**SANDIA REPORT**
SAND2010-7747
Unlimited Release
Printed November 2010

# Exhaust-Gas Measurements from NASA's HYMETS Arc Jet

Paul A. Miller

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

**NOTICE:** This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

| | |
|---|---|
| Telephone: | (865) 576-8401 |
| Facsimile: | (865) 576-5728 |
| E-Mail: | reports@adonis.osti.gov |
| Online ordering: | http://www.osti.gov/bridge |

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

| | |
|---|---|
| Telephone: | (800) 553-6847 |
| Facsimile: | (703) 605-6900 |
| E-Mail: | orders@ntis.fedworld.gov |
| Online order: | http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online |

SAND2010-7747
Unlimited Release
Printed November 2010

# Exhaust-Gas Measurements from NASA's HYMETS Arc Jet

Paul A. Miller
Lasers, Optics, and Remote Sensing Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1423

**Abstract**

Arc-jet wind tunnels produce conditions si mulating high-altitude hypersonic flight such as occurs upon entry of space craft into planetary atmospheres. They have traditionally been used to study flight in Earth's atmosphere, which consists mostly of nitrogen and oxygen. NASA is presently us ing arc jets to study entry into Mars' atmosphere, which consists of carbon dioxi de and nitrogen. In both cases, a wide variety of chem ical reactions take place among the gas constitu ents and with test articles placed in the flow. In support of those studies, we made measurements using a residual gas analyzer (RGA) that sampled the exhaust stream of a NASA arc jet. The experim ents were conducted at th e HYMETS arc jet (Hypersonic Materials Environmental T est System ) loca ted a t the NASA Langley Res earch Cen ter, Hampton, VA. This report describes our RGA measurements, which are intended to be used for m odel validation in com bination with sim ilar m easurements on other systems.

## ACKNOWLEDGMENTS

We are grateful for support of this work by the NASA Johnson Space Center, Houston, TX, under the guidance of Brian Shafer. This work was made possible by efforts of Scott Splinter and Jeff Gragg, NASA Langley Research Center, who made available and operated HYMETS for these tests. It was a pleasure to collaborate with them in designing and executing the test matrix.

We appreciate the excellent technical support provided by Ron Allman, Sandia, in assembling, shipping, installing, testing, and operating the RGA system. He also provided a valuable sounding board for developing our approach to conducting tests.

# CONTENTS

1. Introduction ..... 9
2. Experimental apparatus ..... 9
3. Experimental procedure ..... 12
4. Results ..... 14
5. Discussion ..... 23
Distribution ..... 25

# FIGURES

Figure 1. Measured response of RGA system to static fill of dry air admitted into laboratory vacuum chamber. The water signal is due to the background in the RGA system. .....10

Figure 2. RGA system during initial testing. For the HYMETS tests, long tubing was connected to the input at the left, replacing the 5-μm pinhole used for sampling ambient laboratory air. ... 10

Figure 3. RGA data from measurement of laboratory atmosphere. Notice that $N_2$ appears at both M/Q = 28 and 29, the latter being due to a different isotope. Also note that Ar (~1% of ambient air) appears both singly and doubly ionized. OH and N are formed by dissociation of water vapor and $N_2$ in the ionizer. ..... 11

Figure 4. RGA system connected to HYMETS exhaust line. .....11

Figure 5. Flexible bellows tubing connects to the horizontal 18"-long ¼"-diameter rigid tubing used to sample the exhaust gases in the vertical exhaust line at the right. ..... 12

Figure 6. View of arc electrode assembly. The cathode is at the left. The six prominent copper lines above the electrode stack are used for gas injection. ..... 13

Figure 7. Arc potential and current waveforms for air (at left) and $N_2$-$CO_2$ mixtures (right). Once the set points were reached, the discharge parameters remained constant. Numerical values for the specific conditions are given in the table below. ..... 15

Figure 8. Data from measurements in air at 200 A arc current, 550 slpm flow. The top graph shows the time evolution of RGA signals from eleven selected species of interest. Notations at the top of the graph indicate several specific times of importance during the experimental sequence. The data points on the $O_2$ trace indicate times when complete spectra were taken; data points are omitted from the other traces for clarity. The bottom graph shows spectra averaged over the three main times of interest. ..... 16

Figure 9. Data from measurements in the $CO_2$ mixture at 200 A arc current, 419 slpm flow. The graph shows the time evolution of RGA signals from eleven different species of interest. Notations at the top of the graph indicate several specific times of importance during the experimental sequence. The data points on the $O_2$ trace indicate times when complete spectra were taken; data points are omitted from the other traces for clarity. ..... 19

Figure 10. Complete data set for the air mixture. The test sequence consisted of 11 different combinations of gas flow and arc current, ranging from the initial low values of 100 slpm at 100 A to the final values of 550 slpm at 300 A. Between each condition there was a period of several minutes under vacuum while a bolometer was allowed to cool off. .....20

Figure 11. Complete data set for the $CO_2$ mixture. The test sequence consisted of 11 different combinations of gas flow and arc current, ranging from the initial low values of 76 slpm at 100 A

to the final values of 419 slpm at 300 A. Between each condition there was a period of several minutes under vacuum while a bolometer was allowed to cool off. .....21

Figure 12. Data from the mixture most closely representing the Martian atmosphere. As with all the other cases, 5% of the flow was argon. .....22

Figure 13. Complete data set for selected $CO_2$-$N_2$ mixtures. In time, they were 1:1, 1:2, 1:3, 1:4, 1:5, 97:3, and the standard $CO_2$ mixture with gas injection ports changes. Current was 200 A for all cases. ..... 23

# NOMENCLATURE

| | |
|---|---|
| HYMETS | Hypersonic Materials Environmental Test System |
| MFC | mass flow controller |
| M/Q | mass-to-charge ratio of gas species measured by the RGA system |
| NASA | National Aeronautics and Space Administration |
| RGA | residual gas analyzer |
| slpm | standard liters per minute, a measure of volumetric gas flow rate |
| SNL | Sandia National Laboratories |

# 1. INTRODUCTION

Wind tunnels have been used extensively for many years to simulate flight conditions in the laboratory. Arc-jet wind tunnels use electrical arcs to preheat the working gas in order to obtain hypersonic speeds. Such systems can, for example, perform realistic tests of re-entry bodies returning to earth from orbit. Under these conditions, many complex chemical reactions take place, both among the gas constituents and between the gas and test articles placed in the flow.

Recently we were contacted by Brian Shafer, NASA Johnson Space Center, Houston, TX, concerning studies of hypersonic flight into Mars' atmosphere that are being conducted with NASA arc jets. Together with other Sandia personnel we developed a project to perform experiments and modeling of these systems. One element of this project was to make experimental measurements of species concentrations in the exhaust of HYMETS (Hypersonic Materials Environmental Test System), an arc jet located at the NASA Langley Research Center, Hampton, VA. This report documents those measurements.

The measuring system included a sampling probe inserted into the exhaust stream, a vacuum system to transport the sampled gas stream, and a residual gas analyzer (RGA) to measure the spectrum of mass-to-charge ratios of the gas species. Operation of the RGA was controlled by software customized for this test. In Section 2 of this report we describe the experimental techniques in more detail. In Section 3 we describe the test matrix and the procedures used for each test condition. Section 4 presents results.

This experiment produced a large quantity of data, of which only a small subset has been analyzed in detail. In the data that has been analyzed, we detected no signals that can be attributed to generation of CN or HCN, and we observed conversion of a large fraction of $CO_2$ to CO.

