**Gas Emission Measurements from the RD 180 Rocket
Engine Tests at the NASA Marshall Space Flight Center**

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Introduction

The Science Laboratory operated by GB Tech was tasked by the Environmental Office at the NASA Marshall Space Flight Center (MSFC) to collect rocket plume samples and to measure gaseous components and airborne particulates from the hot test firings of the Atlas III / RD 180 test article at the MSFC. This data will be used to validate plume prediction codes and to assess environmental air quality issues.

Background

NASA's Marshall Space Flight Center in Huntsville, Ala., was under a Space Act agreement with Lockheed Martin Astronautics of Denver to provide a series of test firings of the Atlas III propulsion system configured with a Russian designed RD-180 engine. The RD-180 is being evaluated for use in the evolved Atlas that will replace the current MA-5 engine class.

Plume samples were collected and analyzed for hot test firings 3 and 4 from the S1C test stand area on November 4 and December 16, 1998. Fourier Transform Infrared (FTIR) spectroscopy was used to measure carbon dioxide (CO_2), nitrogen oxides (NO_X), and sulfur dioxide (SO_2). A dual beam non-dispersive infrared (NDIR) process was used to provide concentrations of carbon monoxide (CO). Total hydrocarbon content (THC) was measured using a flame ionization method. All gas components were measured in the ppm range.

The EPA has set National Ambient Air Quality Standards (NAAQS's) for criteria pollutants that identify ambient concentrations necessary to protect human health and welfare from any known or anticipated adverse effects of a pollutant. Four criteria air pollutants relevant to the releases associated with RD 180 engine testing have NAAQS's. The pollutants include CO, NO2, SO2, and suspended particulate matter less than 10 microns in size (PM10) which are airborne particles that are so small in size that they can remain airborne and disperse as a gas. Airborne particles were also collected and analyzed and is discussed in Part II of this report.

The state of Alabama and the city of Huntsville have adopted the National Ambient Air Quality Standards (NAAQS's) for criteria pollutants.

Engine Description

Pratt & Whitney at West Palm Beach has joined with NPO Energomash of Russia to market and to develop the license technology for the RD-180 engine. The engines are powered with liquid oxygen / kerosene propellants that feature a LOX lead start and a staged combustion cycle that provide 860,400 lbs. of thrust at sea level.

The RD 180 is a total propulsion unit that has the following features:

- High-pressure turbopump assembly that exhibits a two stage fuel pump and a single stage oxygen pump

- Oxidizer rich preburner and an oxidizer start and shutdown modes,

- 2 thrust chambers with a chamber pressure of 3,734 psia

- 50 – 100 % continuous throttling

- Total system dry weight 11,675 lbs.

- Self contained hydraulic system powered by kerosene from the fuel pump

Facility Location & Description

MSFC is located on approximately 1,841acres and is surrounded by a large federally owned area consisting of the U.S. Army's, Redstone Arensal (RSA) and the Wheeler Wildlife Refuge. This area is a physical barrier between engine testing and the general public. Huntsville, Alabama borders on the east, north, and west; Madison on the west-northwest; and Decatur on the west-southwest.

Development of space propulsion systems has been the primary mission of the MSFC since its establishment in 1960. The U.S. Army has been developing and testing rocket engines at RSA soon after World War II.

RD 180 engine testing occurred at the Alternate Test Facility (AETF). The AETF is located in the southwest portion of MSFC and orientated to the west-southwest. This location places the AETF within the boundary of the Wheeler National Wildlife Refuge and is approximately 1000ft (305m) from the Wheeler Lake wetlands.

The AETF was constructed in 1964 for the static testing of the Saturn V engines. This facility has also been known as the Propulsion and Structural Test Facility, S-1C Stand, Saturn Test Stand, and Technology Test Bed. The stand was modified in 1974 to perform shuttle external tank structural tests and again in 1986 to accommodate Space Shuttle Main Engine (SSME) testing.

Sample Location and Collection

At some location downstream of the nozzle exit, the exhaust temperature will be quenched or reduced below the temperature necessary for sustained combustion. Discussions with Dr. T Wang at NASA/ MSFC indicated the exhaust emission levels would achieve stability at a distance of approximately of 300 feet from the nozzle exit plane. The temperature at the sampling assembly was monitored during both engine tests and is discussed in the Test & Environmental Conditions section.

