ULTRA-LOW EMISSION ENCLOSED LANDFILL GAS FLARE

-A Full Scale Factory Test-

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- A Full Scale Factory Test -

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ABSTRACT

In our increasingly environmentally-conscious society, landfill gas flare emission requirements are continuing to become more and more stringent as people (and government) become more aware of the environmental and health detriments of these emissions. This paper discusses the baseline emission results from a full scale test on a typical enclosed landfill gas flare being fired with a simulated landfill gas. In addition, a full scale test has been completed on a newly developed Ultra-Low emission enclosed landfill gas flare, and those results are discussed in detail and compared to the emission results of the baseline flare previously tested. The enclosed flares ("typical" and Ultra-Low emission) were rated for 1500 scfm of landfill gas and were tested at the John Zink Company Research and Development Facility in Tulsa, Oklahoma. The testing comprised firing a natural gas and carbon dioxide mixture while measuring NOx, CO, O_2 and flame length on both the "typical" flare and on the Ultra-Low emission flare.

The baseline "typical" flare testing comprised varying the flow rate, methane concentration, and operating temperature as well as introducing ammonia into the gas stream to simulate nitrogen-bound compounds that convert directly to NOx when oxidized. The results indicate drastic fluctuations in the emissions due to the varying methane concentrations and operating temperatures tested.

The Ultra-Low emission flare testing comprised varying the flow rate, methane concentration, and operating temperature. The results indicate reductions in NOx in excess of 60% and CO in excess of 80% (based on 1400°F operating temperature) as well as substantially shorter flame lengths.

The results from the "typical" flare test are used as a baseline for all comparisons with the Ultra-Low emission flare in order to demonstrate the significance of the improvement.

TEST ARRANGEMENT - PHASE I

The initial Phase I testing to determine the "baseline" emissions information on a typical John Zink enclosed landfill flare utilized an 8'-0" O.D. x 45' OAH stack. The testing took place at the John Zink International Research and Development Facility in Tulsa, Oklahoma starting in November, 1996 with completion of the Phase II testing in September, 1997.

Since large volumes of landfill gas with varying compositions were not readily available, a mixture of Tulsa Natural Gas (TNG) and carbon dioxide (CO_2) was used to simulate the landfill gas.

COMPOSITION OF TULSA NATURAL GAS (TNG)

Compound	Vol%
CH_4	93.4
C_2H_6	2.7
C_3H_8	0.6
C_4H_{10}	0.2
N_2	2.4
CO_2	0.7

LHV - 914
HHV - 1013

With a methane concentration in the TNG of 93.4% and an overall heating value in the TNG of 914 (as opposed to the 910 of methane), TNG is considered an acceptable substitute for methane in the landfill gas simulation. The TNG was metered through ASME designed orifice runs and then mixed with CO_2 before it entered the flare.

A 40,000 lb liquid CO_2 tank provided the second component source for the simulated landfill gas. The liquid CO_2 was vaporized utilizing a steam vaporizer, then metered through ASME designed orifice runs, and then mixed with TNG before it entered the flare. A sketch of the test setup is shown in Figure I-1.

Several feet downstream of the orifice runs is a rotometer used to monitor the flow rate of ammonia into the fuel stream. The purpose of the ammonia injection is to determine the effects of fuel-bound nitrogen on emissions.

The enclosed flare used was 8'-0" O.D. with approximately 2" of ceramic fiber insulation on the inside. The stack overall height was 45', with 40' of stack height above the burner tips. The Phase I test comprised John Zink's standard landfill gas enclosed flare burners, floor arrangement, and inlet damper openings. The only difference between the unit tested and a standard 8'-0" O.D. flare was the additional 5' of stack height, which had no effect on the emissions data taken.

The flare stack was equipped with thirteen (13) type "K" thermocouple assemblies. Each thermocouple was attached to a digital read out that read in degrees F. The thermocouples were placed at three elevations above the burner assemblies: 15'-0", 26'-0", and 36'-0". At each elevation, four (4) thermocouples placed 90° apart protruded into the stack approximately 14"-16". At the top elevation of 36'-0" above the burner assembly, one (1) additional thermocouple was attached to the stack protruded 4'-0" into the stack to sample the temperature in the center of the unit. A sketch of the thermocouple placement is shown in Figure I-2.

A cross-type sample probe is located one-half stack diameter down from the top of the stack. Figure I-3 is a sketch of the design of the sample probe. The probe was made from ½" diameter schedule 40, inconel 600 pipe. A carbon steel or stainless steel probe would not have been adequate because of the presence of carbon within the steel that could give erroneous carbon monoxide (CO) readings. The probe ports are drilled to 1/8" diameter. The positions of the ports are located in accordance with 40 CFR Pt. 60, App. A, Method 1. The flue gas is pulled from the probe to a data shack where it is cooled to drop out all liquids.