# 2. EXPERIMENTAL APPARATUS

We decided to sample the exhaust gas at an existing HYMETS port located downstream from the water-cooled coils that cool the exhaust stream and that cause a shock wave that converts the supersonic flow to subsonic. Upstream from those coils, the environment was such that our sampling probe likely would have been destroyed. At the sampling location our probe protruded 3" into the 6"-diameter exhaust pipe.

The sampling probe was ¼"-outside-diameter stainless-steel tubing with a 25-μm-diameter sampling hole in the end of the tube, obtained from Lennox Laser[1]. Previous measurements by HYMETS personnel indicated that the static pressure at our sampling location was in the range 1 to 10 Torr. Setup measurements in our laboratory, shown in Figure 1, indicated that a 25-μm hole would be appropriate for this pressure range. (As backups, we also procured sampling tubes with 12 and 50-μm holes, but they were not needed for these tests.) The data in Figure 1 compare partial pressures indicated by the RGA system vs. total pressure indicated by a capacitance manometer. Nonlinearity at higher pressures is evident; neither system was

calibrated. The pressure ratios are fairly constant over the pressure range. While our RGA data do not give precise quantitative information, we feel that the data provide good information on relative abundances and on trends.

The sampling tube was connected using standard vacuum fittings to valves and an 8-foot-long section of 1" ID flexible stainless-steel vacuum tubing that connected to our vacuum system. The long tube was necessary because of the layout of the HYMETS facility.

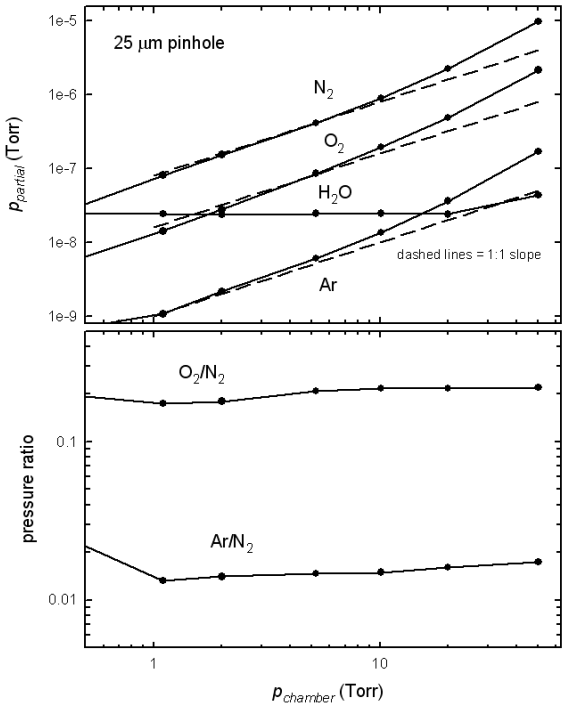


Figure 1. Measured response of RGA system to static fill of dry air admitted into laboratory vacuum chamber. The water signal is due to the background in the RGA system.

The vacuum system consisted of a 4 ½" turbo-molecular pump backed by a mechanical roughing pump. The system is shown in Figure 2. Base pressure in the foreline was below 10 milliTorr according to a thermocouple gauge. Base pressure in the high-vacuum region, after more than 24 hours pumping, was generally in the $10^{-8}$-Torr range. We initially shipped the vacuum system to NASA Langley in July, 2010. At that time we assembled it and operated it without connecting it to HYMETS, which was involved at that time with other testing. We left the system valved off under vacuum from July 15 until September 13, 2010, on which date we connected the system to HYMETS and began the present series of tests. The tests were conducted on September 14th and 15th. At all times, the major contaminant in our vacuum system was water. HYMETS itself also had high water levels during the experiment, though that didn't cause obvious effects on most of the data.

The RGA was a quadrupole mass spectrometer from Stanford Research Systems that we controlled using software written for this particular experiment. The RGA output indicates partial pressure for a range of species according to the ratio of mass to charge of the species. Consequently, there is ambiguity between, for example, singly-ionized nitrogen and carbon monoxide, both having M/Q = 28. This means that a significant

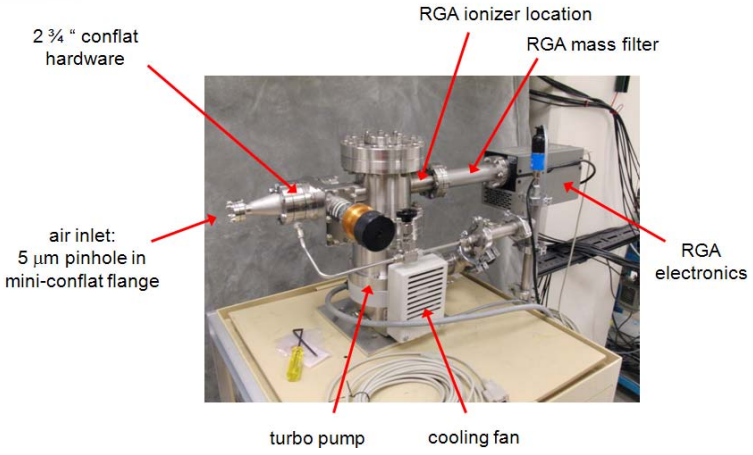


Figure 2. RGA system during initial testing. For the HYMETS tests, long tubing was connected to the input at the left, replacing the 5-μm pinhole used for sampling ambient laboratory air.

amount of interpretation of the data is required, and one must make use of auxiliary information. For example, when sampling air, signals at M/Q = 28 indicate molecular nitrogen, whereas when using Mars-simulant gases, both carbon monoxide and nitrogen will contribute to the M/Q = 28 signal. Furthermore, a signal at M/Q = 14 could arise from either singly-ionized atomic nitrogen or doubly-ionized molecular nitrogen. One also must be aware that species will be generated by dissociation in the RGA ionizer that are not present in the source gas stream. Figure 3 shows sample data from ambient laboratory air. Notice that the individual peaks, while narrow, are not delta functions. Consequently, very low concentrations of species at M/Q = 26 and 27 (CN and HCN) would not be easily separated from the wings of the strong peak for $N_2$.

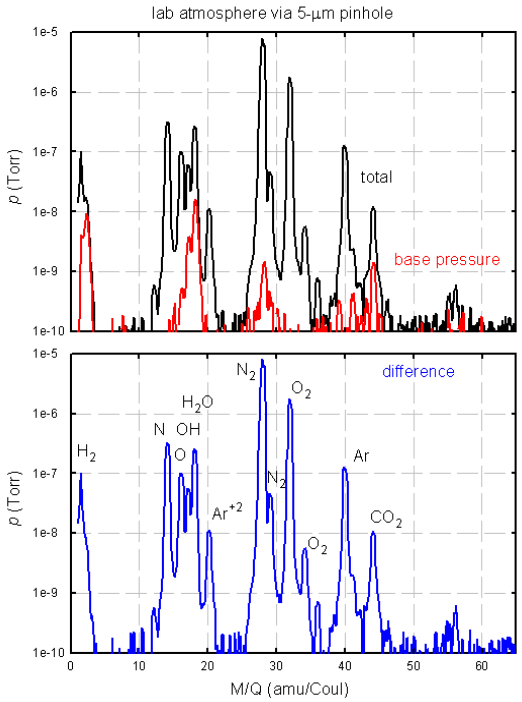


Figure 3. RGA data from measurement of laboratory atmosphere. Notice that $N_2$ appears at both M/Q = 28 and 29, the latter being due to a different isotope. Also note that Ar (~1% of ambient air) appears both singly and doubly ionized. OH and N are formed by dissociation of water vapor and $N_2$ in the ionizer.

