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Direct Mass Spectrometric Measurements in a Highly Expanded Rocket Exhaust Plume

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A cryogenically cooled (~20K) mass spectrometer probe was developed and utilized for sampling the major and minor species in the far field of a 1-lb$_f$-thrust liquid bipropellant (monomethylhydrazine/nitrogen peroxide) rocket engine exhaust plume. Carbon dioxide sorption pumping of the hydrogen in the exhaust plume was employed and shown to be adequate for maintaining a proper vacuum within the molecular-beam-type conical probe. Major species concentration measurements were of sufficient quality to permit limited quantitative interpretation and relative comparison of the individual mass peaks for various engine operating conditions. The small bipropellant thruster was determined to operate at far less than maximum efficiency, as was expected for a thruster of its size.

Introduction

THERE has been a continual need for a diagnostic technique that can be used to study chemical processes in the reacting flowfields of rocket engines. This need relates to such considerations as engine performance, radiation, gas dynamic interactions, and others. The parameters that most fully specify the chemical processes in flowfields, as well as in combustion chambers, are species densities (mole fractions), total temperature, and the rotational and vibrational temperatures of the constituents. Various diagnostic techniques individually or collectively qualify as potentially useful tools for measurement of these parameters. However, since it has been suggested[1] that minor constituents may play an important role in some of the observable effects relating to the characteristic performance of the total plume, an ultimately superior diagnostic method would be required to identify and measure species density with exceptional dynamic range. This requirement in particular makes mass spectrometry attractive. Under the initial sponsorship of the Defense Advanced Research Projects Agency (DARPA), the development of mass spectrometry for the study of exhaust plumes of rocket engines was undertaken. The effort included the unique application of real-time nondisturbed plume mass sampling.

In reality, the direct sampling mass spectrometer probe is merely a miniaturization of a molecular beam system which utilizes a quadrupole mass spectrometer as the detector. By immersing the probe in the exhaust plume of a rocket engine, a molecular beam of exhaust products is formed which is directed into the sampling volume of the mass spectrometer ion source. Consequently, ions are created, extracted, and directed through a mass discriminator and then onto a particle multiplier. The ultimate result is a set of measurable signals that are proportional to the number densities of molecules in the exhaust plume which (after ionization) possess particular charge mass ratios. The interpretation of the signals is dependent upon a reliable calibration, a knowledge of the additional daughter mass peaks created in the ion source (cracking patterns) from plume parent constituents, and the ability to maintain the very stringent vacuum conditions necessary to operate a molecular beam system.

To facilitate calibration, determination of cracking patterns, and establishment of pumping ability, the probe mass spectrometer system used in this investigation was evaluated in a variety of sonic orifice expansions of pure gases and mixtures prior to immersing the probe in a rocket exhaust plume. The free jets emanating from the sonic orifices permitted the sensitivity for a variety of suspected plume gases to be determined for several mass spectrometer operating conditions. In addition, the effects of ion source electron energy (cracking pattern) and the pumping limited operational regime of the probe were established. This provided the information necessary to properly position the probe in the exhaust plume of a rocket engine operating at a given thrust level. Due to availability and economy, a 1-lb$_f$ thruster, fueled with monomethylhydrazine (MMH) and nitrogen peroxide (N_2O_4), was employed for the rocket exhaust analysis.

Experimental Apparatus

Vacuum Chamber

The rocket plume studies were carried out in the AEDC 4- × 10-ft Research Vacuum Chamber (RVC), shown in Fig. 1. The chamber is cryogenically pumped by gaseous helium, liquid nitrogen, and liquid helium surfaces. Since hydrogen is

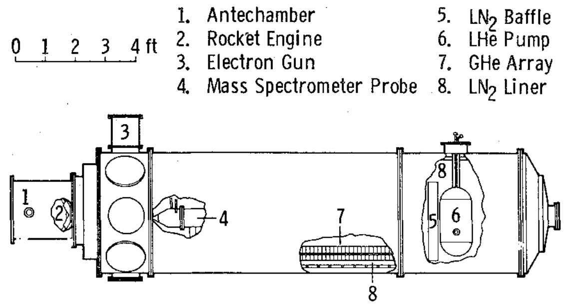

Fig. 1 Schematic of 4- × 10-ft research vacuum chamber and rocket configuration.