TEST ARRANGEMENT

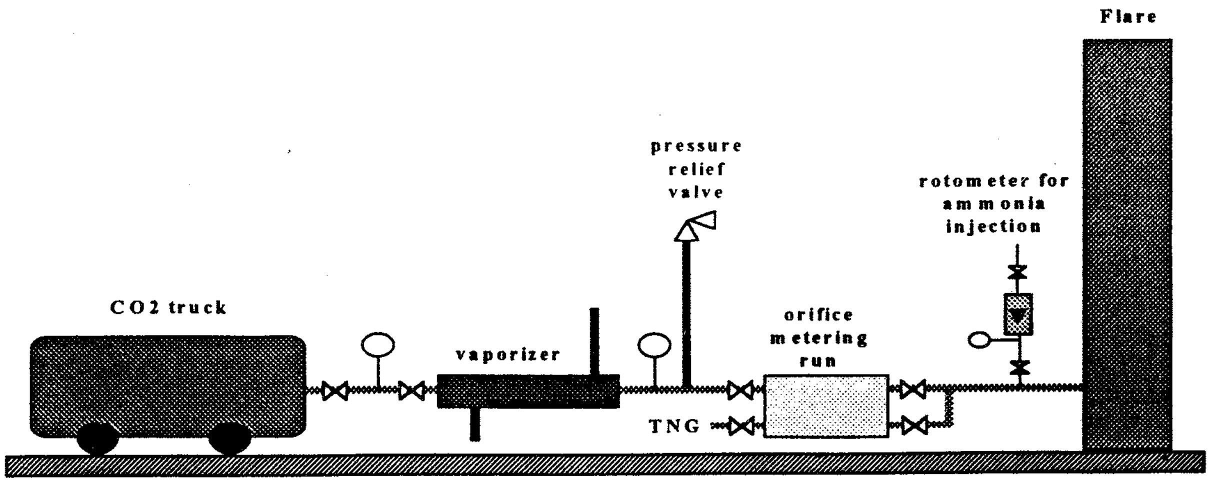


Figure I-1

THERMOCOUPLE POSITIONS

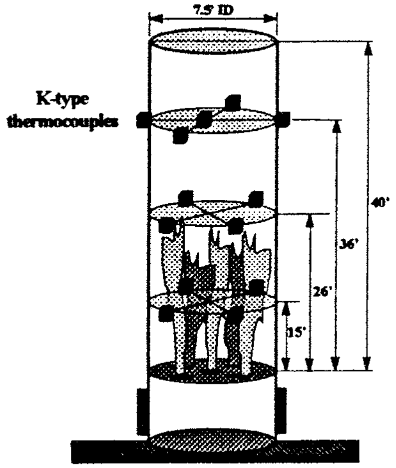


Figure I-2

DESCRIPTION OF SAMPLE PROBE

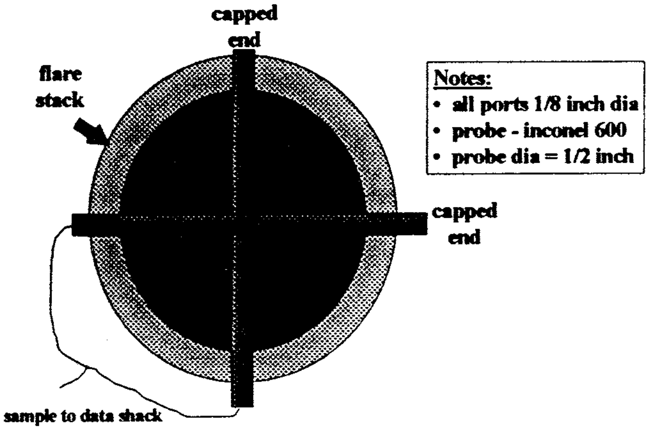


Figure I-3

The parts per million on a dry volume basis of CO and NOx were measured as well as percent oxygen (O_2).

TEST DESCRIPTION - PHASE I

Phase I of the testing was to determine the baseline emission factors and flame characteristics on a standard John Zink enclosed landfill gas flare. These factors and flare characteristics were used in comparison to Phase II testing of the Ultra Low Emission Flare. By comparing the results, step change improvements could be documented.

Test Series A1 - Standard Flare Performance

A total of twelve (12) different flow conditions was tested with the standard flare design. Each flow condition consisted of collecting emissions at four (4) different stack temperatures. The NOx, CO, and O_2 data was collected every 5 seconds for approximately 3 to 5 minutes. The data was collected both manually and using a data acquisition system. In addition, the flame length was measured through sight ports on the stack. Following are the flow conditions tested:

- **Flow rates (scfm)**: 1500, 1000, 500

At each flow rate, the following compositions were tested:

- **%TNG/%CO_2**: 65/35, 55/45, 45/55, 30/70

At each flow composition, emissions were taken at the following temperatures:

- **Stack Temperature (°F)**: 1400, 1500, 1600, 1800

Due to capacity limitations of the enclosed flare, measurements were taken only at 1800°F on the 65% TNG case and measurements were not taken at 1800°F on the 55% TNG case. With these four cases not included, the total number of test points was 44. At each test point, average NOx, CO, and O_2 readings were taken over a 3 to 5 minute interval, based on the digital recorder on the data acquisition system. In addition, 13 temperature readings were taken for a total of 572 temperatures.

Test Series A2 - Effects of Fuel Bound Nitrogen on NOx Production

Since fuel-bound nitrogen can have a drastic effect on the NOx production in the combustion process, two (2) tests that included injection of ammonia into the fuel stream were completed. At each flow condition, between 0 and 200 ppm of ammonia was injected for this analysis. Below is a description of the flow conditions tested:

- **Flow Rates (scfm)**: 1500 and 1000

At each flow rate, the following compositions were tested:

- **%TNG/%CO_2:** 65/35, 55/45, 30/70

At each flow condition, emissions were taken at the following temperatures:

- **Stack Temperature (°F)**: 1400, 1600

STANDARD FLARE PERFORMANCE - PHASE I

Stack Temperatures

Temperatures in the standard John Zink enclosed flare were taken with thirteen (13) different type K thermocouples. Four (4) thermocouples were placed 90 degrees apart at three elevations: 15', 26', and 36' above the burner tips. One additional thermocouple was placed to measure the center of the flare at the 36' level. The 572 temperatures taken indicated a wide temperature variance within the enclosed flare at each elevation. In fact, temperature differentials of over 200°F were common at the same elevation as well as from elevation to elevation. For example, with a TNG concentration of 55% and a flow rate of 1000 scfm, the temperature at the 15' elevation varied from 1550°F to 1740°F with an average operating stack temperature of 1606°F as measured at the 36' elevation (sample port level). A temperature differential between elevations is noted at virtually every test point. These differentials range from 50°F to more than 200°F from the lower thermocouple elevation to the top elevation. Examples of these temperature ranges are given in Appendix A as Stack Temperature vs. Stack Height graphs.

NOx and CO

NOx and CO were measured at flow rates of 1500 scfm, 1000 scfm, and 500 scfm of a simulated landfill gas in a standard John Zink enclosed flare. At each flow rate, the composition changed from 65% TNG to 55% to 45% to 30% TNG (balance CO_2) and the temperature was varied between 1400°F to 1800°F+. Appendix A has a summary of these emissions in a graph form. The NOx emissions were plotted and compared to the industry standard limitation of 0.06 lb/mmbtu fired. The CO emissions were plotted and compared to the industry standard limitation of 0.20 lb/mmbtu fired. From these graphs, we can note the following trends:

NOx Emissions

- For a given fuel flow rate, increasing the volume percentage of TNG in the TNG/CO_2 fuel composition increases the pounds of NOx per mmBtu fired.
- For a given fuel composition and flow rate, increasing the stack temperature increases the pounds of NOx per mmBtu fired.
- For a given fuel composition and stack temperature, increasing the fuel flow rate decreases the pounds of NOx per mmBtu fired.

CO Emissions

- For a given fuel composition and stack temperature, increasing the stack temperature decreases the pounds of CO per mmBtu fired.

Flame Length

A total of 44 different flow conditions was tested. The flame length was measured by observing the flame through sight ports (located approximately every five feet) on the flare stack. At times, the flame length would flicker approximately +/- 3 feet in height. Here, the flame length is defined as the length from the burner outlet to the maximum height of the flame during flickering. Appendix A includes a plot of the flame length versus local average stack temperature and percent volumetric flow rate of TNG/heat release.

The data in the flame length graph shows that the flame length increases with stack temperature for a given fuel composition and flow rate. This trend is expected since increasing the stack temperature reduces the percent excess oxygen in the stack. A reduction in excess oxygen in the stack requires more time for the fuel to find the remaining oxygen resulting in a longer flame.

This data also shows that the flame length increases with an increase in the heat release for fuel compositions greater than 55% TNG by volume. However, for fuel compositions less than approximately 55% TNG by volume, the general trend of the flame length appears to be that it decreases with an increase in the heat release.

The overall general trend, as shown in Appendix A, shows that the flame length also increases with an increase in the percent of TNG in the fuel stream. One data point, however, appears to deviate from the general trend. This data point occurs at 30% TNG, 1500 scfm, and a stack temperature of 1800°F. The reason for this anomaly is not clear.

The overall test data suggest an interesting phenomenon, that for a given flare stack temperature, there exists a fuel composition and heat release that will produce a minimum flame length. At this minimum flame length at a given temperature and composition, any increase or decrease in the flow rate will lengthen the flame.