Figure 4 shows the RGA system connected to the exhaust line of HYMETS. A long section of tubing was needed to reach across the racks of bottles that supply the gas mixture for HYMETS. Figure 5 shows a close-up view of the ¼"-diameter sampling tubing where it entered the exhaust line. For all the data taken at HYMETS, we operated the RGA using default settings and with its noise floor set to the value 4. We scanned M/Q values from 1 to 50; there usually is little of interest at higher values. With these settings, one scan took 8 seconds.

Ideally, one would like the RGA to sample species in the gas flow without affecting the species distribution. However, the necessity of a relatively long vacuum line between the sampling aperture and the RGA means that all detected species will have interacted with the vacuum walls many times.

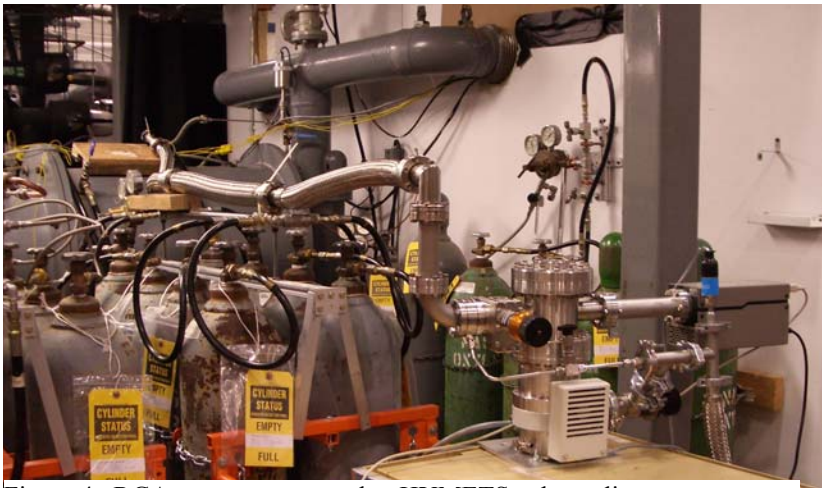


Figure 4. RGA system connected to HYMETS exhaust line.

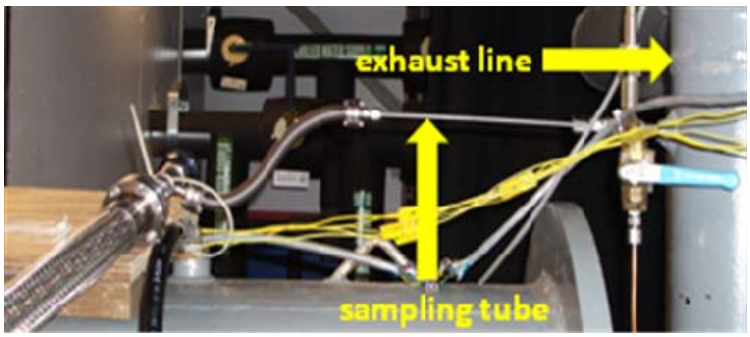


Figure 5. Flexible bellows tubing connected to the horizontal 18"-long ¼"-diameter rigid tubing used to sample the exhaust gases in the vertical exhaust line at the right.

## 3. EXPERIMENTAL PROCEDURE

At HYMETS we took data over a range of experimental parameters, varying gas species, arc current, and gas flow rate. The first data set employed a gas mixture representative of dry air. That mixture contained 5% argon, 75% nitrogen and 20% oxygen. Argon is included above the normal concentration present in the atmosphere for discharge ignition and stability. The second data set employed a $CO_2$ mixture consisting of 5% argon, 24% nitrogen, and 71% carbon dioxide. This second mixture is relevant to Mars' atmosphere, but has less carbon dioxide to reduce cathode damage because oxygen resulting from dissociation of carbon dioxide reacts rapidly with the cathode material. The third data set contained various ratios of nitrogen to carbon dioxide, as specifically requested by Johnson Space Center.

The gas flows were designed around a matrix of mass flow rates (lbm/s), but the HYMETS control system controlled on volumetric flow rates (slpm). Table 1 lists the test matrix that we executed. The matrix was developed in consultation with HYMETS staff to sample the entire range of operation that was safe for our configuration. The volumetric flow rates for the $CO_2$ mixture were adjusted so that the actual mass flow rates were the same as the corresponding values for air. For example, 100 slpm of the air mixture has the same mass flow (0.0049 lbm/s) as does 76 slpm of the $CO_2$ mixture.

| | MFC (SLPM) | I (A) | | |
|---|---|---|---|---|
| Air | 100 | 100 | 150 | |
| | 200 | 100 | 200 | 300 |
| | 400 | 100 | 200 | 300 |
| | 550 | 100 | 200 | 300 |
| $CO_2$ | 76 | 100 | 150 | |
| | 152 | 100 | 200 | 300 |
| | 305 | 100 | 200 | 300 |
| | 419 | 100 | 200 | 300 |

Table 1. Matrix of arc conditions.

The experimental sequence consisted of measurements at each combination of gas flow and arc current. Each condition ran for a few minutes, followed by a cooling period of 5 to 15 minutes without gas flow. We went through the air matrix starting at 100 slpm and stepped through 100 A followed by 150 A. We then increased the gas flow to 200 slpm and stepped through the currents at 100 A, then 200 A, and then 300 A. We went through the $CO_2$ matrix in the same order.

These two groups of air and $CO_2$ measurements constituted the 22 conditions of the first two data sets. Per request from Johnson Space Center, a third data set was taken at fixed current (200 A) and fixed mass flow rate (0.0193 lbm/s). For these tests, 5% of the flow was argon along with $CO_2$-to-$N_2$ ratio values of 1:1, 1:2, 1:3, 1:4, 1:5, and 97:3. The last value corresponds to the Martian atmosphere (except for the argon).

A final test repeated operation with the standard $CO_2$-$N_2$ mixture at 305 slpm, 200 A, but with a change to gas injection locations. This was done to obtain data for comparison with an earlier experiment. Figure 6 shows the assembly of 32 electrodes that constitute the arc column. For reference, we number the gas injection lines from 1 to 6 from left (cathode end) to right. For all tests with air, nitrogen was injected though lines 1, 2, 3, and 4; argon also was injected through line 4; and oxygen was injected through lines 5 and 6. For tests with $CO_2$, except the very last test, nitrogen was injected through lines 1 and 2; argon was injected through line 4; and $CO_2$ was injected through lines 3, 5, and 6. For the last test, nitrogen was injected through lines 1 and 2; argon was injected through line 5; and $CO_2$ was injected through lines 3, 4, and 6.

