INVESTIGATION REPORT

ENVIRONMENTAL CHARACTERISTICS OF THE

ALM COMBUSTOR AND GAS TURBINE

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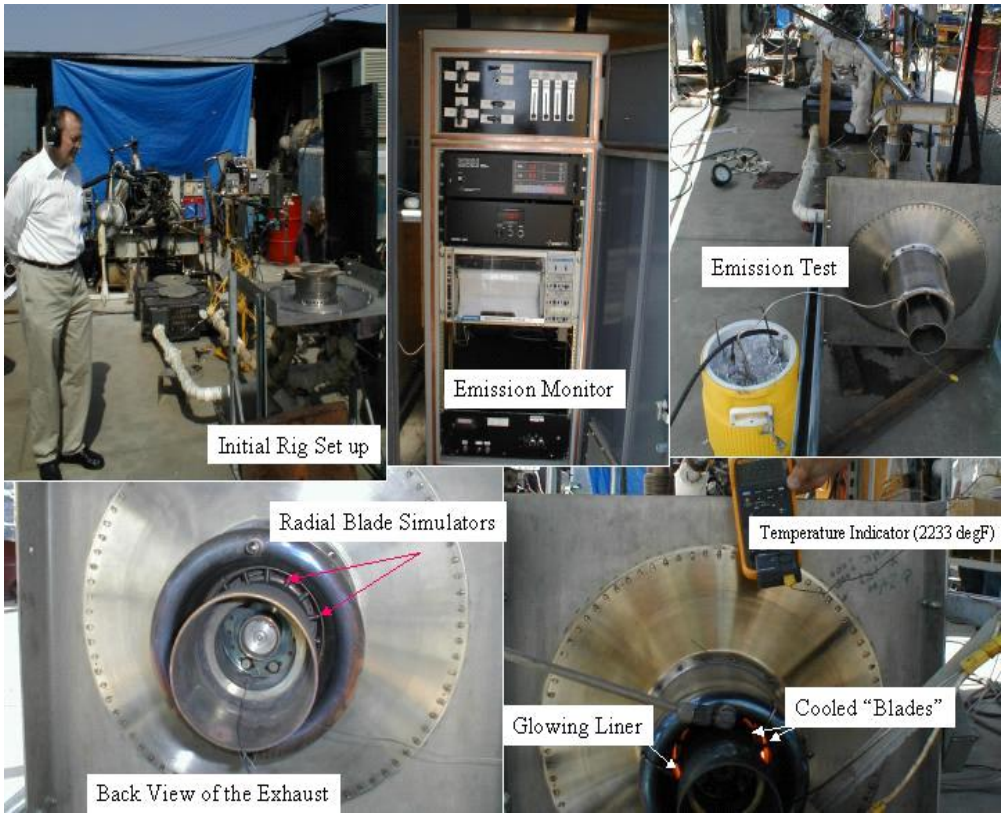
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Introduction

ALM developed and owns the intellectual property rights for a combustor of novel design, which is based on a new technique and technology of fossil fuels combustion. Multiple tests of the ALM combustors and engines showed a remarkable reliability, an unusual sustainability of combustion at low temperatures, and high uniformity of flame in the combustor. All of that taken together leads to us to the conclusion that the ALM combustor possesses a significant advantage over conventional gas turbine combustors with respect to a low concentration of harmful substances in exhaust.

The present report deals with the environmental characteristics of the ALM combustor, primarily the patterns of formation and emission of the most harmful components of exhaust gases: nitrogen oxides (NO_x) and carbon monoxide (CO). The report combines the results of the ALM combustor tests conducted in October-November 2001 with the results obtained in November 2002.

Preliminary tests showed that the accuracy and sensitivity limits of the employed gas analyzers were the main sources of errors in emission measurements. For this reason, special attention was paid to the selection and calibration of suitable gas analyzers of nitrogen oxides and carbon monoxide. This very important point of the tests will be discussed in the experimental part of the present Report. The second part of the Report presents the results and discussion of measurements of harmful compounds, nitrogen oxides and carbon monoxide levels, in the ALM combustor exhaust. The report also contains conclusions and recommendations regarding the emission characteristics of the ALM engine as well as potential combustor applications and their specifics.

1. EXPERIMENTAL SECTION

This section includes the reasoning for gas analyzers selection, their calibration using the standard gas mixtures analysis, as well as evaluation of the gas analyzers' applicability to the ALM combustor emission characterization.

1.1. Gas Analyzer Selection

[This section has been removed because it discusses semi-closed cycle operations. It is available upon request. For open cycle, go to section, 1.3 which is the next paragraph below]

1.3. 400 HCLD and API 200A Gas Analyzers

The 400 HCLD gas analyzer, manufactured by California Analytical Instruments, Inc., possesses a NO/NO_x resolution on the concentration of 0.1 ppm or even better. The instrument was designed to meet the specific requirements of the EPA, Federal Register 40, for continuous measurement of nitrogen oxides levels in vehicle exhaust gases, power plant exhaust, as well as in the air of production facilities and in the environment. The linearity of signal in the low NO_x concentration range, below 5 ppm, and a low effect of moisture and carbon dioxide presence in the analyzed sample on the analyzer readings should be attributed to the prominent advantages of the model versus competitive gas analyzer technologies. In the presence of moisture and carbon dioxide, the error of readings is ~1% when CO_2 concentration is up to 10% and H_2O concentration, up to 3%.