EFFECTS OF FUEL BOUND NITROGEN ON NOx PRODUCTION

A total of twelve (12) different flow conditions were tested in an effort to determine the effects of fuel-bound nitrogen on NOx production in enclosed landfill flares. Tests consisted of injecting ammonia into the fuel stream at ammonia concentrations ranging form 0 to 200 ppmv. Tests were performed at 65%, 55% and 45% TNG (balance CO_2) at flow rates of 1500 scfm and 1000 scfm and at stack temperatures of approximately 1400°F and 1600°F. See Figure II-1 for a graph of the results shown as a percentage increase in NOx production versus ppmv ammonia. This graph is typical for all flow rates.

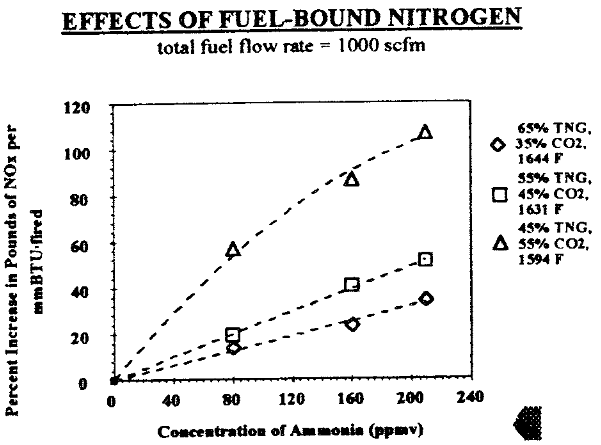


Figure II-1

The data shows, for all cases tested, that as the concentration of ammonia in the fuel stream increases, the NOx level also increases. The data appears to show that the NOx level increases linearly with ammonia concentration and that the slope of the line is not significantly dependent on stack temperature.

Ammonia Injection Conclusions

- The presence of a fuel-bound nitrogen in a landfill gas stream can dramatically increase NOx emissions. In some instances, 100 ppmv of ammonia in the landfill gas stream can increase the pounds of NOx per million BTU fired by as much as 100%.
- The data shows that the percent increase in NOx due to the presence of a fuel bound-nitrogen is more dramatic as the concentration of CO_2 in the fuel mixture increases.

ULTRA-LOW EMISSION FLARE - PHASE II

The goal of the Ultra-Low Emission Flare testing was to successfully develop an enclosed landfill flare that could achieve the following:

- NOx emissions less than 0.03 lb/mmbtu throughout a range of 30% to 55% methane at varying flow rates.
- Lower CO emissions than the standard John Zink enclosed flare system.
- Shorter flame lengths
- Reduction in flame radiation
- Higher destruction efficiency

Before the initial design of the Ultra-Low Emission Flare could be developed, it was necessary to understand the components and mechanisms of NOx formation. The components of NOx are:

- NO (90%)
- NO_2 (9%)
- N_2O (1%)

The mechanisms of NOx are:

- Thermal NOx
- Fuel NOx
- Prompt NOx

Thermal NOx is defined as that NOx produced from the combustion air which contains atmospheric nitrogen and oxygen. For example, N2 and O2 in the combustion air are further broken down into N and O radicals with the addition of high heat. These N and O radicals can produce NO as follows:

$$\mathbf{O + N_2 \rightarrow NO + N}$$
$$\mathbf{N + O_2 \rightarrow NO + O}$$
$$\mathbf{N + OH \rightarrow NO + H}$$

Ways to reduce Thermal NOx production:
- Reduce peak flame temperature

It should be noted that Thermal NOx is the largest contributor to NOx formation in the combustion process.

Fuel NOx is defined as that NOx produced from nitrogen that is chemically or organically bound in the fuel, such as ammonia (NH_3). When the nitrogen-bound compound is exposed to high heat, the N radical is broken from the molecule and readily attaches to an O radical. Once NO is formed, it is also possible to combine with an N radical to form N_2 at low O_2 concentrations in the flue gas.

$$\textbf{Fuel N} + O_2 \rightarrow NO + O$$
$$\textbf{Fuel N} + NO \rightarrow N_2 + O$$

Conversion to NO:

- Dominant at high O_2 concentrations

Conversion to N_2:

- Dominant at low O_2 concentrations

Ways to reduce Fuel NOx:

- Maintain low O_2 concentrations

Since fuel-bound nitrogen compounds are not typically in high concentrations in landfill gas, it is not practical or cost effective to operate enclosed flares at low O_2 levels in an effort to reduce Fuel NOx formation.

Prompt NOx is defined as that NOx formed in the initial portion of the flame zone when fuel and air react. For example, when methane (CH_4) is exposed to high heat, it is initially broken into CH/CH_2 plus some H radicals. This CH and CH_2 now combine with N_2 to form HCN and NH, which now acts as fuel-bound nitrogen.

$$N2 + CH \rightarrow HCN + N$$
$$N2 + CH2 \rightarrow HCN + NH$$

Ways to reduce NO formation:

- Reduce CH and CH2 concentrations, i.e., burn fuel lean (air rich)

With an understanding of the three (3) mechanisms of NOx formation, it is apparent that the critical factor in NOx reduction is reduction of peak flame temperature, thus reducing the reactivity of the molecules involved, allowing them to more readily convert directly to CO_2 and H_2O as follows:

$$CH_4 + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2$$

Test Arrangement for Phase II Testing

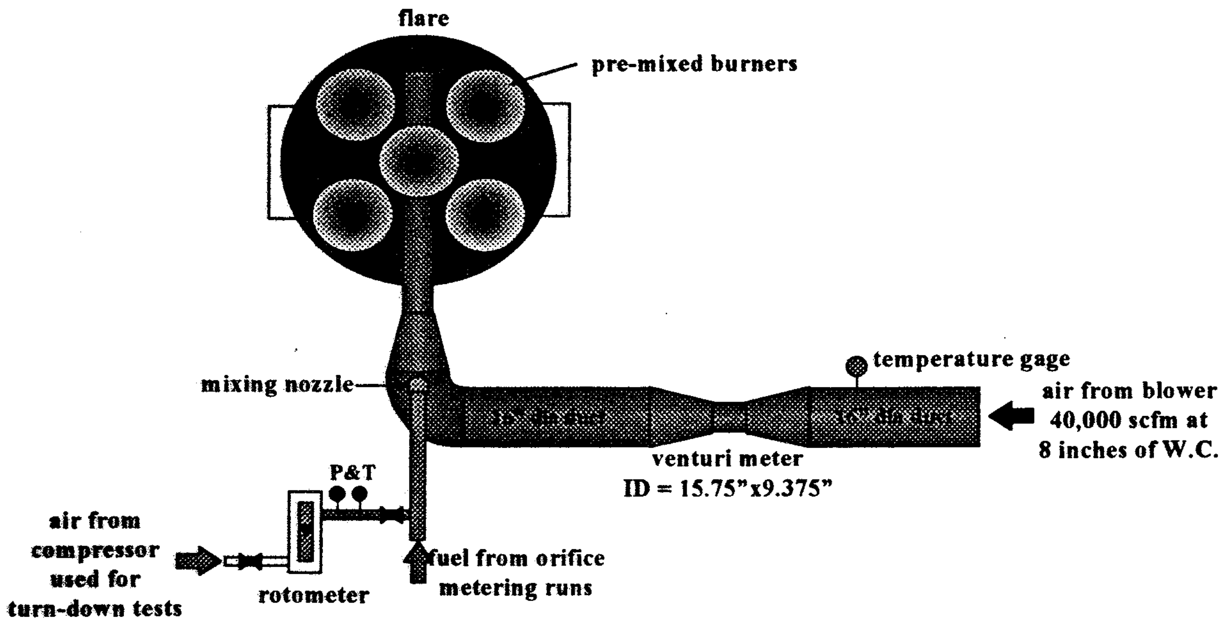


Figure III-1

Reducing peak flame temperatures can be accomplished several ways. The most common are:

- Staged fuel (fuel lean)
- Staged air (low O_2)
- Dilution

With the three (3) NOx formation mechanisms outlined above, we can formulate the following table:

	NOx Reduction		
	Thermal NOx	Prompt NOx	Fuel NOx
Staged Fuel	↓	↓	↑
Staged Air	↓	↑	↓
Dilution	↓	↓	–

Table III - 1

Based on Table III - 1 above and the fact that fuel staging and air staging will lengthen the flame on a standard burner while dilution shortens the flame length by promoting mixing, Phase II testing utilized a dilution process mixing an air stream with the TNG/CO_2 mixture.

TEST ARRANGEMENT - PHASE II

Phase II testing was the development of an Ultra-Low Emission enclosed landfill flare. The flare tested was the same size as the baseline or standard flare, which was 8'-0" O.D. x 45' OAH. The same fuel mixing setup was utilized in Phase II as in the original baseline test. The fuel gas/CO_2 mixture then mixed with an air stream near the shell of the enclosed flare as illustrated in Figure III-1.

The flow rate of air was measured using a venturi meter designed according to ASME specifications. Approximately 15 duct diameters upstream of the venturi meter and 5 duct diameters downstream are allowed. The air was supplied from a blower capable of supplying 40,000 scfm at a pressure of 8 inches of water column.

Again, a total of 13 type K thermocouples were located in the stack for measurement of the flue gas temperatures and the same cross-type inconel sample probe was used.

TEST DESCRIPTION - PHASE II

Phase II of the testing was for an Ultra-Low Emission landfill flare configuration utilizing a pre-mixture of air and simulated landfill gas (TNG/CO_2). This testing is designated as Test Series B.

Test Series B1 - Single Burner Stability and Turndown Performance

Test Series B was completed in two steps. Step one was to determine the best burner design to be utilized for the completion of the testing. A single burner was used in this procedure in an effort to minimize redundant and tedious changes during the performance testing. The criteria utilized to determine the overall burner design was flame stabilization and turndown capability. Flame stability was determined with 30% TNG and 70% CO_2 and the turndown tests were performed with 65% TNG and 35% CO_2.

Test Series B2 - Multiple Burner Performance

Once the single burner design was completed, five (5) of these burners were utilized in the enclosed flare for the maximum capacity requirement of 1500 scfm flow rate. A total of eleven (11) different flow conditions were tested in the Phase II program. At each flow condition, NOx, CO, and O_2 data were collected. The flow conditions tested are as listed below in Table IV-1.

Flow (SCFM)	%TNG	%CO2	%XS Air
500	55	45	48
500	55	45	33
1500	45	55	38
1500	45	55	11
1500	45	55	53
500	45	55	31
500	30	70	30
1000	30	70	30
1000	30	70	43
500	30	70	30
300	55	45	47

Table IV-1

ULTRA-LOW EMISSION FLARE PERFORMANCE - PHASE II

The purpose of these tests was to determine the emissions (NOx and CO) emitted from the new Ultra-Low Emission Flare design and compare these results with the standard enclosed landfill flare design.

NOx and CO

NOx and CO were measured at each condition as outlined in Table IV-1. The NOx emissions were plotted and compared to the baseline standard landfill gas enclosed flare as tested in Phase I and is shown on graphs in Appendix B. The CO emissions were plotted and compared to the baseline standard landfill gas enclosed flare as tested in Phase I and is shown on graphs in Appendix B also. From these graphs, we can note the following:

NOx Emissions

- For a given fuel flow rate, increasing the volume percentage of TNG in the TNG/CO_2 fuel composition increases the pounds of NOx per mmBtu fired.
- For a given fuel composition and flow rate, increasing the stack temperature increases the pounds of NOx per mmBtu fired.
- For a given fuel composition and stack temperature, increasing the fuel flow rate decreases the pounds of NOx per mmBtu fired.
- For a given fuel composition and stack temperature, increasing the amount of air that is premixed with the fuel decreases the pounds of NOx per mmBtu fired.
- The NOx emissions on the Ultra-Low Emission Flare were a minimum of 60% less than the standard enclosed landfill gas flare at high excess air mixture rates.

CO Emissions

- For a given fuel composition and stack temperature, increasing the stack temperature decreases the pounds of CO per mmBtu fired.
- At low TNG concentrations, the CO increased as the temperature decreased and the flow rate decreased.
- At high TNG concentrations, the CO increased only slightly as the temperature decreased down to 1200°F.

SUMMARY AND CONCLUSIONS

In the Phase I testing of the standard John Zink enclosed landfill gas flare, several key factors are to be noted including the wide variation of temperatures between thermocouples at the same elevation in the flare stack. Typically, if a temperature measurement were taken at a given elevation, that temperature was believed to be a good indicator at that particular elevation. However, the fact is that the temperature could be as much as 200° hotter or cooler at the same elevation in the stack.

The next major item of note is that for a given fuel composition and stack temperature, increasing the fuel flow rate actually decreases the pounds of NOx per mmBtu fired. Flame length is another item that is seldom mentioned in flare designs. It should be noted from this testing that the flame length in the standard enclosed flare increases approximately 10 feet when the TNG increased from 55% to 65% in the fuel gas. Otherwise, the flame lengths tended to trend as expected.

It is widely known that fuel-bound nitrogen increases NOx, but this testing now confirms the drastic effects that take place. In some instances, as little as 100 ppmv of ammonia can increase the pounds of NOx per mmBtu fired by 100%.

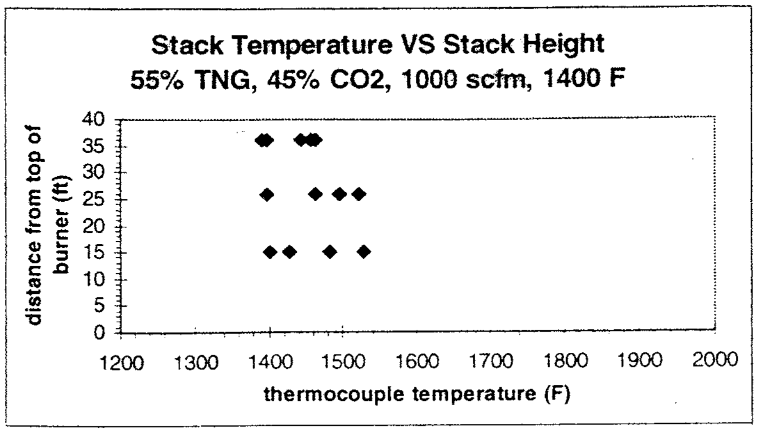
Phase II testing of the Low Emission Flare resulted in drastic reductions in NOx and CO, especially when compared to the generally accepted emission rates of 0.06 lbs/mmBtu fired of NOx and 0.20 lbs/mmBtu fired of CO. Even the reductions in NOx emissions from the standard John Zink enclosed landfill gas flare ranged from 60% to over 80%.

