	36	0	0	887	1502	1396	1289	1230	1082
5	36	0	0	890	1841	1814	1640	1478	1278
6	36	0	0	879	1787	1815	1711	1669	1433
7	36	0	0	879	1784	1866	1763	1758	1553
8	36	0	0	859	1374	1195	1021	865	705
9	36	0	0	865	1974	1730	1399	1162	927
10	36	0	0	-	1907	1960	1837	1545	1205
11	36	0	600	871	1330	1222	1110	1002	803
12	36	0	0	872	1753	1661	1421	1310	1035
13	36	0	0	872	1776	1817	1661	1552	1248
14	36	0	3000	877	1629	1813	1729	1664	1402
15	36	0	100	872	1624	1779	1661	1654	1449
16	36	0	3300	875	1597	1768	1725	1685	1469
17	36	0	170	733	1675	1561	1303	1197	932
18	36	0	0	735	1713	1782	1607	1484	1151
19	36	0	3100	733	-	-	-	-	-
20	36	0	0	856	1739	1369	1136	1052	852
21	100	0	0	866	1776	1781	1426	1256	1003
22	100	0	0	869	1766	1865	1768	1595	1212
23	100	0	0	873	1810	1864	1813	1806	1388
24	100	0.46	0	863	1796	1741	1517	1373	1142
25	36	0.29	0	863	-	-	-	-	-
26	36	0.94	0	863	-	-	-	-	-
27	36	0.15	0	863	-	-	-	-	-
28	36	0	0	863	-	-	-	-	-
29	36	0	1375	862	1740	1838	1798	1788	1630
30	36	0.44	1375	862	-	-	-	-	-
31	36	0.7	1375	862	-	-	-	-	-
32	36	0.01	1375	862	-	-	-	-	-
33	0	0	0	856	1223	1118	996	960	765
34	0	0	0	860	1830	1606	1339	1245	998
35	0	0	0	872	2087	1960	1671	1509	1210
36	0	0	0	878	2178	2093	1879	1719	1355
37	36	0	0	847	1240	1177	1079	1077	880
38	36	0	0	851	1440	1486	1436	1392	1183
39	36	0	0	816	1894	1896	1729	1655	1422
40	36	0	1750	823	1915	1950	1823	1757	1534
41	36	0	0	823	1680	1637	1529	1450	1276
42	36	0	0	835	1742	1691	1501	1407	1127
43	36	0	0	836	1840	1820	1661	1565	1312
44	36	0	0	853	1985	1944	1771	1671	1468
45	36	0	100	573	1552	1465	1264	1191	972
46	36	0	0	573	1885	1814	1613	1485	1180
47	36	0	0	577	1871	1870	1769	1704	1442
48	36	0	500	577	1888	1903	1821	1757	1526

Run Number	Inlet Gas Composition, Volume Fraction				Outlet Gas Composition, Volume Fraction			
	X_{O_2}	X_{CO_2}	X_{H_2O}	X_{N_2}	X_{O_2}	X_{CO_2}	X_{H_2O}	X_{N_2}
1	0.15	0.05	0.10	0.70	0.12	0.06	0.13	0.69
2	0.15	0.05	0.10	0.70	0.05	0.10	0.19	0.67
3	0.15	0.05	0.10	0.70	0.02	0.10	0.21	0.66
4	0.15	0.05	0.10	0.70	0.11	0.07	0.13	0.69
5	0.15	0.05	0.10	0.70	0.08	0.08	0.16	0.68
6	0.15	0.05	0.10	0.70	0.05	0.09	0.19	0.67
7	0.15	0.05	0.10	0.70	0.03	0.10	0.21	0.66
8	0.19	0.05	0.10	0.66	0.16	0.06	0.13	0.65
9	0.19	0.05	0.10	0.66	0.12	0.08	0.16	0.64
10	0.19	0.05	0.10	0.66	0.08	0.10	0.19	0.63
11	0.14	0.05	0.10	0.71	0.11	0.07	0.13	0.70
12	0.14	0.05	0.10	0.71	0.08	0.08	0.16	0.68
13	0.14	0.05	0.10	0.71	0.05	0.09	0.18	0.68
14	0.14	0.05	0.10	0.71	0.02	0.11	0.21	0.67
15	0.14	0.05	0.10	0.71	0.03	0.10	0.20	0.67
16	0.14	0.05	0.10	0.71	0.01	0.11	0.22	0.66
17	0.15	0.05	0.10	0.70	0.08	0.08	0.16	0.68
18	0.15	0.05	0.10	0.70	0.06	0.09	0.18	0.67
19	0.15	0.05	0.10	0.70	0.03	0.10	0.21	0.66
20	0.19	0.05	0.10	0.66	0.15	0.06	0.13	0.65
21	0.19	0.05	0.10	0.66	0.13	0.08	0.15	0.65
22	0.19	0.05	0.10	0.66	0.09	0.09	0.19	0.63
23	0.19	0.05	0.10	0.66	0.06	0.10	0.21	0.63