The API 200A Gas analyzer, manufactured by Advanced Pollution Instruments, Inc., is characterized by an outstanding NO/NO_x resolution on the level of 10 ppb. At the same time, a substantial reduction in the NO_x concentration in the presence of moisture and carbon dioxide is a serious disadvantage of the instrument when used for analysis of combustion products. The analysis error in this case may be as high as 10-20%.

The accuracy of both analyzers, which were used for emission measurements, was verified by analyzing the standard mixture with NO_x concentration of 2.5 ppm. The following reproducible results were obtained in conducting this analysis:

Scott Certificate	400 HCLD	API 200A
2.5 ppm	2.48 – 2.53 ppm	2.20 – 2.38 ppm

Thus, both chemiluminescent analyzers showed high accuracy and reproducibility of the measurement results and, consequently, they proved completely suitable for the ALM combustor and engine tests. It should be also pointed out that, despite the revealed flaws of the ENERAC 3000E gas analyzer, this instrument could be recommended for use in tests, provided the upper emission limit is below 5 ppm.

2. RESULTS AND DISCUSSION

One of the principal properties of the combustion process in the ALM combustor consists of partial recirculation of exhaust (ballast) gas (EGR simulation) when a semi-closed cycle is used. In addition, the ALM combustor features a number of superior characteristics, such as extensive combustion, homogeneity of flame that is close to ideal, absence of "hot spots" and/or substantial temperature gradients. The same combustor properties are also applicable to open cycle operation (i.e. without exhaust gas recirculation). A substantial reduction of harmful emissions is one among a number of important characteristics of the ALM combustor, and it is interesting in this respect to compare the combustor and engine emission characteristics in the open and semi-closed cycle modes.

As it was mentioned above, the main goal of the experimental campaign was to study the environmental characteristics of the ALM combustor, particularly the real and potential emission of the most harmful components, which are nitrogen oxides (NO_x) and carbon monoxide (CO). The thermodynamic and kinetic conditions of NO_x and CO formation are quite different and accordingly, the trends of each are discussed separately below.

2..1 NO_x Emission

The ALM combustor can run at high operating temperatures and in a relatively low-temperature operating range of 1000-2000 F. At the same time, nitrogen oxidation is a high-temperature reaction so that formation of nitrogen oxides is governed by the constant of thermodynamic equilibrium rather than by chemical reaction kinetics. By virtue of the equilibrium constant perceptible amounts of NO_x (15-20 ppm) form at the combustion temperatures above 1550^0 C (~2900 F) only when combustion takes place at, or close to the atmospheric pressure. Thus, with the ability to maintain sustainable combustion in a lower temperature range, it is apparent that very low NO_x emissions should be easily achievable in the ALM combustor. However, during the tests in October 2001, a significant NO_x concentration in the ALM combustor exhaust gases was found. The higher NOx emissions must be mainly due to the wrong gas sampling technique or bad discrimination of the background emission from the ballast gas (EGR) source (EGR was simulated in the semi-closed cycle tests by using exhaust gases from an independent engine that was far from being "clean"). Moreover, an appreciable NO_x emission is not infrequently observed in low-temperature combustors and furnaces as a result of flame non-homogeneity and related "hot spots", which in some instances can cause a temperature gradient of 1000-1500 F. Once generated, NO_x then goes to the cold zones, it is quenched there, and stays unchanged up until exhaust gas discharge.

Therefore, the following study presents in essence a verification of homogeneity of fuel combustion in the ALM combustor or, in other words, a verification of proper gas dynamic mixing in the combustor. The combustion chemistry in the classical open cycle mode is a simpler system. Therefore, the study of the semi-closed cycle with simulated EGR reveals the basic pattern of nitrogen oxide formation and emission in the ALM combustor and engine. These patterns were then verified in the open-cycle combustor tests. For these reasons, the results of the semi-closed cycle study are discussed first.

2.1.1. Semi-Closed Cycle with Simulated EGR

[2.1.1 has been removed because it discusses the semi-closed cycle tests. It is available upon request. For open cycle tests go to 2.1.2 directly below this paragraph]

2.1.2. ALM Combustor and Engine Operation - Open Cycle

The 690-cm3 combustor was tested in an open cycle, without ballast gas flow (simulated EGR) from an external source, in a series of special tests conducted on 10.31.01. In this test run, the combustor was fed hot air as an oxidant. Combustion products were sampled at the combustor outlet with the help of a water-cooled sampler. The exhaust gases were analyzed by simultaneously using two gas analyzers, which are the EMS and ENERAC 2000. The average emission values that were obtained using these two instruments are shown in Table 5.

Table 5

NO_x Emission - Smaller Combustor (*V*=690 cm^3)
Open-Cycle (hot air as an oxidant)

Temperature, F	1100	1185	1313	1470	1770	1940	2050	2250	2300
NO_x Emission, ppm	0	2	2	0	3	0	0	2	0

It is significant that neither analyzer was able to detect the presence of NO_x in the ALM combustor exhaust. The observed NO_x concentration in the 2-3 ppm range (see Table 5 above) at relatively low temperatures was due to the instability of the gas analyzers and to an inherent drift of their baseline. The latter was caused by fluctuations of the ambient temperature because the gas analyzers were installed in the open air, and no provisions were made for their thermostatic control.