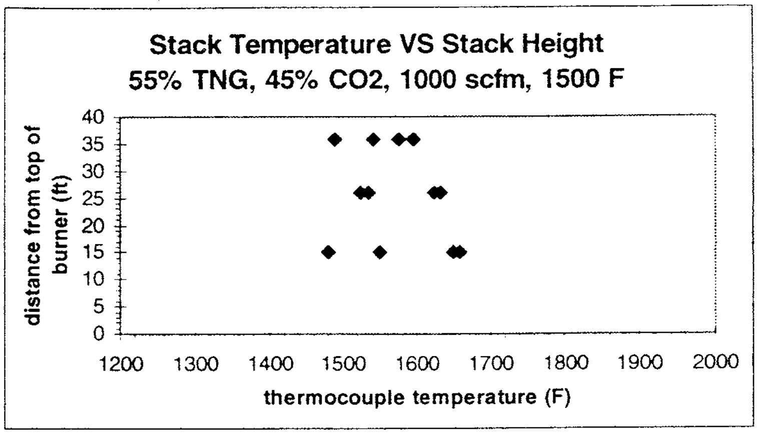
With the low CO emissions obtained (especially down to 1200°F), it is expected that the destruction efficiency on NMOC's will also be greater than the industry standard of 98%.

Finally, low CO emissions down to 1200°F, mean that lower operating temperatures can be maintained on the Ultra-Low Emission Flare, thus lowering the NOx even further than the numbers stated in this paper.

APPENDIX A

Standard Flare Performance


Stack Temperature VS Stack Height
55% TNG, 45% CO2, 1000 scfm, 1400 F
distance from top of burner (ft)
0
5
10
15
20
25
30
35
40
1200
1300
1400
1500
1600
1700
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
55% TNG, 45% CO2, 1000 scfm, 1500 F
distance from top of burner (ft)
0
5
10
15
20
25
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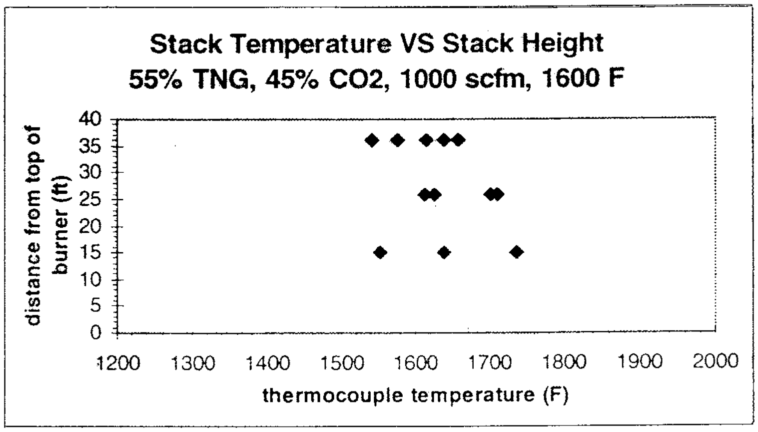
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
55% TNG, 45% CO2, 1000 scfm, 1600 F
distance from top of burner (ft)
0
5
10
15
20
25
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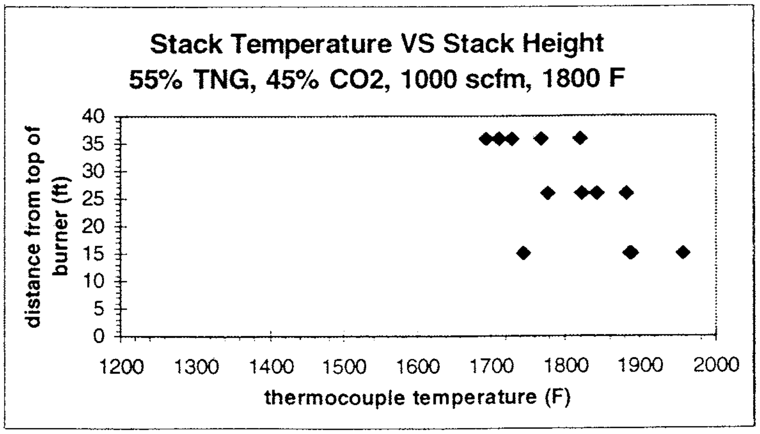
40
1200
1300
1400
1500
1600
1700
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
55% TNG, 45% CO2, 1000 scfm, 1800 F
distance from top of burner (ft)
0
5
10
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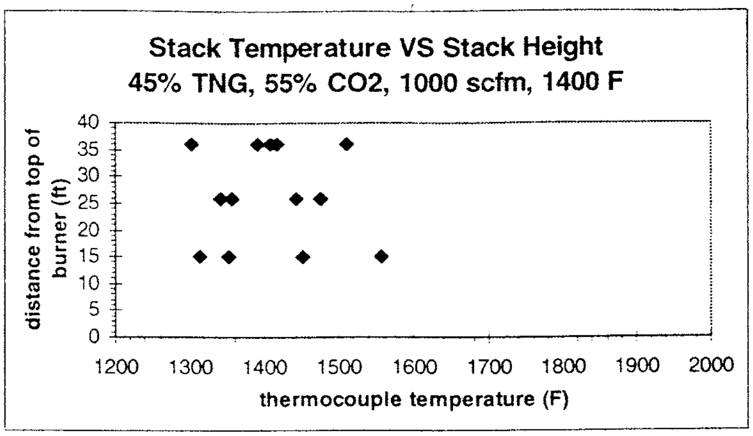
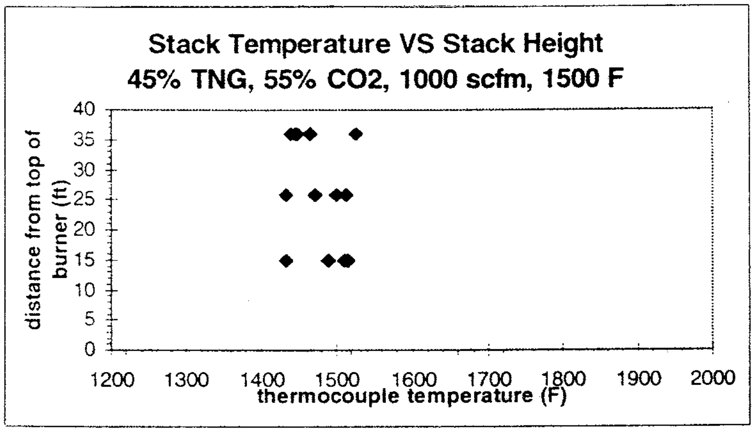
1700
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
45% TNG, 55% CO2, 1000 scfm, 1400 F
distance from top of burner (ft)
0
5
10
15
20
25
30
35
40
1200
1300
1400
1500
1600
1700
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
45% TNG, 55% CO2, 1000 scfm, 1500 F
distance from top of burner (ft)
0
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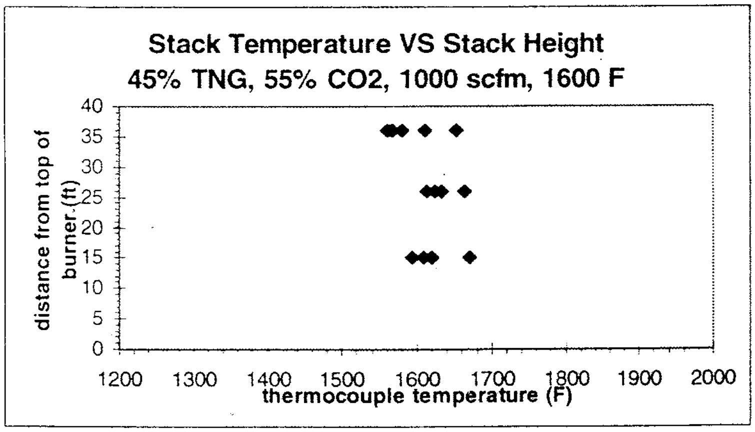
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
45% TNG, 55% CO2, 1000 scfm, 1600 F
distance from top of burner (ft)
0
5
10
15
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30
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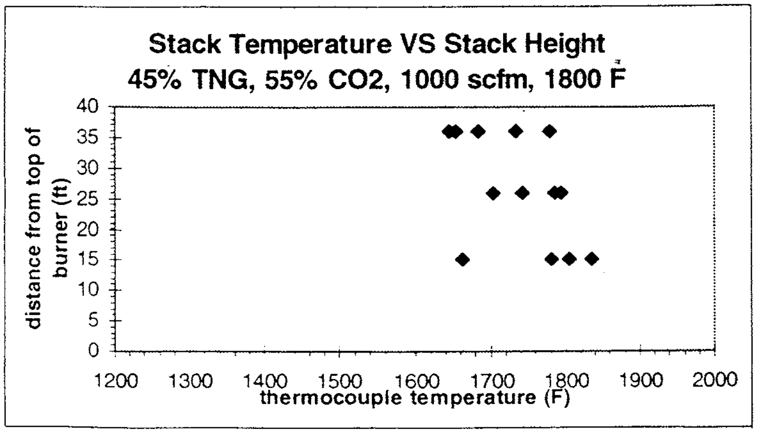
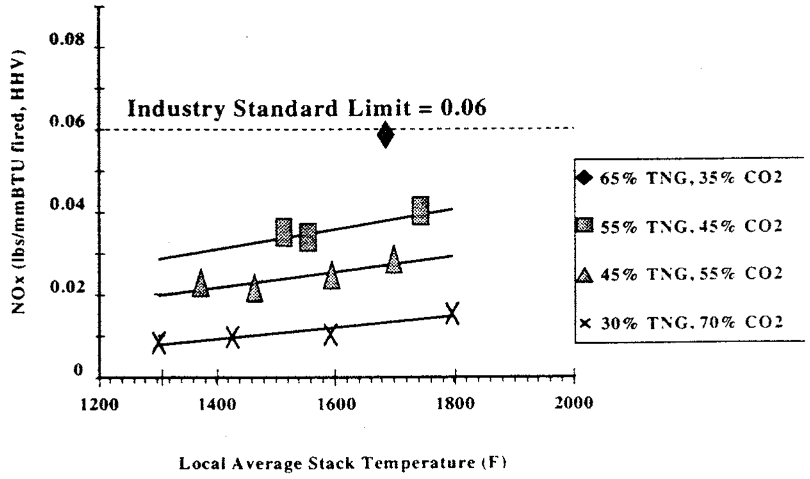
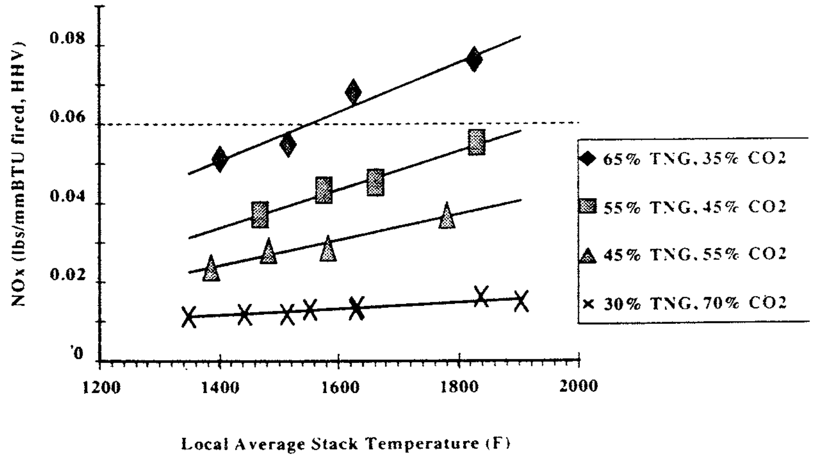
1300
1400
1500
1600
1700
1800
1900
2000
thermocouple temperature (F)