24	0.15	0.05	0.10	0.70	0.09	0.08	0.16	0.68
25	0.15	0.05	0.10	0.70	0.09	0.08	0.16	0.68
26	0.15	0.05	0.10	0.70	0.09	0.08	0.16	0.68
27	0.15	0.05	0.10	0.70	0.09	0.08	0.16	0.68
28	0.15	0.05	0.10	0.70	0.09	0.08	0.16	0.68
29	0.15	0.05	0.10	0.70	0.02	0.11	0.21	0.66
30	0.15	0.05	0.10	0.70	0.02	0.11	0.21	0.66
31	0.15	0.05	0.10	0.70	0.02	0.11	0.21	0.66
32	0.15	0.05	0.10	0.70	0.02	0.11	0.21	0.66
33	0.19	0.05	0.10	0.66	0.16	0.06	0.13	0.65
34	0.19	0.05	0.10	0.67	0.12	0.08	0.16	0.64
35	0.19	0.05	0.10	0.66	0.09	0.09	0.19	0.63
36	0.19	0.05	0.10	0.66	0.06	0.10	0.21	0.63
37	0.18	0.04	0.09	0.69	0.14	0.06	0.12	0.68
38	0.18	0.04	0.09	0.69	0.12	0.07	0.14	0.67
39	0.15	0.05	0.10	0.69	0.06	0.09	0.19	0.66
40	0.15	0.05	0.10	0.69	0.05	0.10	0.19	0.66
41	0.15	0.05	0.10	0.69	0.10	0.08	0.15	0.67
42	0.15	0.05	0.10	0.69	0.09	0.08	0.16	0.67
43	0.15	0.05	0.10	0.69	0.07	0.09	0.17	0.67
44	0.16	0.05	0.10	0.69	0.08	0.09	0.17	0.66
45	0.17	0.05	0.10	0.68	0.11	0.08	0.15	0.66
46	0.17	0.05	0.10	0.68	0.08	0.09	0.18	0.65
47	0.17	0.05	0.10	0.68	0.05	0.10	0.21	0.64
48	0.17	0.05	0.10	0.68	0.04	0.11	0.22	0.64

Run Number	NO/NO_x Concentration, Wet Basis: [NO] Inlet (ppm)	[NO_x] Inlet (ppm)	[NO] Outlet (ppm)	[NO_x] Outlet (ppm)	NO_x Reduction (%)	lb/MBtu Inlet NO_x (as NO_2)	lb/MBtu Outlet NO_x (as NO_2)
1	863	927	726	841	8	2.34	1.64
2	863	927	588	630	[illegible]	2.34	0.84
3	863	927	438	455	48	2.34	0.55
4	445	500	425	478	3	1.26	0.93
5	445	500	423	431	11	1.26	0.69
6	445	500	370	387	19	1.26	0.52
7	445	500	298	314	33	1.26	0.38
8	865	929	834	914	0	2.40	1.83
9	865	929	699	759	16	2.40	1.21
10	865	929	637	671	24	2.40	0.89
11	908	972	725	871	9	2.44	1.69
12	908	972	695	746	21	2.44	1.19
13	908	972	625	658	29	2.44	0.90
14	908	972	363	413	55	2.44	0.49
15	908	972	466	475	48	2.44	0.60
16	908	972	320	361	60	2.44	0.42
17	873	918	699	768	14	2.32	1.23
18	873	918	668	719	18	2.32	1.00
19	873	918	356	380	56	3.32	0.96
20	820	911	753	832	7	2.36	1.63
21	820	911	659	720	19	2.36	1.20
22	820	911	591	641	26	2.36	0.88
23	820	911	556	589	31	2.36	0.72
24	836	918	707	763	14	2.32	1.24
25	836	918	690	741	17	2.32	1.21
26	836	918	759	810	9	2.32	1.32
27	836	918	681	728	18	2.32	1.18
28	836	918	651	707	21	2.32	1.15
29	836	918	379	404	53	2.32	0.48
30	836	918	388	413	52	2.32	0.49
31	836	918	388	413	52	2.32	0.49
32	836	918	388	413	52	2.32	0.49
33	865	929	853	924	0	2.40	1.86
34	867	931	738	777	14	2.48	1.25
35	865	929	607	623	30	2.40	0.85
36	865	929	564	580	34	2.40	0.72
37	845	919	795	876	3	2.63	1.87
38	846	919	782	826	8	2.66	1.52
39	944	998	548	574	40	2.48	0.78
40	944	998	453	478	50	2.48	0.63
41	944	998	902	954	2	2.48	1.58
42	935	998	887	930	4	2.48	1.47
43	935	998	785	819	15	2.48	1.20
44	892	946	794	820	10	2.43	1.21
45	839	911	746	859	3	2.38	1.43
46	839	911	736	796	9	2.38	1.11
47	839	911	555	613	29	2.38	6.75
48	839	911	468	510	40	2.38	0.60