Therefore, the test data demonstrate a virtual absence of NO_x generation by the ALM combustor at temperatures below 2300 F (~1260^0 C).

High environmental value of the ALM combustor had to be corroborated when the combustor was integrated with an engine. The point is that the when the turbine and generator are installed downstream of the combustor, a back pressure is built up for the combustor, which results in a shift in the thermodynamic equilibrium of nitrogen oxidation reactions, which is favorable for NO_x formation as mentioned above with reference to the *Titan* turbine.

During the November 2002 testing campaign, the 690-cm3 combustor was tested for emissions. During these tests, based on the results of the combustor trials discussed above and also given the requirements of the potential customer, the temperature in the

combustor was held below 2300 F. The main goal during these tests was to achieve the ultimate reliable detection of low of NO_x emission levels. With this objective in view, three different types of gas analyzers having a high resolution for NO_x (see subsection 1.2) were used in the tests. Nitrogen oxides concentration was measured by the ENERAC 3000E gas analyzer in the experimental runs of November 19-21. Exhaust gas was sampled at the engine outlet, and the emission characteristics were related to the gas temperature at the turbine inlet.

Table 6 summarizes the test results. It is important to note that the ENERAC 3000E gas analyzer was unable to detect any NO_x emissions in any of the tests conducted in the temperature range of 1600-2250 F under a broad variation in engine calorific intensities.

Table 6

ALM Engine NOx Emission - Open Cycle
ENERAC 3000E

Temperature, F	1627	1800	1902	1945	2004	2052	2133	2267
NO_X Emission, ppm	0	0	0	0	0	0	0	0

Therefore, given the relatively low sensitivity of the gas analyzer, it may be presumed that the NO_x emission concentration in the ALM engine could be as much as, but does not exceed 2.5 ppm, based on the instrument calibration with the standard gas mixtures (see subsection 1.2).

The use of the chemiluminescent gas analyzers, 400 HCLD and API 200A, allowed for more precise measurements of the ALM engine emissions than the ENERAC 3000E. The chemiluminescent gas analyzers are discussed in subsection 1.2. The 400 HPLD gas analyzer was used to measure the ALM engine NO_x emissions in tests of 11.22.02. This equipment offered an opportunity to detect both the sum of nitrogen oxides $(NO)_x$ and individually nitric oxide, (NO) and nitrogen peroxide (NO_2). The results for a broad operating temperature range are presented in Table 7.

Table 7

ALM Engine NO_x Emission at Different Temperatures
400 HCLD

Temperature, F	1420	1604	1792	1887	1945	2010	2064	2100	2176	2210
NO_x, ppm	1.37	1.53	1.65	1.36	1.45	1.79	1.41	1.61	1.81	1.97
NO_2, ppm	0.11	0.06	0.07	0.03	0.03	0.05	0.04	0.02	0.05	0.08

The obtained data confirm low ALM engine NO_x emissions. In this respect, Table 7 clearly shows the low NO_2 concentration. Since the equilibrium constant requires perceptible formation of nitrogen peroxide to occur at significantly higher temperatures than those

needed for formation of lower nitrogen oxides, the unusually low NO_2 levels in the exhaust gas undeniably give evidence of flame uniformity, absence of "hot spots" and any significant temperature gradients in the ALM combustor.

In the engine experimental runs conducted on November 22 and 25, 2002, a high sensitivity NO_x analyzer, API 200A (see subsection 1.2), was used. Completely reproducible NO_x emission test results are given in Table 8.

Table 8

ALM ENGINE NO_x Emission Measured with API 200A Gas Analyzer

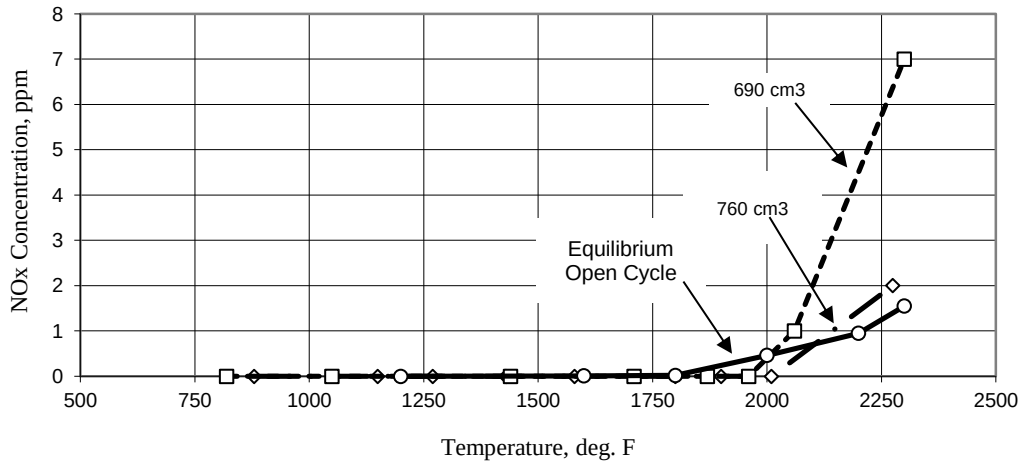
Temperature, F	1538	1725	1807	1911	2010	2153	2201	2241
NO_x, ppm	1.06	1.49	1.25	0.995	0.988	1.19	1.42	1.73

Therefore, to summarize all results obtained with the use of different gas analyzers, it can be concluded with certainty that the ALM engine does not produce NO_x emission higher than 2 ppm at the temperatures in the combustor below 2250-2300 F, i.e., under the design operation conductions and calorific intensities of the combustor.