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a significant plume constituent for a typical liquid-amine-fueled engine, and since only an LN_2 baffled 10-in. oil diffusion pump was available on the chamber for removing noncondensables, a 37-liter-capacity liquid helium pump was installed in the chamber as shown in Fig. 1. The liquid helium for operating the pump was supplied from a portable 500-liter dewar through a short (6 ft) high-efficiency cryogenic transfer line. To keep the heat loads at a minimum, the liquid helium pump was completely surrounded by LN_2-cooled panels, including a chevron baffle immediately upstream to insure that plume gases would be accommodated to a maximum of 77 K before depositing on the LHe pump wall. Pressures from atmospheric to high vacuum were measured by thermocouple gages, Alphatrons,® and ionization gages. The ultimate chamber vacuum was approximately 1×10^{-7} Torr.

An antechamber which contained the rocket engine was employed to permit work on the engine while the chamber remained at test conditions. This eliminated the need for heating the propellant and the cooling-water feed lines.

A permanent diagnostic system for the 4- × 10-ft RVC is the electron gun shown in Fig. 1. This permits electron beam fluorescence measurements to be conducted for any installed test article, and hence, a measurement of flowfield number density and temperature made if the particular gas electron beam cross sections are known.

Mass Spectrometer Probe

The gaseous-helium-cooled probe, Fig. 2, which housed the mass spectrometer was fabricated from stainless steel in two separate sections. The face of the probe was conical, with a cone half-angle of 30 deg. A 15-deg half-angle thin-walled nickel skimmer was soldered to the stainless steel conical section. The skimmer was fabricated by electroplating nickel onto an aluminum pattern until a desired thickness was obtained. The aluminum pattern was then removed by dissolving it in a sodium hydroxide solution. A 0.020-in.-diam orifice was formed at the apex of the conical nickel shell by eloxing. At a position far enough from the orifice to avert degradation of the molecular beam, a nichrome wire was attached to the inner wall of the skimmer with Sauereisen® cement. The nichrome wire served as a 10 W heater for heating the conduction-cooled skimmer to prevent pumping of exhaust gases or internally injected CO_2. This inhibited clogging and reduction of probe mass flux and signal with time. The forward section was cooled by circulating GHe through its concentric cylindrical walls. The aft section was not cooled and contained the electrical feed-throughs, CO_2 injection port, pumpout port with remotely controlled solenoid valve, and an ionization gage.

The mass spectrometer system employed in the probe included an EAI® circular rod quadrupole mass filter, a close-coupled preamplifier with high-frequency response, an RF power supply and associated electronics, and an Extranuclear Laboratories® ionizer assembly and paraxial electron multiplier system. The entire assembly was mounted to the uncooled section probe wall with the ionizer and filter (quadrupole) sections extending into the cooled probe section (Fig. 2).

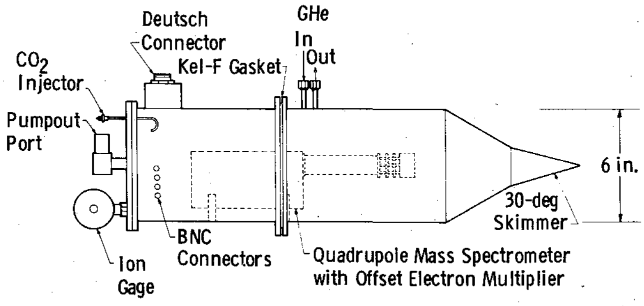

Fig. 2 Schematic of conical probe.