A 20-foot sampling assembly was used to elevate the sampling cylinders. The sampling assembly was constructed from a 6 inch I beam steel column with a 5-foot horizitional platform welded to the top end. The platform was used for securing the sampling cylinders and thermocouples.

Samples were collected in stainless steel G1 cylinders with an internal volume of 2100 cu. inches. The Samplers were evacuated to less than 20 microns of Hg and were carried to the site approximately 8 hours before the test firing. The cylinders, thermocouples and electromagnetic valve cables were connected to test equipment and were fastened to the sampling assembly at ground level. After a final check was performed on all sampling hardware, a crane was used to lift and place the sampling assembly next to a 20-ton concrete block.

The concrete block was used to the secure the sampling assembly. Chains were placed around the lower section of the I beam column and were fastened around the anchor block. Thermocouple cables and the electromagnetic valve control wires were fastened down the I beam column. Data loggers were connected to the output of the thermocouple cables to record plume temperatures. Each data logger was placed in a double wall plastic bag and was secured to the back of the I beam column 2 feet below the top of the concrete block.
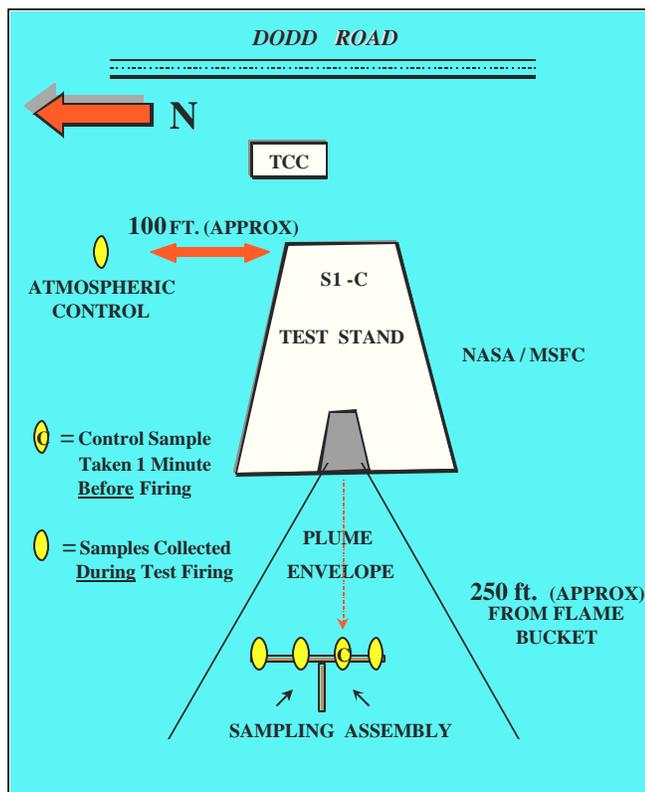

Sampling Assembly Installation
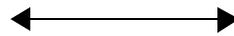
Sampling Assembly Installed and Secured for Engine Exhaust Collection

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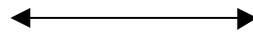
Sample Location Diagram

Sampling Features

- The plume control and sampling cylinders were elevated 20 feet at a distance of 250 feet west (downfield) from the flame bucket's exit or 300 feet aft of the nozzle exit plane.

- The plume sampling assembly (sample collection lines and the gas cylinders) was located 4 to 6 feet north from the center horizontal axis of the flame bucket.

- The atmospheric control sample was not placed in the plume envelope and was located approximately 100 feet north from the east boundary plane (front side) of the test stand at an approximate height of 10 feet. This control was used to determine if any background contaminants were present during engine testing (e.g. exhaust from diesel engines that pump water to the AETF deluge system).

- A 90 degree, ¼" x 3" stainless steel sample line was connected to the inlet port on each sampling cylinder through a two position electromagnetic valve. The atmospheric entrance of the sampling lines was pointed toward the flame bucket and was directed downward 90 degrees to minimize water intrusion. All sampling components are constructed from 304 stainless steel, except for the aluminum components of the electromagnetic valve.