All the data for nitrogen oxide levels in the exhaust gases that were obtained during the combustor and engine tests in both open and semi-closed cycles are combined in Fig.1, with the equilibrium NO_x concentrations calculated for the same temperature range on the basis of the equilibrium constants of nitrogen oxidation reactions. The emission values other than zero in the low-temperature range are not presented in Fig. 1 because they are absolutely unrealistic.

Nitrogen oxides cannot be formed from air at the temperatures of 1400-1800 F under any conceivable conditions. Their appearance in the gas analyzer readings was most likely caused by the presence of "dead zones" in the combustor. The "dead zones" accumulate NO_x at the moment the engine is started when the equivalence ratio is relatively high, which is favorable for nitrogen oxides generation. The dead zones then slowly wash out under nominal operating conditions, so that simply distort the real composition of the exhaust gases. The fact that the NO_x emission concentrations in Tables 7 and 8 at the temperatures of 1900-2000 are lower than the emission concentrations at the temperatures of 1400-1600 F reasonably supports the above explanation.

Figure 1. NOx Concentration vs. Temperature



It is interesting that the curves showing the ALM combustor emissions in the semi-closed cycle give the levels that somewhat surpass the values attainable at thermodynamic equilibrium as it can be seen in Fig.1, whereas the NO_x concentrations in the exhaust gases of the combustor and of the engine as a whole are substantially at the equilibrium concentration in the open cycle. The overestimated NO_x equilibrium levels shown by the semi-closed cycle test results quite possibly stem from the accuracy of the employed gas analyzers or, which is more likely, they were caused by the backpressure at the Titan turbine outlet when the *Titan* turbine ran with the ALM combustor, which resulted in a respective increase in the background (simulated EGR) NOx emission concentration.

Again, the smaller combustor (690 cm^3) causes a higher pressure drop than the larger combustor (760 cm^3), so that the backpressure in the *Titan* turbine leads to a respective increase in the background NOx emission concentration.

On the other hand, the complete concurrence of the NO_x emission values with the equilibrium for open-cycle operation of the ALM engine quite possibly points to a high efficiency of this engine type, which is determined by the flame uniformity and thoroughness of combustion products mixing in the combustor that are close to ideal.

The above-described tests have persuasively corroborated that the ALM combustor as incorporated in the engine has excellent environmental characteristics and it cannot harm the environment from NO_x emissions. With the sustainable gas dynamics of combustion at low temperatures, the ALM combustor does not produce "hot spots" that might have any perceptible effect at operation temperatures of 2200-2300 F.

2..2. Carbon Monoxide Emission

Unlike nitrogen oxides, carbon monoxide is a nonequilibrium intermediate product of fossil fuel combustion. This suggests that conditions that are favorable for a low NO_x emission should at the same time promote significant formation of carbon monoxide in the process of fuel combustion. For this reason, the low-temperature combustion process in the ALM

combustor on its face may appear to be problematic for reducing carbon monoxide emissions.

With conventional methods for lowering CO emission of combustors and furnaces, the combustion products residence time in the combustion chamber is extended or, in other words, the effective calorific intensity is reduced on the one hand, and on the other hand, the operation temperature is raised to such an extent as not to impair any other process quality indicators including nitrogen oxide emissions. At the same time, the calorific intensity could be reduced by appropriately lowering the fuel and air flow rates, as well as the EGR flow rate (for the semi-closed cycle) and/or by increasing the effective volume of the combustor.

The above-mentioned specifics, coupled to the two-step nature of carbon monoxide release in the flame, which comprises a primary CO formation at fuel combustion in zones with oxygen shortage and the following CO burn-out at the oxidant excess, determine the complexity of the study of CO emission patterns in combustors. The most complicated aspect of such a study consists of the need to vary two parameters of the combustion process, with all other parameters remaining unchanged. It means, for example, that CO versus residence time should be obtained at approximately constant combustion temperature and equivalence ratio, whereas getting the relationship between CO yield and operating temperature has to be done with the residence time remaining unchanged.

Availability of the ballast gas (simulated EGR) flow in the semi-closed cycle combustor tests enabled overcoming these experimental complications because a variation in the ballast gas flow rate allows the residence time of combustion product in the combustor to be changed without changing the actual equivalence ratio. For this reason, the results of the semi-closed cycle experiments will be discussed first.