Basic operation of the system consists of the molecular beam plume sample entering on the geometrical axis of the mass spectrometer and being directed into the ionizer. While in the ionizing region the beam passes along the axis of a cylindrical grid which accelerates electrons, from four filaments which form a square surrounding the grid, toward the axis. Very high emission currents are possible from such an arrangement. The emitted electrons traverse a diameter of the cylindrical grid region and interact with the neutral beam sample, generating a certain level of ionization. The ions thus formed are extracted and focused by an ion lens assembly prior to entry into the quadrupole mass filter section, which can be tuned to the mass number of interest. The ions which pass completely through the quadrupole section are extracted by the negative potential of the first dynode of the 17-stage high-gain copper-beryllium paraxial electron multiplier and give rise to the signal.

The probe had a small (⅛ in.) copper tube attached to the uncooled aft section end flange which served as a CO_2 injector for utilizing internal probe cyrosorption pumping. The injected CO_2 was pumped on the 12-20 K GHe-cooled section walls and provided a means for removing the hydrogen in the rocket exhaust plume by absorbing it into the pores of the CO_2 frost.[2,3] A Veeco® ionization gage was also mounted on the aft flange and served a threefold purpose: it permitted the probe pressure to be monitored during operation; it allowed the CO_2 deposition rate to be determined; and, in the case of sudden pressure rises which could damage the mass spectrometer system, it automatically shut down the RF and particle multiplier high voltages.

Also connected to the end flange was a ¾ in.-o.d. 2-in. long stainless steel tube with a remotely controlled solenoid-operated vacuum valve attached. This valve permitted the probe to be evacuated by the vacuum chamber at a high rate of speed. Otherwise, the 0.020-in.-diam. orifice would have functioned as a leak to the vacuum chamber whenever the probe reached a given pressure differential with the chamber.

Rocket Engine

The 1-lb_f thruster used in the rocket plume study was originally supplied by McDonnell-Douglas Aircraft Corporation for use on a NASA manned orbiting laboratory test which was conducted at AEDC. The bipropellant MMH/N_2O_4 thruster was designed to operate in both steady-state and subsecond-pulsed modes. The engine performance was previously documented by Marquardt Corporation personnel who found that the engine's combustion efficiency, 0.83, was lower than conventional bipropellant engines. A schematic of the 1-lb_f thrust engine is shown in Fig. 3. It consists of a single doublet, water-cooled injector head, high-response soft-seat solenoid propellant valves, and two 5-μ nominal filters upstream of each valve. The nozzle (40:1 contoured with 0.582-in.-diam exit) and combustion chamber were integral parts, machined from a single piece of molybdenum.

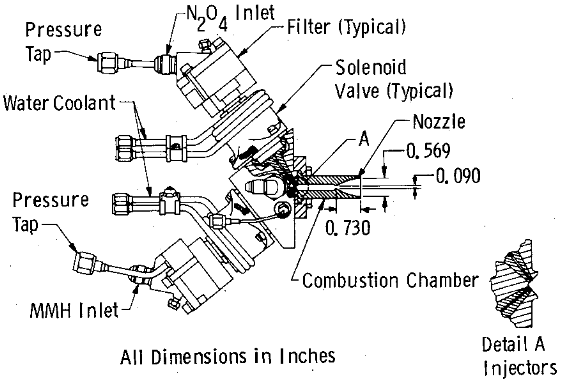

Fig. 3 One-pound thrust engine and valves.

The fuel, military-grade monomethylhydrazine, and the oxidizer, military-grade high-purity "green" nitrogen peroxide, were stored in 1-gal run tanks in separate consoles. Omniflow® stainless steel turbine flowmeters were used for both propellants. Sections of the propellant supply lines immediately adjacent to the engine were encased in a stainless steel shroud as shown in Fig. 1. As mentioned previously, this permitted access to the engine while the chamber was at test conditions.

The dry nitrogen (prepurified quality) pressurization system which was used to pressurize the propellant tanks and to purge the lines and engine was also utilized as a cold-gas calibrator for the mass spectrometer system for obtaining run-to-run and day-to-day sensitivity checks.