- The plume samples and atmospheric control sample were collected over a test period starting at T+3 seconds. Sample collection was terminated at T+56 seconds. The plume control was collected

over a period of T minus 2 minutes through T minus 1 minute. Time events of the sample collection were controlled by actuating the electromagnetic valves on the sampling cylinders via the firing sequence program at the Test Control Center (TCC). When the valve is open the sample flows into the evacuated cylinder under its own atmospheric pressure.

- 3 Way, 2 Position, Electromagnetic Valves, Model - MV543 were used for collecting all samples. Operating Volts, 24VDC @ 1.33 Amps. When no voltage is applied to the sampling valve, the sampling configuration is closed. The closed configuration or "off" condition is the default setting for the sampling valves. Prior to T minus 2 minutes, all valves were in the default or closed configuration.

- The plume deflector on the AETF (S1-C) test stand has a J shaped configuration. The flame bucket boundary exit faces west-southwest and has a 15 degree-inclination.

Test & Environmental Conditions

Air temperature measurements were performed at the sampling assembly to assure that the exhaust gas temperature was quenched or reduced below the temperature necessary for sustaining combustion. At this point no further production of combustion products will occur. A temperature rise was noted for each test, but is within the normal living range. Approximately 50% of temperature increase is attributed to the activation of the water deluge system. This condition has been observed on previous tests when water was flowing at the maximum rate to the flame bucket, but was suddenly shut off or reduced due to unplanned test delays.

Water for the deluge is pumped to the test stands from above ground storage tanks at approximately 6 minutes before testing. NASA reported the water deluge system delivered 200,000 gallons of water per minute. The water exits the sides of the flame bucket through several hundred openings. Each opening has a diameter of 5/32" at a pressure of 160 psig. This configuration generates an enormous spray volume that blankets the flame bucket and surrounding area, including the sampling assembly.

To assure valid temperature measurements, two independent measurement systems were used. Each system consists of an Omega Model OM160 Data Logger, Model MOD-03/31 Signal Conditioner with a thermocouple probe, temperature range –40C to 110 C / -40F to 230 F. The thermocouple probes were fastened at the top of the sampling assembly adjacent to the inlet port of the sampling cylinders. A distance of 3 feet separated each thermocouple. The temperature recording session started 8 hours before the test and ended approximately 18 hours later. The recorded measurements were down loaded to a PC and are reported for each test firing. Temperature measurements for both systems agreed within 10%.

Test Firing 3

Prior to the engine test, the air temperature at the plume sampling cylinders was approximately 8 degrees C^0. The maximum temperature recorded was approximately 27 degrees C^0.

The firing occurred on November 4, 1998 at approximately 6:27PM. There was a heavy cloud ceiling at the time of the firing and it had been cloudy most of the day. Winds were out of the north – northwest at 5 mph.

Test Firing 4

Prior to the engine test, the air temperature at the sampling assembly was approximately 12 degrees C^0. The maximum plume temperature recorded during the firing was approximately 30 degrees C^0.

The firing occurred on December 16, 1998 at 5:47PM. The weather was clear with sunny skies for most of the day. Between 5:00 PM and 6:00 PM wind direction was variable (southwest to west southwest) due to an approaching weather front. Maximum wind speed was 10 mph.

Max. Air Temperature at the Sampling Assembly
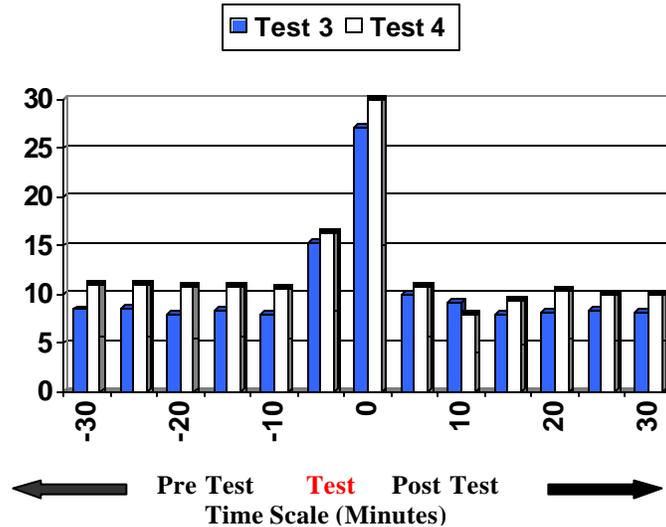
Engine Test Profile

The LOX/fuel mixture for both tests was 2.72. Maximum throttle run of 90% occurred on test 3 and lasted 26.55 seconds. The maximum throttle level for test 4 was 85%; this level was maintained for 12 seconds.