2.2.1. Combustor CO Emissions - Semi-closed Cycle

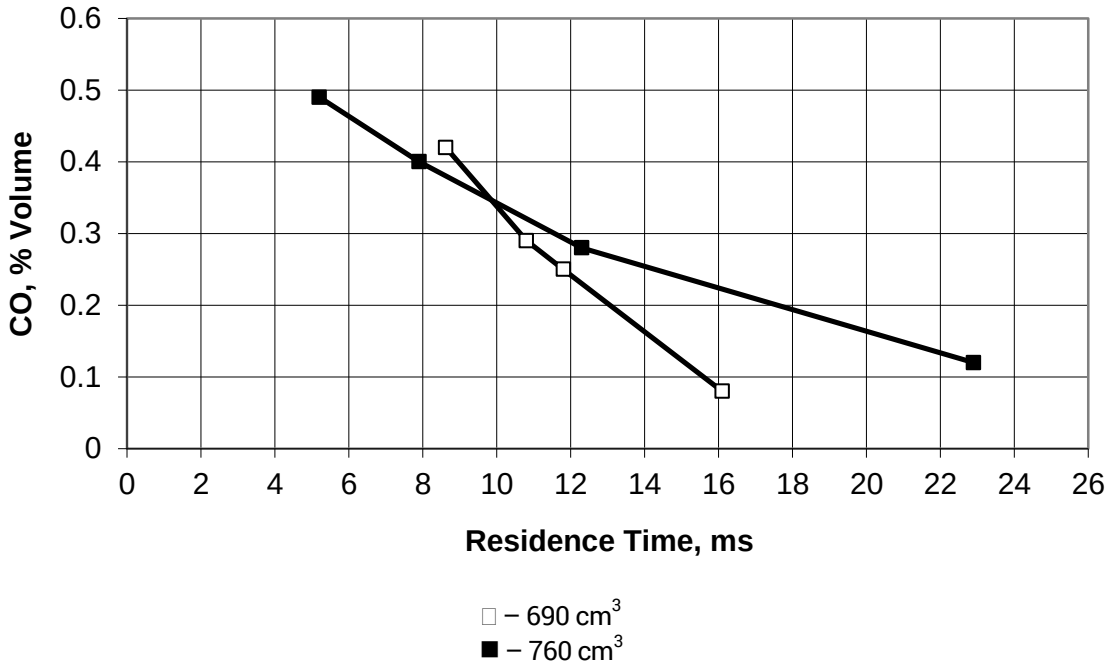
[Skip to page 14 for discussion on open cycle combustor tests for CO, Section 2.2.2. The paragraph below discusses semi-closed cycle tests. The objective of the semi-closed cycle tests was to obtain the relationship between carbon monoxide concentration in the exhaust gases on one hand and combustion products residence time and operation temperature on the other hand for two ALM combustors, with the effective volumes of 760 and 690 cm^3, respectively. THESE TESTS WERE **NOT INTENDED TO MEASURE EXACT CO LEVELS. THE PRECISE CO EMISSIONS TESTS WERE PERFORMED IN THE OPEN CYCLE TESTS.** CLICK HERE TO GO TO PAGE 14 **OR SCROLL DOWN.**

The tests of the larger ALM combustor (1) with the effective volume of 760 cm^3 were carried out on October 26, 2001. The combustion temperature ranged between 980 and 1040 F, with the equivalence ratio of 0.27 to 0.24 . The residence time varied in the range of 5 to 25 ms.

The tests of the smaller ALM combustor (2) with the effective volume of 690 cm^3 were conducted on October 30, 2001. The combustion temperature was ~1100 F, the equivalence ratio 0.31 to 0.39. The residence time varied in the range of 8 to 16 ms.

The combustion products residence time in all cases was changed by partially bypassing the *Titan* engine combustor exhaust gases coupled to an appropriate fuel rate adjustment. It has to be noted here that, unlike NO_x emissions, the *Titan* engine never generated any perceptible CO background emission over the entire experimental campaign. Carbon monoxide emission versus residence time is presented in Fig.2 for both combustors tested.

Figure 2. Carbon Monoxide Concentration vs. Residence Time



As it can be seen, CO versus residence time is very close to linear for combustor (2), while the same curve for combustor (1) is remarkably different from linear, particularly at high residence time values. According to numerous publications, carbon monoxide oxidation follows the chemical kinetics of the 1st order. Thus, the linear character of the kinetic curve suggests that CO combustion in combustor (2) proceeds in the kinetic field and is governed by the 1st order reaction.

At the same time, the kinetic curve deviation from linear relationship indicates an insufficient mixing in combustor (1) and the associated diffusion limitations. Hence, Fig. 2 shows that the geometric design of combustor (2) is better than that of combustor (1).

It has been found that curve (1) in Fig. 2 can be described by the following equation of the 1st order:

$$x = a_1 - b_1[\exp(-kt)], \quad (1)$$

where: x is the CO concentration in the combustion products, mol.;

a_1 is the CO initial concentration, mol = 1.0

k is the kinetic constant = 2.15 mol/s

b_1 is the temperature dependent coefficient = 9.8

t is the residence time, ms

A reaction kinetic equation for combustor (1) reflects the effect of the diffusion mass transfer for this design:

$$x = a_2 - b_2[\exp(-kt)] + D_{eff}[\exp(-mt^2)], \quad (2)$$

where: a_2 = 6.3 mol;

b_2 = 4.4;

k = 2.15 mol/s;