Data Acquisition Equipment

The following quantities were measured by the data acquisition systems: electron multiplier output current, mass spectrometer sweep control voltage, rocket engine combustion chamber pressure, propellant supply pressures and temperatures, vacuum chamber pressures, probe internal pressure, propellant flow rates, and rocket engine chamber wall and nozzle wall temperatures. The mass spectrometer outputs were recorded on a multichannel oscillograph. The mass spectra of the major and minor species of the exhaust plume were recorded on separate channels to permit each to be taken with a different gain setting.

The majority of the data was recorded on magnetic tape with the aid of a Digital Equipment Corporation PDP-8 minicomputer. In addition to on-line data acquisition, the PDP-8 served as the general control device, periodically sampling critical parameters and making a decision whether to terminate engine operation or to proceed with the sequence. A complete description of data acquisition and all other aspects of the research effort is presented in Ref. 4.

Experimental Procedure

Calibration

The greatest difficulty encountered in employing mass spectroscopy as a quantitative diagnostic tool is obtaining a reliable and consistent calibration for all gases which are of interest. When operating a mass spectrometer in a hostile environment, such as a rocket engine exhaust, the operating characteristics of the system tend to change unpredictably.[5] Therefore, the preferable method of extracting quantitative data from mass spectra is to calibrate the mass spectrometer for each gas of interest prior to each data run.

To further complicate data interpretation, the data necessary to distinguish between signals from parent molecules and from cracked daughter peaks of larger mass species must be obtained. These data are a function of the ion source electron energy. Although cracking pattern data are well established for magnetic-sector-type mass spectrometers,[6] limited quadrupole data for plume species can be found in the literature.

For calibration with particular gases, the probe was immersed in the flowfield of a sonic orifice expansion prior to each set of data runs. The analytical formulas from Ashkenas-Sherman[7] were used to calculate the number density in the expanding plume at the mass spectrometer sampling point. Thus, a calibration curve of mass spectrometer signal versus number density could be obtained for a range of stagnation pressures. Changes in run-to-run sensitivity of the mass spectrometer were taken into account by flowing nitrogen at a fixed pressure through the rocket engine immediately after each calibration and just prior to each engine firing. This permitted an adjustment to the measured signal during rocket firing by the relation

$$S_{\text{adjusted}} = (s_c/s_r)\, S_{\text{measured}}$$

where s_c and s_r represent the sensitivities at calibration and rocket firing, respectively. Pressure levels were maintained at low enough levels to avoid significant N_2 condensation.[8] Additional verification of calculated sonic orifice number densities used for calibration were obtained by utilizing electron beam fluorescence. The electron beam was located slightly upstream of the mass spectrometer probe so that $1/r^2$ extrapolation would be accurate.

Agreement between calculated and measured number densities in the low-pressure sonic orifice expansions was quite good (max. 6% difference) for both N_2 and H_2. A complete discussion and examples of sonic orifice measurements with an electron beam are given by Williams[9] and Lewis.[10]

The unavailability of most plume gases for use in calibration required that measurements for available gases be extrapolated to the others. Since the relative mass signal of a particular species is primarily a function of the ionization cross section by electron impact, previously published values[11] of the cross sections at 70 eV were used to extrapolate nitrogen number density calibration data for the particular species of interest. Previous experience had proven these values to be acceptable for the purposes of this investigation.

The parent mass signals were distinguished from daughters of other species by using the same source[11] for the dissociation coefficient. Acceptability was investigated by placing a nude quadrupole mass spectrometer in a small vacuum chamber and sampling several light hydrocarbons and conventional plume species. The cracked spectra determined in this manner compared favorably with the published values.