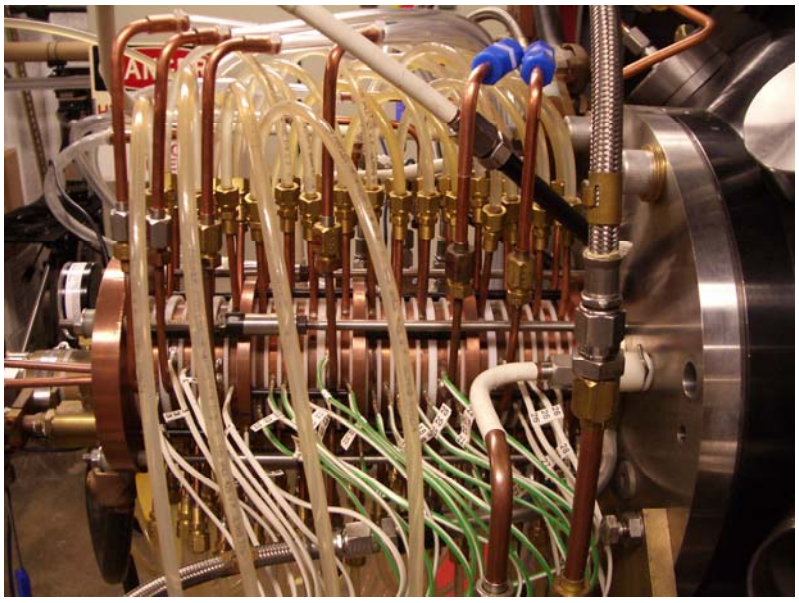

Figure 6. View of arc electrode assembly. The cathode is at the left. The six prominent copper lines above the electrode stack are used for gas injection.

HYMETS normally operates with a test item mounted on a sting inserted into the flow close to the exit of the arc column. HYMETS has four, pneumatically operated, radially mounted stings that can be inserted into the flow, one at a time, for performing more than one test per run. For

this experiment, we obtained RGA data both with and without a sting-mounted sample (1”-diameter silicon carbide disk) in the flow.

The basic sequence for each test consisted of several sequential steps:

1. Gas flow and electrical arc started at low values.
2. Gas flow and arc current ramped up to target conditions with sting in the flow.
3. Target conditions achieved and stabilized (“set point”).
4. Arc maintained for up to one minute with a sting in the flow.
5. Several stings cycled into and out of the flow for pressure and flux measurements over a period of a few seconds.
6. Arc maintained for less than one minute with no sting in the flow.
7. Electrical arc extinguished while gas flow continued.
8. Gas flow stopped.

With a sting in the flow, a strong shock forms in front of the test article which reduces the strength of the shock and the heat flux at the cooling coils located downstream. Without the sting in the flow, under the highest power conditions, there is danger of damaging the cooling coils. The test sequence that we adopted minimized that risk and allowed comparison of RGA signals with and without the sting-mounted silicon carbide disk in the flow.

## 4. RESULTS

Time dependent measurements of arc potential and current were taken during each test. Once set-point conditions were obtained, the potential and current were very constant. Waveforms are shown in Figure 7. In that figure we overlay all the waveforms for each gas in the matrix above to show the stability of the discharge. Specific numerical values for the matrix of conditions are shown in Table 2.

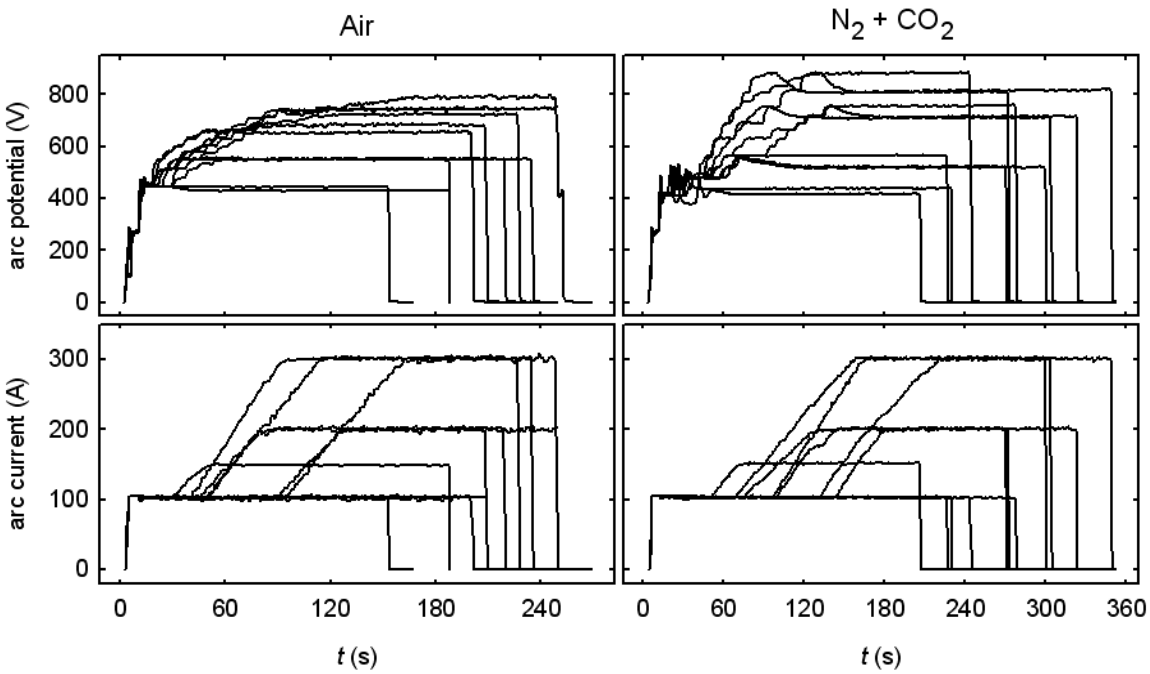


Figure 7. Arc potential and current waveforms for air (at left) and $N_2$-$CO_2$ mixtures (right). Once the set points were reached, the discharge parameters remained constant. Numerical values for the specific conditions are given in the table below.

| | SETPOINTS | | | | MEASURED | | | CALCULATED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MFC (SLPM) | *I* (A) | | | *V* (V) | | | *P* (kW) | | | *W* (eV/molecule) | | |
| Air | 100 | 100 | 150 | | 444 | 429 | | 44 | 64 | | 6.19 | 8.98 | |
| | 200 | 100 | 200 | 300 | 548 | 554 | 555 | 55 | 111 | 167 | 3.82 | 7.73 | 11.61 |
| | 400 | 100 | 200 | 300 | 655 | 685 | 724 | 66 | 137 | 217 | 2.28 | 4.78 | 7.57 |
| | 550 | 100 | 200 | 300 | 749 | 746 | 780 | 75 | 149 | 234 | 1.90 | 3.78 | 5.94 |
| CO2 | 76 | 100 | 150 | | 440 | 417 | | 44 | 63 | | 8.08 | 11.48 | |
| | 152 | 100 | 200 | 300 | 525 | 523 | 520 | 53 | 105 | 156 | 4.82 | 9.60 | 14.32 |
| | 305 | 100 | 200 | 300 | 755 | 716 | 711 | 76 | 143 | 213 | 3.45 | 6.55 | 9.76 |
| | 419 | 100 | 200 | 300 | 882 | 810 | 813 | 88 | 162 | 244 | 2.94 | 5.39 | 8.12 |
| 1:1 | 324 | | 200 | | | 755 | | | 151 | | | 6.50 | |
| 1:2 | 347 | | 200 | | | 742 | | | 148 | | | 5.97 | |
| 1:3 | 361 | | 200 | | | 755 | | | 151 | | | 5.84 | |
| 1:4 | 370 | | 200 | | | 768 | | | 154 | | | 5.79 | |
| 1:5 | 377 | | 200 | | | 765 | | | 153 | | | 5.66 | |
| 97:3 | 272 | | 200 | | | 665 | | | 133 | | | 6.82 | |
| CO2 | 305 | | 200 | | | 725 | | | 145 | | | 6.63 | |

Table 2. Measured and calculated average parameters for all conditions tested during the quasi-steady-state operation of the arc discharge that occurred after the set point conditions had been achieved. The measured mass flows and currents were very close to the above set-point values.