Stack Temperature VS Stack Height
45% TNG, 55% CO2, 1000 scfm, 1800 F
distance from top of burner (ft)
0
5
10
15
20
25
30
35
40
1200
1300
1400
1500
1600
1700
1800
1900
2000
thermocouple temperature (F)

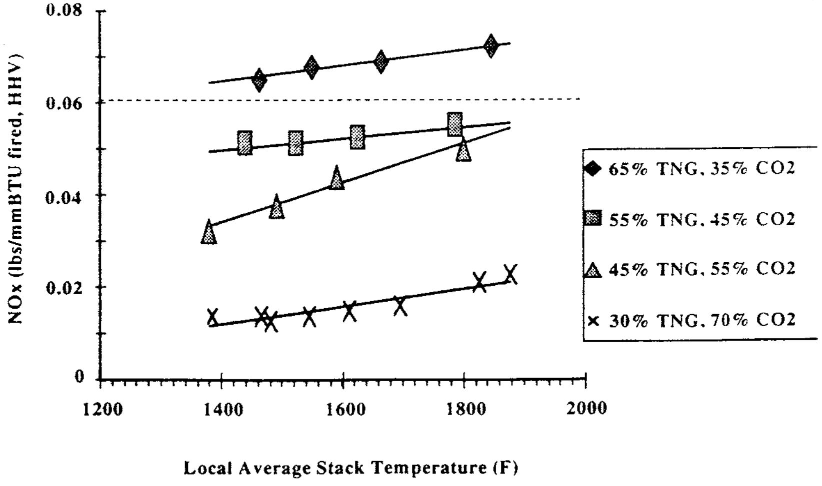
NOx Level VS Local Average Stack Temperature, 1500 scfm