Determination of Operating Regimes

As the mass flux into the sampling probe is increased, a point is reached where the molecular beam being skimmed by the probe breaks down and a corresponding catastrophic signal reduction occurs. It was necessary to insure that this critical flux was not approached during engine firing. This was accomplished by moving the probe further downstream, away from the engine, and hence reducing the intercepted mass flux. It was also necessary that the probe remain within the Mach disk of the plume since the technique was based on free-jet sampling. The determination of the operating regime for the mass spectrometer probe was made by increasing the stagnation pressure of the sonic orifice flows used in calibration until molecular beam breakdown occurred. This condition was found to be consistent for nitrogen as long as the temperature of the probe cryogen was maintained at 18 K or below. The calculated mass flux at breakdown was then used to establish the minimum probe-to-engine separation distance, with the method of characteristics calculations used to determine the mass flux levels in the rocket engine exhaust plume. The maximum allowable probe-to-engine separation was dictated by the plume Mach disk location. Estimates for Mach disk location are obtainable using the Lewis-Carlson[12] empirical formula if the vacuum chamber pressure is known. An estimate of the vacuum chamber pressure during engine operation was obtained by flowing a room-temperature simulated plume mixture (20% H_2, 50% N_2, 30% CO) through a miniature stainless steel nozzle with the vacuum chamber at test conditions and recording the chamber pressure with an ionization gage. The resultant vacuum chamber pressure was used in the Lewis-Carlson approximation to estimate the Mach disk location without requiring engine operation.

Rocket Engine Operation

The 1-lb_f-thrust bipropellant rocket engine was not operated in a pulsed mode during this research effort. The steady-state operating times for the engine ranged from one second to several minutes. Fuel and oxidizer feed tanks were initially pressurized to give an optimum O/F ratio of 1.65, and a thrust of 1-lb_f. In subsequent runs the fuel tank pressure was varied to obtain data at various O/F ratios. Prior to each firing, trapped nitrogen was removed from the fuel lines to insure a smooth and continuous burn. Flowmeters were used to monitor the mass flow rates of both fuel and oxidizer. During engine operation, instrumentation output was recorded either continuously on the Visicorder oscillograph or every 30 ms in the PDP-8, including all the control voltages and currents for the various instruments.

Results and Discussion

Vacuum Chamber Performance

Probe mass sampling of the rocket engine exhaust was predicated upon sampling the exhaust in the first Mach cell of the free jet. Based on the simulated mixture experiments, a probe-to-engine separation distance of 35.82 in. (63 nozzle exit diameters) was chosen. To insure that the Mach disk would not interfere with the probe sampling required a maximum vacuum chamber pressure of less than 25 mTorr be maintained. The vacuum chamber pressure was measured with an Alphatron located behind the engine and partially open to directed backflow. Figure 4 presents a plot of the vacuum chamber pressure as a function of time for three successive runs. The pressures have not been corrected for gage factors. If the sample gas is nearly all hydrogen, then the indicated pressures must be multiplied by a gage factor of 5. Even with that assumption, the pressure is well below the 25 mTorr limit. The apparent improved behavior with each successive run in Fig. 4 can be attributed to the action of hydrogen on the Alphatron. It is expected that, in reality, each properly corrected pressure trace would be nearly the same as run 1.

The 37-liter-capacity liquid helium pump was continuously fed with liquid helium at a slow rate, and it was possible to conduct several minutes (approximately 90) of firing over a two-day test period while using one 500-liter dewar to supply the LHe.

Rocket Engine and Probe Performance

Probe Pumping

As previously noted, the use of a molecular-beam-forming mass spectrometer probe is feasible only if a proper skim can take place and if a molecular-beam-quality vacuum can be maintained within the probe. Since hydrogen was a major constituent in the bipropellant engine exhaust, and since a 12K surface would not cryopump hydrogen, a means of pumping the hydrogen in the probe had to be devised. It was known that CO_2 deposited on the surface at a temperature less than 20K will absorb H_2.[2] There was some question, however, whether the high-stagnation-temperature H_2 would pump well within the probe and whether or not the other plume gases would absorb into the frost and severely limit the hydrogen pumping capacity. A cursory experimental investigation[4] into the "poisoning" of the frost by light hydrocarbons revealed the problem to be negligible, since light hydrocarbon frosts also seemed to have an affinity for hydrogen. That fact, coupled with the small mass flux actually skimmed, permitted the use of CO_2 sorption pumping alone to pump the hydrogen background in the probe.