Sample Pressure Measurements

A Ruska Series 6200 Digital pressure gage (NASA ECN 036448) was used to measure the absolute pressure (psia) for all sampling cylinders. The Standards and Calibration laboratory at the NASA Stennis Space Center calibrated the gage. The gage is temperature compensated and has an accuracy of ±0.06 % full scale (50psia).

To collect the field samples, the sampling cylinders were evacuated in the laboratory to less than 20 microns of Hg and were carried to the sampling site. The vacuum level in the samplers was the only process used to draw in the ambient air samples. After all samples were collected, the samplers were removed from the sampling assembly and returned to the laboratory. Initial pressure measurements (P_s) were performed 48 to 72 hours later. This settling period allowed the samples to adjust to the laboratory environment and to achieve thermal equilibrium. Afterwards, research grade nitrogen (99.99995% purity / B6939) was added to the sample cylinders and final pressure readings (P_f) were performed to determine the volumetric expansion (dilution).

The addition of nitrogen provided a positive pressure to the samplers and diluted any elevated moisture levels that could potentially interfere with the analysis results. The final results for each analyzed component are based on the raw data analysis corrected for the volumetric addition of nitrogen

Total Hydrocarbon Analysis

A Rosemount 400A Hydrocarbon analyzer was used to measure the concentration of hydrocarbons expressed as methane. The analyzer is designed for monitoring atmospheric air for low level hydrocarbon contaminants and determining the hydrocarbon concentration of exhaust emissions from internal combustion engines.

Principle of Operation

The analyzer utilizes the flame ionization method of detection. The sensor is housed in a burner where a regulated flow of sample gas passes through a flame sustained by regulated flows of a fuel gas and air. Within

the flame, the hydrocarbon components of the sample stream undergo an ionization that produces electrons and positive ions. Polarized electrodes inside the burner collect these ions, causing current to flow through an electronic measuring circuit. The ionization current is proportional to the amount of carbon atoms that enter the burner, and is therefore a measure of the concentration of total hydrocarbons in the sample.

To ensure stable drift free operation, an internal temperature controller was used to maintain the analyzer interior at a constant 48 degrees C. This feature minimizes temperature dependent variations in electronic current measuring circuitry and adsorption / desorption equilibrium of background hydrocarbons within the internal flow system.

The analyzer is equipped with a mixed fuel mixture (40% hydrogen / 60% helium) to minimize any error introduced by oxygen synergism and for improving the equality of response to the various species of hydrocarbons.

Calibration

Calibration consists of setting two points, a zero point and a span (upscale) point.

A 4.9 ppm hydrocarbon gas standard (B6680 / AP) in nitrogen was used to span the analyzer. The calibration gas accuracy (± 2%) was certified by a specialty gas supplier and is NIST traceable. The total hydrocarbon (THC) value is expressed as methane. Hydrocarbon free air (B7784/ UC, THC <0.1 ppm) was used to adjust the background sensitivity (bias) of the analyzer. Thus with a hydrocarbon free gas flowing, the applied zero suppression compensates for the background current in the detector.

Quality Control

Zero and upscale calibration/verification checks were conducted both before (n=2) and after (n=4) each sample set in order to quantify calibration drift and measurement system bias. During these checks, the calibration gases were analyzed in the same manner as the plume samples. The maximum calibration drift of the span gas measurements was 2.04%. The zero bias remained unchanged.

Long term instrument precision error based on measuring a NIST traceable gas standard over a 3-month period with over 20 sampling points (n=20) is less than 2 sigma or 3 % of the actual reported value of the standard.

Analysis

The analysis results are listed in tables 1, 2 and 3.

Carbon Monoxide

Determination of carbon monoxide in the samples was performed using a Rosemount 880A Dual Beam Nondispersive Infrared Photometer.