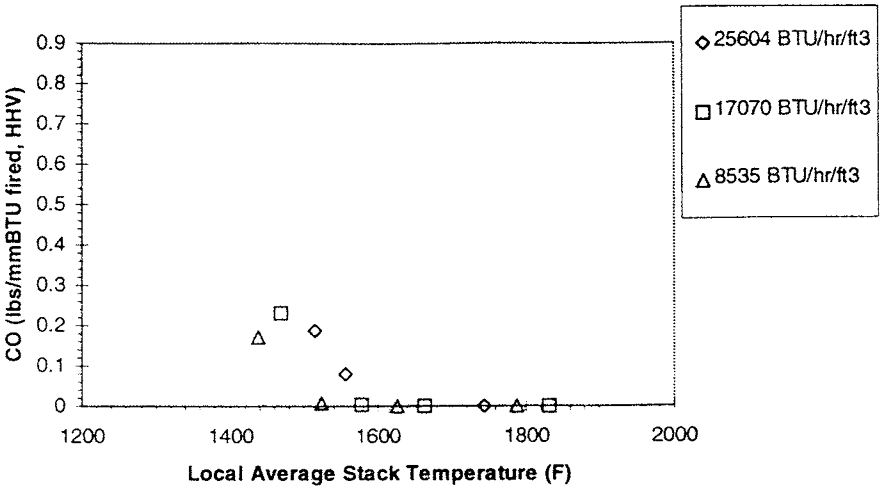
NOx Level VS Local Average Stack Temperature, 1000 scfm



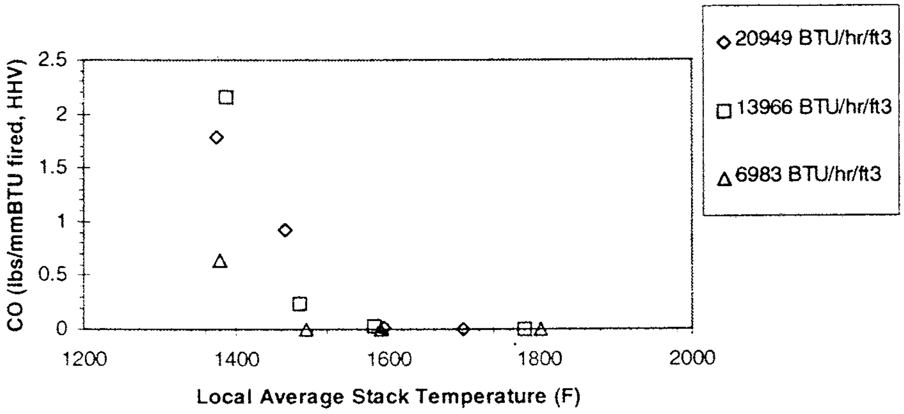
NOx Level VS Local Average Stack Temperature, 500 scfm



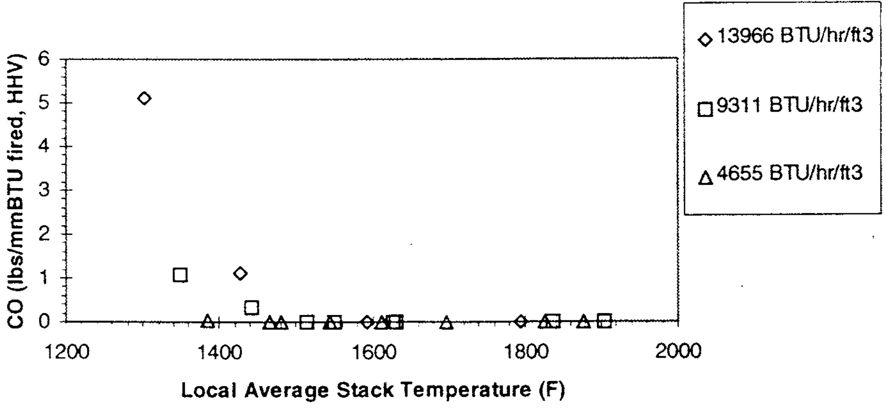
CO Level VS Local Average Stack Temperature, 55% TNG, 45% CO2



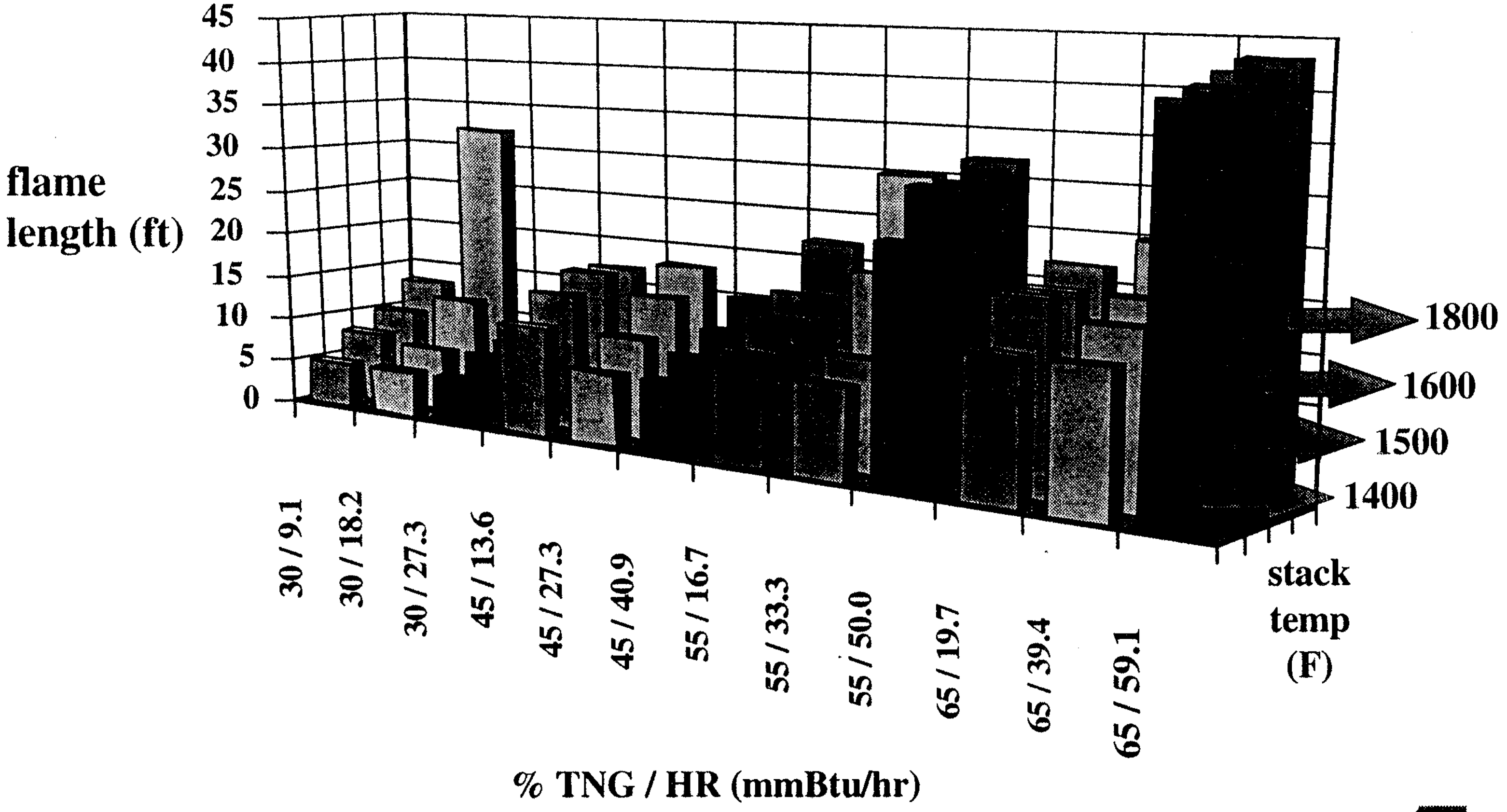
CO Level VS Local Average Stack Temperature, 45% TNG, 55% CO2