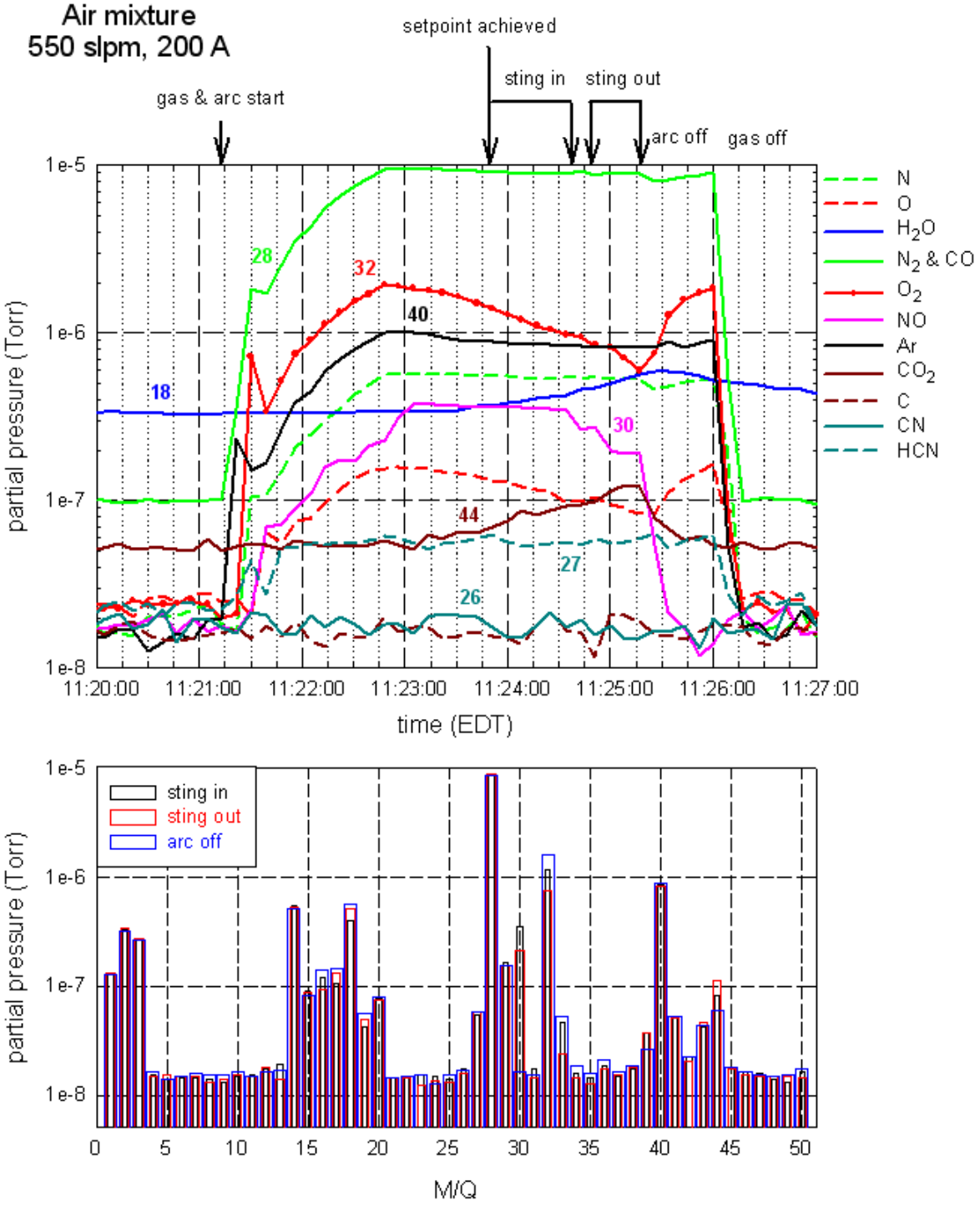


Figure 8. Data from measurements in air at 200 A arc current, 550 slpm flow. The top graph shows the time evolution of RGA signals from eleven selected species of interest. Notations at the top of the graph indicate several specific times of importance during the experimental sequence. The data points on the $O_2$ trace indicate times when complete spectra were taken; data points are omitted from the other traces for clarity. The bottom graph shows spectra averaged over the three main times of interest.

RGA data from one air arc are shown in Figure 8. For this case, it took ~2.5 minutes to start the arc and reach the set point with the sting in the flow. During this time, the gas mixtures and arc current were adjusted by the HYMETS operator from initial arc-starting values towards the desired operating conditions. Then the arc ran stably for ~45 seconds during which time we measured the RGA spectra 6 times. Next, the various stings were cycled in and out of the flow for ~10 seconds, followed by 30 seconds with no stings in the flow. Finally, the arc was extinguished and the gas continued to flow for ~40 seconds, after which the gas flow was terminated.

The RGA signals indicate species with specific mass-to-charge ratios (M/Q) inside the analyzer. The resolution of the instrument is such that there is some spill-over between adjacent values of M/Q. In many cases, M/Q values could indicate more than one species, and significant analysis is required to interpret the data. In addition, some species are formed inside the RGA and are not necessarily indicative of species being sampled.

For the purposes of the present analysis, there are three main periods of interest. First is the period with the sting-mounted silicon carbide disk in the flow (11:23:50 to 11:24:27 in Figure 8), second is the period with no sting in the flow (11:24:50 to 11:25:20), and third is the period of gas flow without the arc (11:25:20 to 11:26:00). Comparison of the first two conditions suggests the importance, or lack thereof, of the sting in the flow with respect to the RGA data. Comparison of the last two conditions enables identification of some species and some RGA effects, as follows.

For this air test, the RGA data showed no detectable signal at M/Q = 26 (e.g. CN) whereas there was a weak but significant signal at M/Q = 27 (e.g. HCN). However, close inspection shows that the latter signal tracked the shape of the $N_2$ signal very closely, and the "HCN" signal was present whether the arc was powered or not. Consequently, we conclude that, in this case, the "HCN" signal was really a leakage signal on the shoulder of the strong adjacent $N_2$ signal at M/Q = 28.

We note that there were signals for N and O, but they followed closely the shapes of the signals for $N_2$ and $O_2$, and these N and O signals did not depend on the presence of the arc. Consequently, we conclude that these N and O signals were species that were formed from $N_2$ and $O_2$ by dissociation inside the RGA and are not representative of free atomic N and O in the gas flow. This behavior is similar to that seen in measurements of lab air (Figure 3). If there was free N and O in the gas flow, then gas-phase or wall interactions probably eliminated them before they could reach the RGA detector.

Signals at M/Q = 28 could, in principle, be due to either $N_2$ or CO. We assume that, in this air test, this signal was entirely due to $N_2$ because (1) the N signal tracks the signal at M/Q = 28 both with and without the arc, and (2) there is no reason to expect CO to be present.

The curve that we attribute to NO (M/Q = 30) rose and fell with the arc, indicating a species generated by the arc. NO is known to be produced copiously in electrical discharges in air. It appears that more NO was generated with the sting in the flow than without the sting. The other species didn't seem to be affected significantly by the sting position. The curve for water

(M/Q = 18) had a slight rise during the arc, but there was no strong variation and, we conclude, no strong interaction with other species. Probably, the water signal was indicative of adsorbed water being released by the HYMETS structure due to heating during the arc, or a small water leak in the system. The water behavior is similar to that of $CO_2$, which was not being injected during this test. This suggests that there was a reservoir of $CO_2$ somewhere in the HYMETS chamber, or that there was slight $CO_2$ leakage through a supply valve. The $CO_2$ signal dropped more rapidly than the water signal when the arc terminated.