Principle of Operation

The photometer uses a selective filter to pass infrared radiation within a narrow range that matches the vibrational energy of the CO molecule. This configuration reduces stray radiation and allows only CO

to be measured. While the absorption frequency depends on the molecular frequency, the absorption intensity is based on the amount of CO present. (See *Principle of Operation* in the "Other Targeted Emissions Section" for further discussion on the interaction of IR radiation with matter).

Calibration

Calibration consists of setting two points, a zero point and a span (upscale) point.

An 84.7 ppm CO gas standard (B6294) in nitrogen was used to span the analyzer. The supplier's reported accuracy for the NIST traceable standard is 2%. CO free nitrogen was used to adjust the background sensitivity (bias) of the analyzer. Thus with a CO free gas flowing, the applied zero suppression compensates for the background bias in the measurement system.

Analysis

The analysis results are listed in tables 1, 2 and 3.

Quality Control

Multipoint calibration error checks were conducted before and after sample testing by introducing 4 different calibration gases directly into the analyzer and recording responses. The maximum error was less than 3%.

Other Targeted Emissions

Other targeted gasses were analyzed using a Bio Rad FTS-40 Fourier Transform Infrared Spectrometer using a multiple reflection gas cell with an optical path of 7.2 meters. Gasses measured were carbon dioxide, (CO_2), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2).

Principle of Operation

IR spectroscopy relies on the fact that all molecules except those with a homogeneous diatomic molecular structure (e.g. O_2, N_2, H_2...etc.) and inert gasses (Ar, He, Ne...etc.) will react and absorb infrared radiation in a characteristic manner. The absorption causes changes in the molecular rotation and vibration. The pattern of absorption is determined by the physical properties of the molecule such as the number and type of atoms, the bond angles and bond strengths. This means that each component spectrum differs from all others and may be considered the molecular signature. By measuring and recording absorption strength as a function of wavelength over the infrared spectral region, the molecules present in the sample can be identified and quantified.

In IR spectroscopy as applied here, two energy spectra have to be recorded, the spectrum of the measurement system without a sample (I_0 or background) and the spectrum of the gas cell containing the sample (I). For the quantitative analyses the absorbance spectrum $A_i(v)$

$$A_i(v) = \log (I_0(v)/(I(v))) = a_i(v) \cdot b \cdot c \qquad \textbf{(1)}$$

is calculated with $a_i(v)$ absorptivity of component i at wavenumber v; b sample path length; c_i concentration (partial pressure) of component i; v wavenumber in cm^{-1}.

Equation 1 is known as Beer's law. Beer's law strictly holds only for isolated molecules, interacting with the radiation. This requirement is best met with gases at low partial pressures diluted in an nonabsorbing (inert) buffer (e.g. ppm concentrations of components in air mixed with nitrogen, as was done in this analysis.

Absorptivity is measured by preparing or using calibration standards of components at known concentrations and measuring the spectra against a reference (background) gas that does not contain the components of interest. These calibration spectra are then used in the sampling analysis: (1) The compounds are detected by matching sample absorbance bands with the bands in the calibration - standard spectra and (2) concentrations are measured by comparing sample band intensities with the calibration intensity levels.

Data Collection

FTIR data collection was set for 4000-650 wavenumbers (cm^{-1}), 16 co-added scans, $1 cm^{-1}$ resolution and a gain of 1.5 for the deuterated triglycine sulfate (DTGS) detector. Data was collected and stored as single beam spectra.

<u>Sampling</u>

Samples and standard gasses were measured in a Model 6 IR absorption cell manufactured by Infrared Analysis Inc. The cell has an internal volume of 530 cc and is equipped with two stainless steel valves with a flow-through tube to allow monitoring of flowing samples. The IR beam is reflected within the gas cell by the three spherical mirrors, which gives multiple passing in increments of 4 passes. The 7.2-meter optical path was obtained by 48 passes with a base path of 0.15meters.The cell was set in the FTIR sample compartment; the compartment was sealed from the atmosphere by using a magnetized rubber gasket.

Samples and calibration gasses were continuously drawn through the inlet of the gas cell and vented to the atmosphere. The sampling flow rate was ~ 500cc/min; the cell was purged with a minimum of 10 cell volumes of the calibration or sample gas before any spectral measurements were acquired. In between each sample and calibration run, the gas cell was purged with at least 5 cell volumes of nitrogen gas.