CO Level VS Local Average Stack Temperature, 30% TNG, 70% CO2



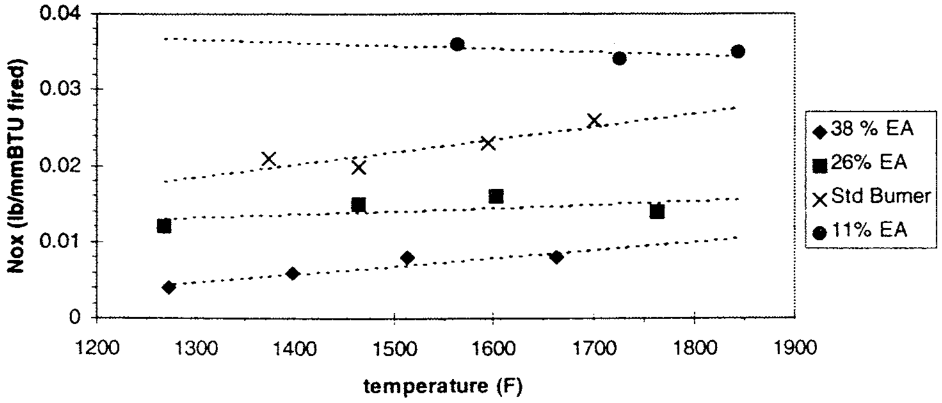
FLAME LENGTH AS A FUNCTION OF HR (MMBTU/HR) % TNG AND LOCAL AVERAGE STACK TEMPERATURE



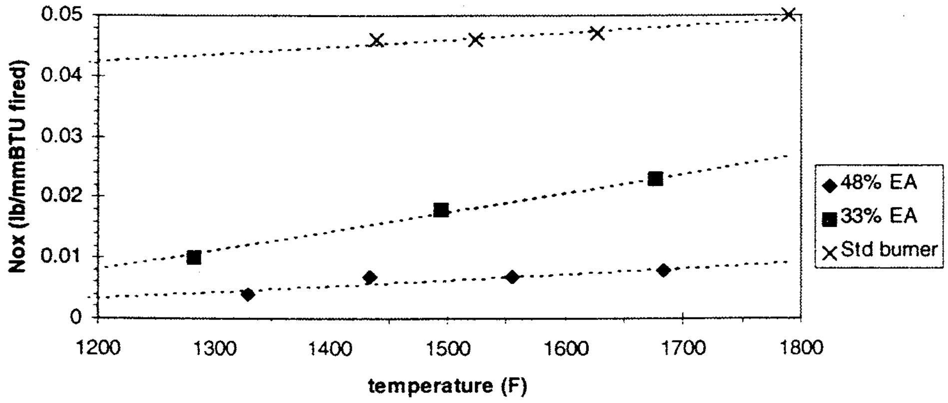
APPENDIX B

Ultra Low Emission Flare Performance

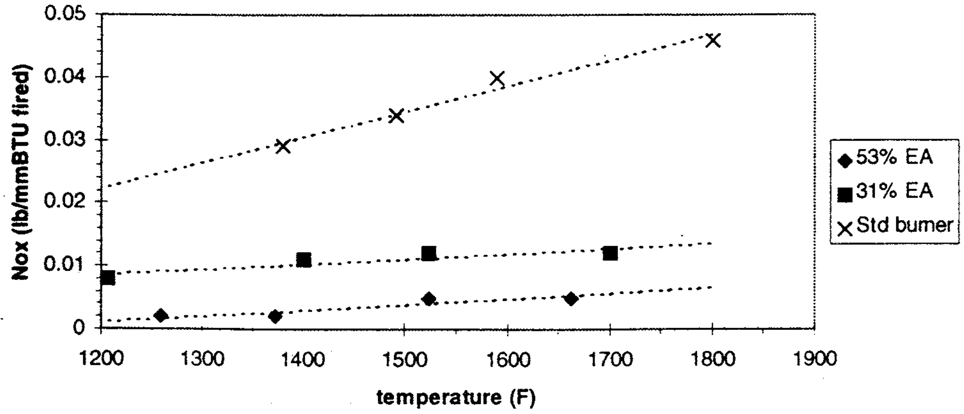
45% TNG, 55% CO2, 1500 scfm



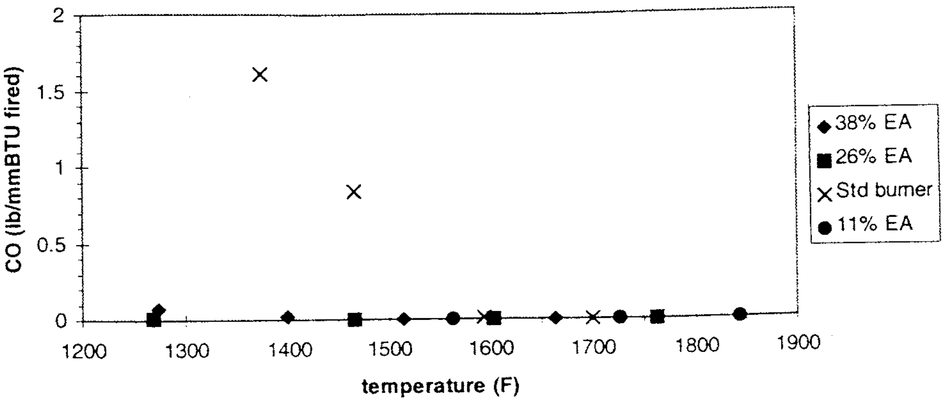
55% TNG, 45% CO2, 500 scfm



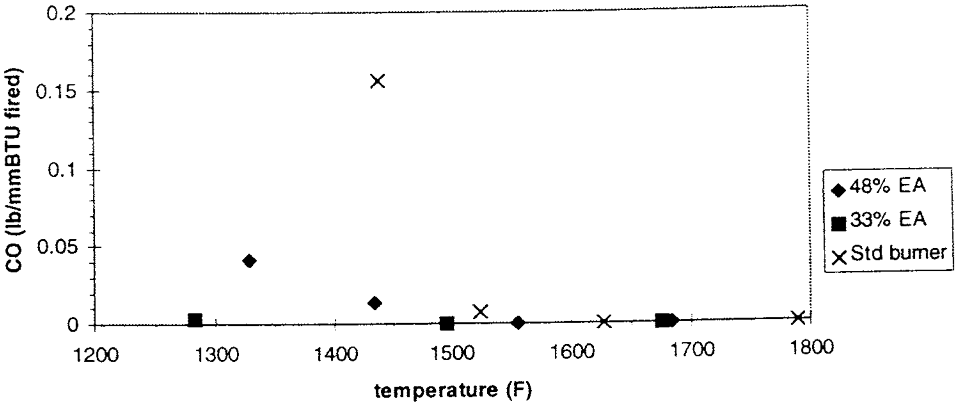
45% TNG, 55% CO2, 500 scfm



45% TNG, 55% CO2, 1500 scfm



55% TNG, 45% CO2, 500 scfm



45% TNG, 55% CO2, 500 scfm