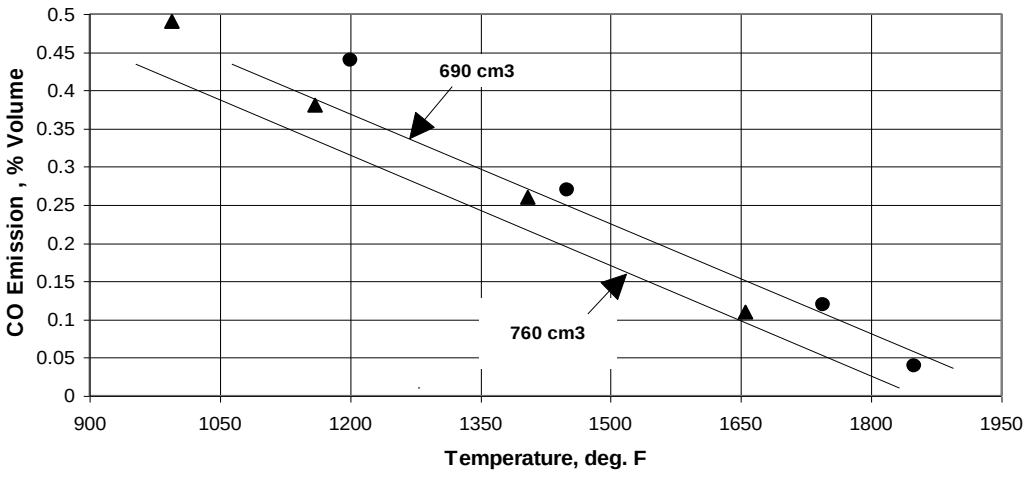
D_{eff} is the CO effective diffusion coefficient (for 1000 F in combustion products D_{eff} = 8.2×10^{-2} mol/cm^2.s);

m is the collision path = 0.4 cm^{-1}. s^{-1}

Extrapolation of the data in Fig.2 according to equations (1) and (2) shows that the residence time, which is required for complete CO elimination, is ~26 ms for combustor (1) and ~17 ms for combustor (2).

Certainly, equations (1) and (2) are connected for a given combustor design and demonstrate a conceptual problem solving approach, rather than being useful as a direct guidance for computation. For instance, the initial CO concentration *a* is determined not only by fuel, temperature, equivalence ratio, etc., but also by the coordinate combustor zone where CO combustion begins to prevail over its formation.

Figure 3. Carbon Monoxide Emission vs. Temperature (E=5.6 Kcal/mol)



Figures 2 and 3 demonstrate that low CO emission cannot be reached at operation temperatures below 2000 F at any reasonable residence time in the existing volume of the combustor.

The measurements of CO emissions in a relatively high-temperature range were carried out on October 30 and 31, 2001. The equivalence ratio was maintained at the concentration of 0.33 to 0.29, the residence time varied in the range of 4.6 to 9 ms, the temperature from 1850 to 2300 F. The results given in Table 9 confirm that CO levels as low as current EPA

standards at the ALM combustor calorific intensity that corresponds to a residence time of ~5 ms can be attained only at operation temperatures higher than 2050 F (1120^0 C).

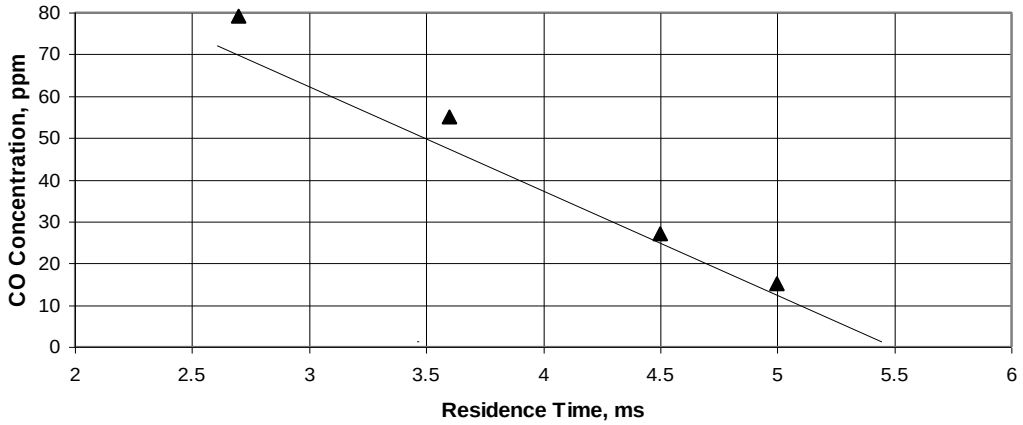
Table 9

Carbon Monoxide Emission at High Temperatures

Date	Time	Flow rate, l/s			Temperature, °F		CO % vol.
		EGR	Air	Fuel			
10.30	14:48	17.2	-	1.44	1870	7.9	0.01
10.31	13:43	-	25.5	1.08	1930	5.9	0.01
10.30	14:50	19.47	-	1.58	2020	5.45	0.01
10.30	14:56	16.9	-	1.59	2280	6.7	0.0
10.31	13:32	-	25.3	1.22	2300	4.6	0.0

The tests of October 30 were repeated on November 2, 2001 with the ENERAC 2000 analyzer whose measurement scale covers a 0-2000 ppm range (subsection 1.2). The temperature and the equivalence ratio remained approximately unchanged over these tests, T = 2130 F, and k = 0.4, respectively. The residence time varied within 3 to 5 ms. The results are shown in Fig. 4.

Figure 4. Carbon Monoxide Emission at 2130 F



It is evident that carbon monoxide combustion follows chemical kinetics of the 1st order also in a range of relatively high temperatures. It is further significant that the reaction rates conform to an established rule at very low reactant concentrations on a ppm concentration where elemental collisions are very rare. In other words, the linear relation between CO residual concentration and residence time in a low concentration range proves in principle that any desired purity of the exhaust may be attained in the ALM combustor with the effective volume of 690 cm^3 at the temperature of 2130 F.