For this test, we note that the $O_2$ (and O) signals decreased steadily during the run, unlike the other species. We do not understand this effect.

Figure 9 shows similar data for the same current and mass flow for the $CO_2$ mixture. The top two curves show signals for $N_2$+CO (top curve) and $CO_2$ (second curve). Note that the two signals exchanged places when the arc was terminated but the gas continued to flow (after 3:31:15). Note also that the $O_2$ signal was present only during the arc. This behavior suggests that, during the arc, we were seeing depletion of $CO_2$ to form CO and $O_2$. Although signal amplitudes were not absolutely calibrated, it appears that approximately half of the injected $CO_2$ was converted to other species.

Note that the O signal, in contrast to the $O_2$ signal, increased when the arc was terminated. This probably is due to conversion of $CO_2$ inside the RGA itself rather than a result of something inside HYMETS.

We saw no detectable CN. As with the air data, the signal at M/Q = 27 does not appear to represent HCN, but rather indicates spill-over from the adjacent $N_2$ channel.

The foregoing two figures each represent one condition of the 11 conditions in the two test matrices for the two gas mixtures. The complete records for those test series are shown in Figure 10 and Figure 11.

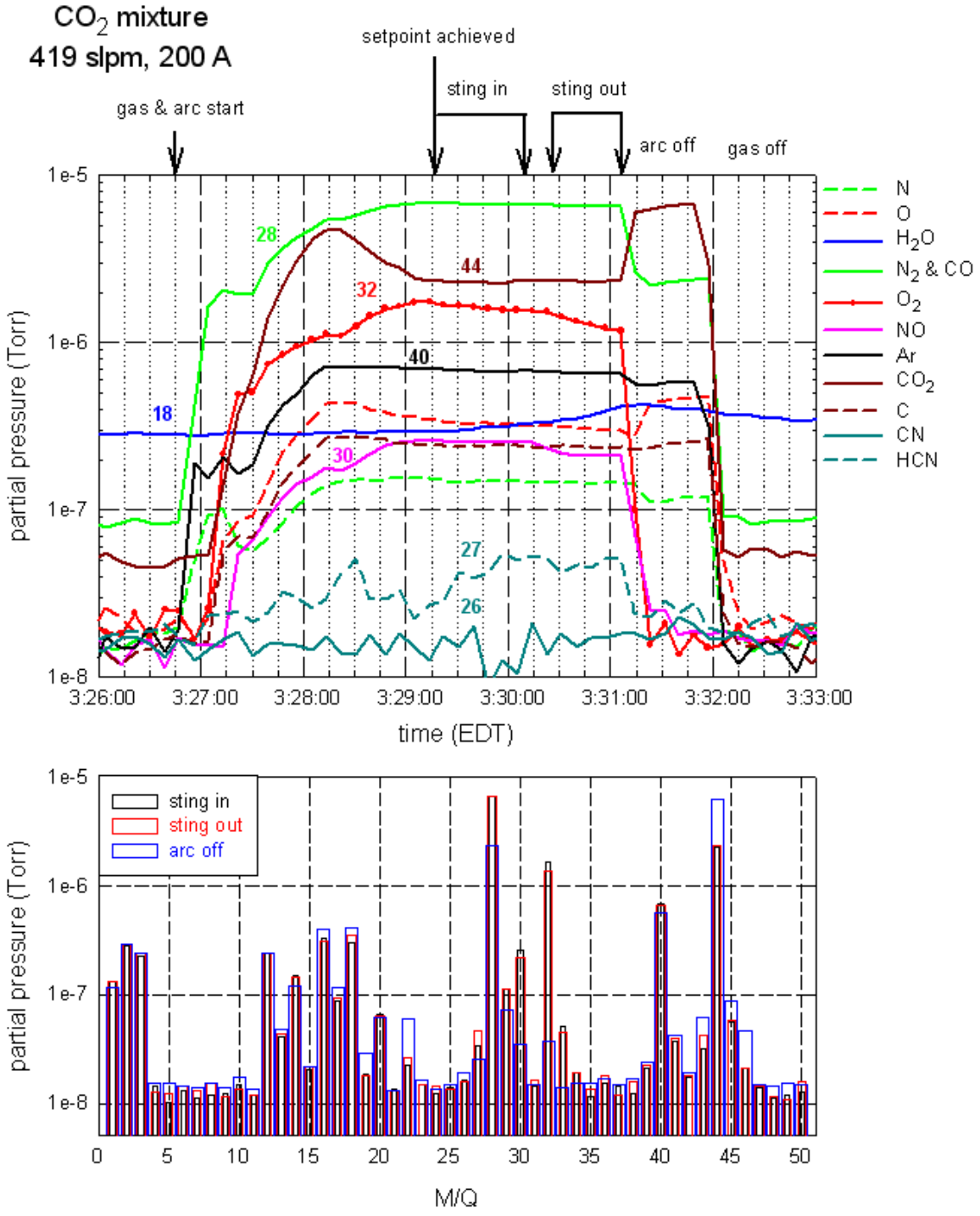


Figure 9. Data from measurements in the $CO_2$ mixture at 200 A arc current, 419 slpm flow. The graph shows the time evolution of RGA signals from eleven different species of interest. Notations at the top of the graph indicate several specific times of importance during the experimental sequence. The data points on the $O_2$ trace indicate times when complete spectra were taken; data points are omitted from the other traces for clarity.