Carbon Dioxide

<u>Calibration</u>

A comparison between the sample spectrum to research grade nitrogen (B6939) was performed to differentiate the relative spectral contribution from CO_2. Four calibration standards were used to bracket the concentration range of the samples. In addition, a 425 ppm CO_2 calibration gas standard (B6294 / MG) prepared by a specialty gas supplier was also used. The gas standard is a NIST traceable gravimetric standard and has a reported accuracy of 2%.

A multicomponent calibration gas mixture (1920 ppm CO_2, 192 ppm NO_2 and 96.4 ppm SO_2) in air (B7009) was used to prepare three calibration standards. The lower concentrations were obtained by diluting the calibration gas with research grade nitrogen (B6939). Measuring the absolute pressures with a digital pressure gage before and after the dilutions were made, the concentration values for the prepared standards were derived. The primary gas (NIST traceable) standard was certified by the vendor and has a reported accuracy of 2%. Linear regression files were constructed that included reference spectra representing the CO_2 standards. The correlation coefficient (r) for the calibration regression line is 0.99936.

<u>Analysis</u>

The analysis results are listed in tables 1, 2 and 3.

Nitrogen dioxide and sulfur dioxide represent integrated samples that must be seen through water interference bands. Moisture possesses a feature rich and complicated infrared spectrum; the major moisture bands occur in two regions 4000-3400 cm^{-1} and 2000-1300 cm^{-1}. Nitrogen dioxide shows two strong spectral regions near 1600 cm^{-1}. Sulfur dioxide is centered at 1360cm^{-1}.

Because of the strong interference from water vapor, a subtractive technique was employed to reconcile the sample spectrum for NO_2 and SO_2. Screening tests were performed to make reasonable assumptions about the moisture absorption in the samples. Absorbance bands near 3700cm^{-1} were measured to determine the moisture absorption level. Several trial and error steps were attempted to prepare a suitable background by mixing humidified nitrogen in dry nitrogen. The goal was to develop a background (reference) that would subtract 80 to 95% of the moisture bands from all of the samples. This range is optimal for seeing through the water bands without over subtraction. Complete or over subtraction of the spectrum can introduce spectral artifacts (e.g. introduction of noise, spike lines, etc.) and degrade spectral features (i.e., band shapes). The trade off is between sensitivity and risk of measuring a residual feature.

After the moisture background is removed, the sample absorbance spectra are compared with the calibration spectra that were acquired with a dry nitrogen background. This process is similar in nature with the analytical method used to measure CO_2.

<u>Calibration</u>

A NIST traceable multicomponent calibration gas mixture (1920 ppm CO_2, 192 ppm NO_2 and 96.4 ppm SO_2) in air (B7009) was used to prepare four calibration standards. The lower concentrations were obtained by diluting the calibration gas with pure nitrogen. Linear regression files were constructed that included reference spectra representing the NO2 and SO2 standards. The correlation coefficients for NO2 and SO2 are 0.99610 and 0.99299 respectively.

<u>Quality Control</u>

Interference responses were assessed and compensated prior to testing.   The position and the slope of the spectral base line were monitored as successive spectra were collected. If the base line within a data set for a particular sample run began to deviate by more than 10%, a new background would be required. No deviations were encountered during the sample runs.

The time domain detector response (interferogram) for the spectrometer remained stable within 2 sigma or 10% over a 4-month period.

Table 1

Exhaust Summary Results					
Test #	THC	CO2	CO	NO2	SO2
3	1.8 ppm	1581 ppm	40 ppm	< 10 ppm	< 10 ppm
4	1.7 ppm	2097 ppm	48 ppm	< 10 ppm	< 10 ppm

Table 2

Plume Control Data					
Test #	THC	CO2	CO	NO2	SO2
3	1.1 ppm	409 ppm	< 1 ppm	< 10 ppm	< 10 ppm
4	1.9 ppm	410ppm	< 1 ppm	< 10 ppm	< 10 ppm

Table 3

Atmospheric Control Data					
Test #	THC	CO2	CO	NO2	SO2
3	1.0 ppm	429 ppm	< 1 ppm	< 10 ppm	< 10 ppm
4	1.9 ppm	401ppm	< 1 ppm	< 10 ppm	< 10 ppm