In fact, the data in Fig. 4 shows that carbon monoxide emission below the EPA limit can be reached at a residence time of ~5 ms, (i.e. in the range of the calorific intensity design point of the ALM combustor). Moreover, a special test run conducted at the temperature of

2280 F with the residence time of 5 ms showed the possibility of reaching practically the complete CO elimination from the ALM turbine exhaust (i.e. 0 to 3 ppm).

Therefore, the tests of the ALM combustor determined the optimal operating conditions from the viewpoint of minimization of harmful emissions. Moreover, a juxtaposition of emission trends for nitrogen oxides and carbon monoxide leads to the conclusion that such optimal conditions fall within the temperature range of 2250-2300 F and the residence time range of 5-6 ms.

2.2.2. Open Cycle

As it was pointed out above, unlike nitrogen oxide, carbon monoxide is a nonequilibrium product of fuel combustion. For this reason, a change in pressure in the combustor cannot have a visible effect on CO formation in the flame. Therefore, it can hardly be expected that transition from the semi-closed cycle to the open cycle mode, or combustor integration with the engine, may affect the pattern of CO emission obtained earlier in the semi-closed cycle tests.

To obtain exact CO levels, the measurements of the ALM engine were carried out during an experimental run performed on November 19-24, 2002. In these tests, the ENERAC 3000E gas analyzer having the sensitivity limits of 0-2000 ppm (see subsection 1.2) was employed for CO concentration recording. As it can be seen from the data of Table 11, the procedure and instrumentation allowed for tracking down a gradual decrease in CO concentration in the engine exhaust with an increases in the operating temperatures in the combustor up until the complete disappearance of carbon monoxide at temperatures close to 2300 F.

Table 11

ALM Engine Carbon Monoxide Emission (ENERAC 3000E)

Temperature, F	1843	2006	2094	2144	2175	2225	2249	2276
CO Emission, ppm	449	263	93	53	38	15	7	0

The obtained results for the ALM combustor and engine CO emissions in the open cycle are in good agreement with the combustion pattern observed for the semi-closed cycle. It is possible to conclude on the basis of all the data reported above that, in order to meet the EPA requirements for carbon monoxide emissions of 18-20 ppm, the temperature in the combustor has to be maintained in the range of 2200-2300 F. **It is very important to emphasize that this temperature range perfectly matches the conditions for minimum NO_x emissions where nitrogen oxides concentration does not exceed 2 ppm.**

Therefore, there is no doubt that the ALM combustor is able to meet the most stringent requirements of the environmental regulations with respect to harmful emissions into the air and for this reason, along with the simplicity of design, the ALM combustor has an outstanding commercial potential.

2.3. ALM Engine and Problem of Low-Calorie Fuels Utilization

Certain features of the ALM combustor, which were revealed in this study, make it possible to look for potential non-conventional applications of the combustor. Among such outstanding features of the ALM engine, first of all, is the ability to maintain sustainable, efficient combustion at low temperatures, ~1000-1600 F at high specific heat value and respectively with small combustor dimensions. One potential application of the combustor is its use for burning low-quality fuels.

The United States Government is highly interested in exploiting the abundant domestic resources of low-quality gases for energy production as a solution that could help offset growing increasing oil imports. Beginning in 1992, the US Department of Energy (DOE) implemented the national Gas Processing Program in an effort to expand development and utilization of domestic energy resources. The program classifies such resources as follows: low-quality on-shore and off-shore natural gas wells, coal bed methane production, gasification of coal and bituminous sand deposits, landfill gas, and biogases.

A specific feature of composition of the above-listed gases is a high content of non-methane components (up to 40-80%), primarily nitrogen and carbon dioxide. Often, the above-mentioned sources of flue gases are in remote locations so that transporting them to a trunk pipeline becomes impossible or uneconomical. In addition, it would not be beneficial to put such gases directly into existing pipelines, even when it is geographically possible, as it would result in the substantial reduction in caloricity and purity of the main flow of fuel gas.

A variety of DOE Programs are focused on the development of gas enrichment processes, however, contemporary technologies for nitrogen and carbon dioxide separation are too expensive to make economical the utilization of low quality fuel resources on any significant commercial scale.

Therefore, it is, clear that the development and large-scale commercialization of small-size, low-capacity, environmentally -friendly power generators, which are capable of burning low-BTU gas fuels with high efficiency, could present a valuable addition to the national energy program. In this respect, it should be noted that the semi-closed cycle tests, which were conducted during this study, in essence provides real evidence of the great potential of the ALM combustor for low-quality fuel utilization in various industries and in agriculture.

The use of the ballast gas (EGR simulation) for fuel gas dilution in the semi-closed cycle test (see subsections 2.1 and 2.2) resulted in obtaining the makeup of a low BTU that it is desirable to utilize. Thus, for example, the estimated gas composition of the fuel/ballast gas mixture that was used during the October-November experimental campaign of 2001 varied within the following limits:

	% vol.
Methane–	16-35
Nitrogen–	38-65
Oxygen–	11-15
Carbon Dioxide–	1.6-6.8

Therefore, the test data discussed in subsections 2.1 and 2.2 in fact corroborate the applicability of the ALM combustor and engine to utilization of the leanest gases of natural or synthetic origin. A sole distinction of some natural gases from the composition given above is that they often contain a significant amount of natural gas liquid (NGL) whose separation may prove uneconomical for small capacity gas fields. It is necessary to say that the engine and combustion process which comprise the ALM's technology provide an opportunity for direct combustion of gas-condensate mixtures without preliminary separation of hydrocarbon liquids. Indeed, the use of a high-efficiency premixing chamber and the vortex processes in the combustor allow for burning both evaporated and sprayed gas-liquid mixtures.