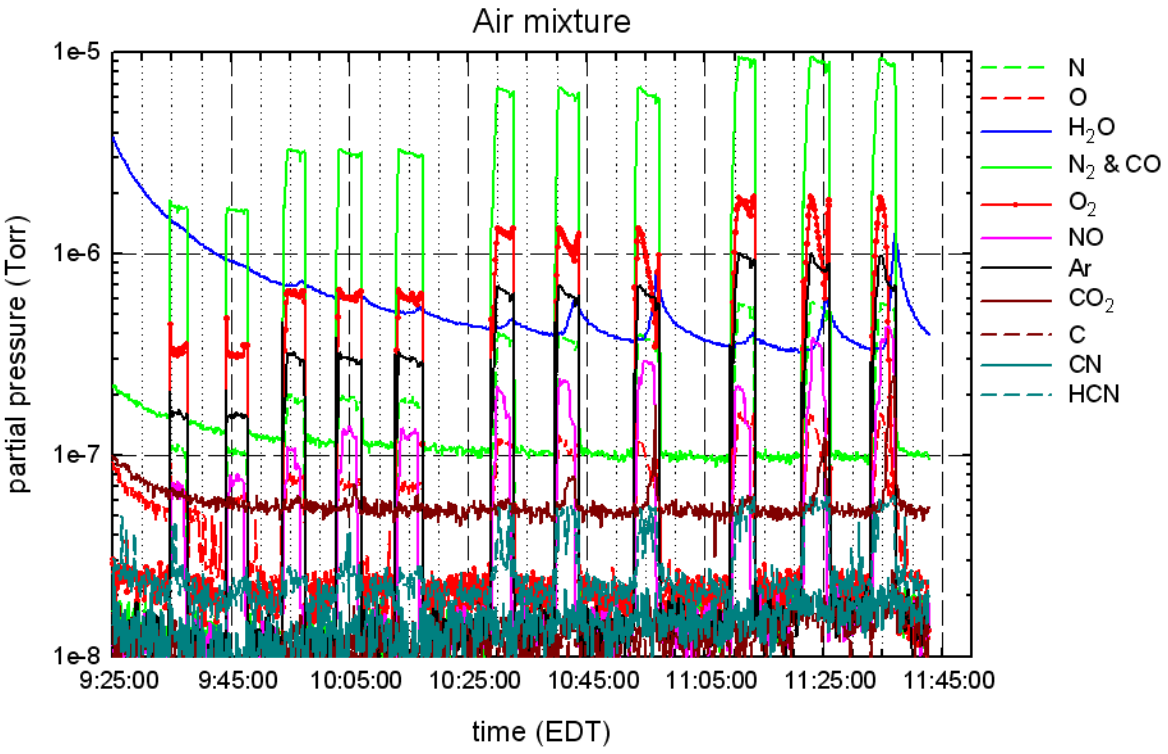


Figure 10. Complete data set for the air mixture. The test sequence consisted of 11 different combinations of gas flow and arc current, ranging from the initial low values of 100 slpm at 100 A to the final values of 550 slpm at 300 A. Between each condition there was a period of several minutes under vacuum while a bolometer was allowed to cool off.

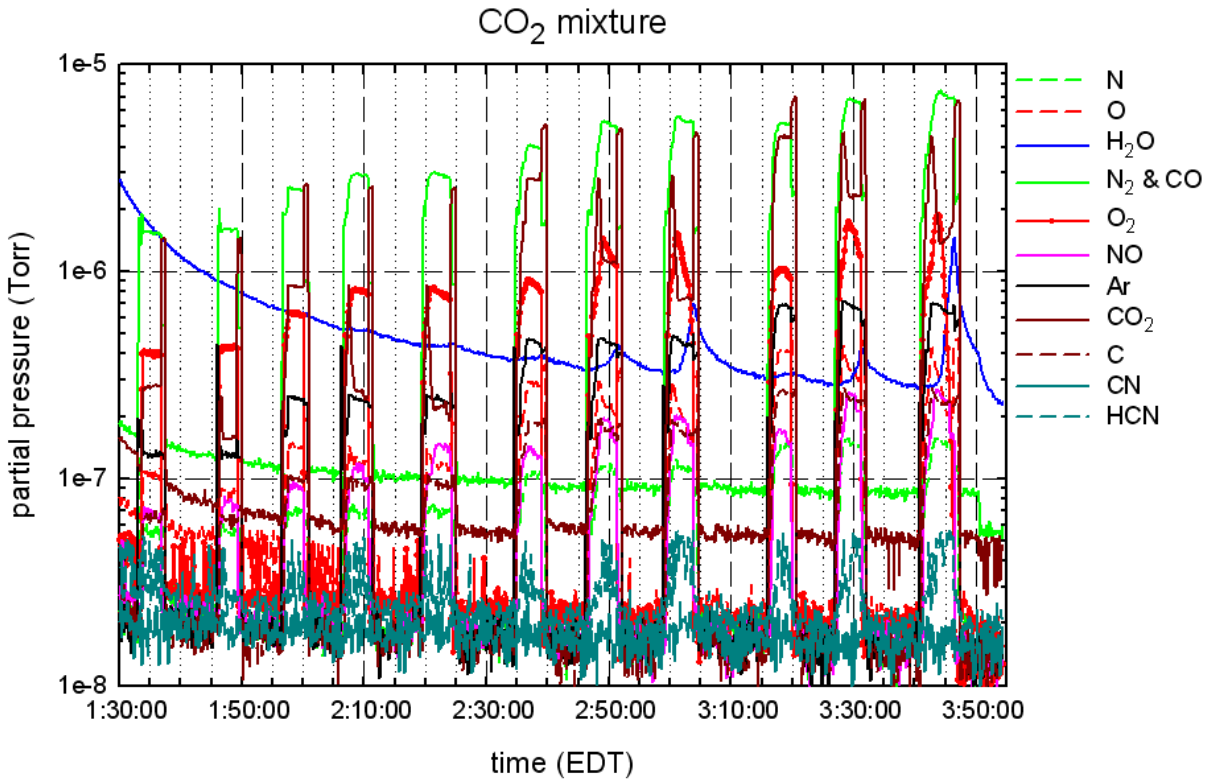


Figure 11. Complete data set for the $CO_2$ mixture. The test sequence consisted of 11 different combinations of gas flow and arc current, ranging from the initial low values of 76 slpm at 100 A to the final values of 419 slpm at 300 A. Between each condition there was a period of several minutes under vacuum while a bolometer was allowed to cool off.

The third set of test data covers the conditions requested by Johnson Space Center, as mentioned previously. Data from the case most closely representing the Martian atmosphere is shown in Figure 12.