Serious environmental and corrosion problems associated with the processing and burning of low-quality gases may arise because of the presence of a wide variety of inorganic impurities. For example, landfill gases and biogases usually contain from 0.1 to 1.5 % of ammonia (NH_3). Gasification gases contain sulfur compounds, such as hydrogen sulfide (H_2S), carbon oxysulfide (COS), carbon disulfide (CS_2), and also up to 700-800 ppm NH_3. Many natural gases contain up to 1000 ppm of thiols (mercaptanos). Ammonia produces NO_x when burned, with a conversion degree from 40 to 100 % (mol), all sulfur compounds produce sulfur oxides (SO_x) or predominantly sulfur dioxide (SO_2) with a 100-percent conversion degree. In other words, NO_x, and SO_x emission levels with burning gases containing nitrogen and sulfur compounds are many times higher than harmful emissions from engines and steam-generating stations that are processing pure fuels (i.e. up to 1000-10,000 ppm NO_x and 1-1.5% SO_x).

Therefore, it is clear that burning low-quality gases demands either undesired impurities removal before the inlet of the power generation plant or exhaust gas neutralization downstream of the heat and power generation plant. Both solutions involve significant capital and operation expenses.

At the same time, most of the mentioned impurities and the combustion products are quite reactive and can interact with each other under certain conditions. It should be also noted that the ALM combustion technology is suitable to accomplish these interactions at a head (premixer) or, at a tail (burning-out chamber or ballast gas heat exchanger) of a power generation unit. It seems that the development of a small-size, portable skid-mounted power generation package, which would combine the ALM combustor and technology with chemical reactors for fuel or/and exhaust gas purification should be made a major priority.

It is not an objective of the present Report to detail possible process flow diagrams and apparatus. It is only important to point out the high adaptability of the ALM combustor and technology for a comprehensive solution to the problem of low-calorie gas fuel utilization and, accordingly, the expedience and importance of the company involvement into the DOE national program.

Naturally, the evolution of this new direction in the ALM activity may demand significant additional investments. Consequently, inclusion into the national program and attraction of

the DOE grants for financing the commercialization of the ALM's technology is, in our opinion, a requirement for a success of the suggested project.

It is well known, that the DOE system for private R&D support includes solicited and unsolicited grant proposals. The system of unsolicited grants is probably most suitable for the suggested project for two reasons: potential financing size and significance of the project. Moreover, a substantial advancement of the ALM combustor from the viewpoint of commercial application allows soliciting the Phase II grant from the start.

In this case, the project presentation at the National Energy Technology Laboratory (NETL), which is responsible for coordination of the DOE Gas Processing Program, should become the first step in the preparation of the grant proposal. It appears that the present Report could be a good basis for preparing the above-mentioned presentation and proposal.

Conclusions

1. The tests conducted in November 2002 with the use of different types of gas analyzers provide strong evidence that the ALM combustor and engine do not inherently produce NOx emission in a broad temperature operating range of up to 2300 F.
2. ***Carbon monoxide oxidation in the ALM combustor is governed, with few exceptions, by the chemical kinetics of the first order in a broad range of the operation temperatures and CO concentrations***. The respective correlations for the CO combustion rates calculation are derived on the basis of the obtained experimental data.
3. ***Carbon monoxide emission versus operation temperature in the ALM combustor has a linear character with the activation energy of E = 5.6 kcal/mol***. An unusually low value of the activation energy, the observed deviations from linearity of the residual CO concentration versus the effective residence time point to an insufficient mixing and essential diffusion limitations in the combustor operation, particularly in the range of very low CO concentrations. It was also found that the ALM combustor of 690 cm^3 effective volume is better from the viewpoint of combustion products gas dynamic mixing than the combustor having lower calorific intensity with the effective volume of 760 cm^3.
4. It was established that the operating temperature of the ALM combustor, with any design calorific intensity or any reasonable residence time, should not be below 2250-2300 F in order to reduce CO emission and match the US EPA requirements.
5. The temperature range of 2200-2300 F is recommended as an optimal operation range of the ALM engine studied. This temperature range provides low emissions of both harmful components of the exhaust gases.
6. ***The real potential of the ALM engine for resolving the problem of utilization of abundant domestic resources of low-calorie gases is reviewed***. The need to commercialize and incorporate the ALM engine and combustor technology into the DOE national program for the development and utilization of low-quality natural gases has been demonstrated.
7. For applications with low-calorie fuels, it is recommended to substantially reduce, or completely dispense with the use of EGR depending on the fuel BTU value.

8. Generally, the conducted tests have persuasively proved a complete environmental tolerance of the ALM combustor and engine. Based on a sustainable gas dynamics of the combustion process at relatively low temperatures and extensive calorific capacity within certain ranges of operating parameters, the ALM combustor can assure any desired purity of its exhaust, particularly with respect to the most harmful components, CO and NO_x.