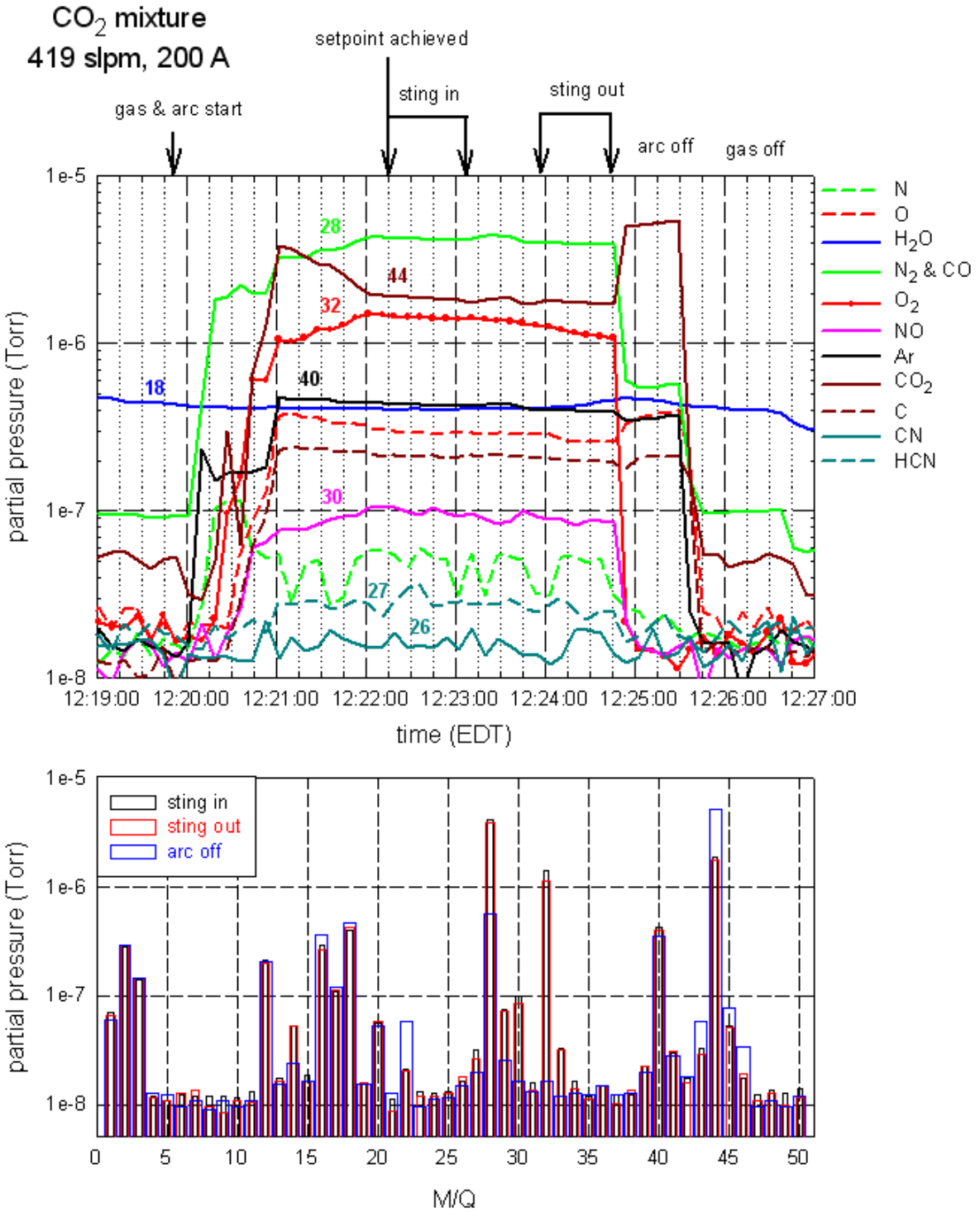


Figure 12. Data from the mixture most closely representing the Martian atmosphere. As with all the other cases, 5% of the flow was argon.

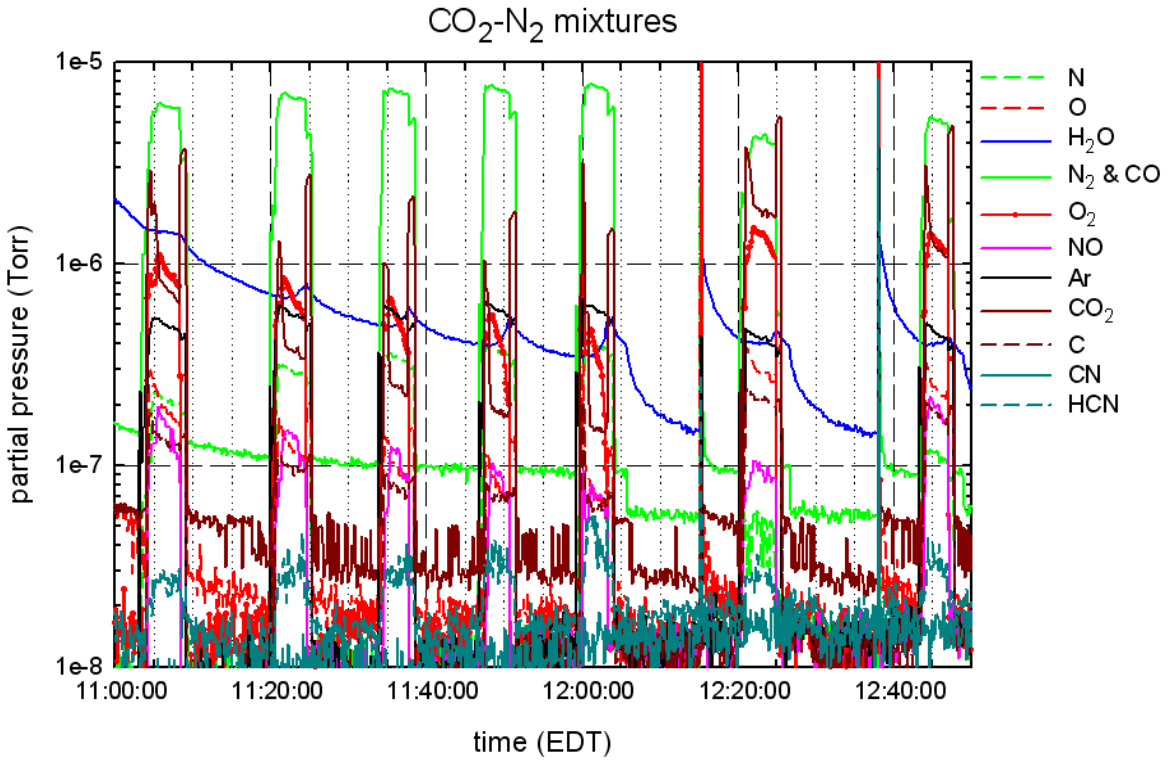


Figure 13. Complete data set for selected $CO_2$-$N_2$ mixtures. In time, they were 1:1, 1:2, 1:3, 1:4, 1:5, 97:3, and the standard $CO_2$ mixture with gas injection ports changes. Current was 200 A for all cases.

## 5. DISCUSSION

The experiment ran very smoothly. Packing and shipping of the RGA system from Albuquerque to Langley and back went without incident. Setup and operation went smoothly. There were no problems with the RGA system and data acquisition and no last-minute fixes were needed. HYMETS operation was excellent and the HYMETS staff was very supportive, flexible, and efficient. It was a delightful collaboration.

No signals were detected that can be attributed to CN or HCN.

Conversion of $CO_2$ to CO was substantial in some cases. For example, for the 97:3 $CO_2$-$N_2$ mixture (Figure 12), the signal at M/Q = 44 went from ~1.8e-6 Torr when the discharge was on to ~5.5e-6 Torr when the discharge was turned off. That suggests that, within the linearity of the detector, roughly 2/3 of the $CO_2$ (i.e. 3.7e-6 Torr) was converted to something else by the discharge, for this particular set of conditions. For the same case, the signal at M/Q = 28 went from ~4e-6 Torr to 0.55e-6 Torr when the discharge was turned off. Ignoring, for a moment, $N_2$ and ignoring the breakup of $CO_2$ in the RGA, this would account for a change of 3.5e-6 Torr in CO, in agreement with the change in $CO_2$. Since the $N_2$ was only ~3% of the $CO_2$, its contribution to signal at M/Q = 28 should have been very small. This indicates that most of the

signal at M/Q = 28 was due to $CO_2$ broken up in the RGA ionizer, which was about 10% of the $CO_2$ signal. With the discharge on, the M/Q = 28 signal should also contain ~10% of the $CO_2$ signal due to breakup in the ionizer, which would be negligible fraction of the total signal with the discharge on. This cursory type of analysis is suggestive. More detailed, structured analysis could be performed in the future for the range of species and conditions that we tested.

The material presented in this report is a sample of the available data in a few selected formats for selected conditions. If future work allows for detailed model validation, then additional graphs or other manipulations of any particular parameters that are needed for the validation will be prepared.

[1] Lennox Laser: http://www.lenoxlaser.com/index.php?dispatch=products.view&product_id=107

# DISTRIBUTION

10 Johnson Space Center
Attn: Chris Madden ES3/B13-129A
2101 NASA Parkway
Houston, TX 77058-3696

5 Scott Splinter
NASA Langley Research Center
8 West Taylor Street
MS 190
Hampton, VA 23681

2 Jeff Gragg
NASA Langley Research Center
8 West Taylor Street
MS 188D
Hampton, VA 23681

| | | | |
|---|---|---|---|
| 1 | MS 0825 | Jeffrey Payne | 1515 |
| 1 | MS 0825 | David Kuntz | 1515 |
| 1 | MS 0836 | Matt Hopkins | 1516 |
| 1 | MS 1086 | Bob Biefeld | 1126 |
| 1 | MS 1086 | Mike Coltrin | 1126 |
| 1 | MS 1423 | Greg Hebner | 1128 |
| 1 | MS 1423 | Ron Allman | 1128 |
| 1 | MS 1423 | Ed Barnat | 1128 |
| 5 | MS 1423 | Paul Miller | 1128 |
| 1 | MS0899 | Technical Library | 9536 (electronic copy) |

Sandia National Laboratories