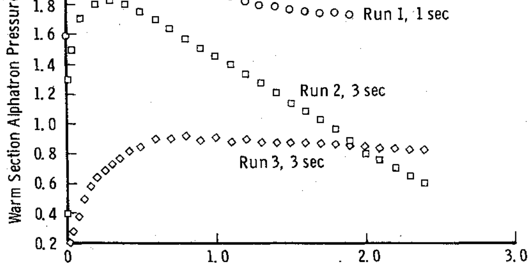

Fig. 4 Vacuum chamber pressure temporal behavior.

The mass spectrometer probe pressure was monitored during engine firings by a Veeco ionization gage installed on the probe rear plate. The only significant variables in the pressure variation for different engine firings were the firing time and the history of the internal CO_2 frost used for hydrogen pumping. Although additional CO_2 was usually deposited prior to each firing, the ability to pump the hydrogen degraded with each successive run. Typical behavior of the probe pressure during a sequence of firings is presented in Fig. 5. For each successive firing, the probe base pressure (before engine operation) is higher and so are the pressure levels throughout the firing. From previous mixture experiments, it was determined that data for probe pressures above 5×10^{-6} Torr were questionable with respect to hydrogen measurements, but were reasonably accurate for other species. It is therefore necessary to examine the probe pressure data before implying the significance of hydrogen number density measurements. Data do not appear throughout the entire 3 s of burn since the computer data gate terminated at 2.4 s into firing. Longer burns than 2.4 s were obtainable by increasing the data sampling interval to times greater than 30 ms.

Major Species

The quantitative measurement of major species in the exhaust plume was dependent upon calibrating the mass spectrometer for each gas of interest. A 0.013-in.-diam. sonic orifice was used to calibrate the mass spectrometer as previously described. A typical calibration for N_2 is shown in Fig. 6. The coordinate scale is given as the stagnation pressure of the room-temperature sonic orifice. Conversion to number density can be obtained easily by employing the far-field approximation for the ratio of static to stagnation number density, from Ref. 7:

$$\frac{n}{n_0} \cong \left[\frac{(\gamma-1)}{2} A^2 \right]^{-1/(\gamma-1)} \cdot \left(\frac{X}{D} \right)^{-2}$$

where (X/D) is the dimensionless downstream position, γ is the specific heat ratio, and A is a constant for a given γ (e.g., 3.65 for $\gamma = 1.40$).[7] The calibrations were employed whenever available; otherwise, the previously discussed extrapolations were utilized.

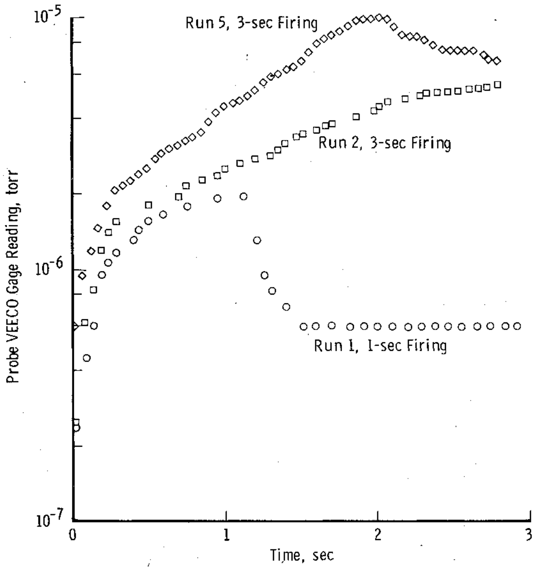

Fig. 5 Probe pressure during rocket firings.

Table 1 Theoretical plume composition – complete combustion

Component	Mole fraction	Molecular weight
H_2O	0.3343	18
N_2	0.3075	28
CO	0.1287	28
H_2	0.1576	2
CO_2	0.0401	44
OH	0.0111	17
H	0.0179	1
O_2	0.0007	32
NO	0.0013	30
O	0.0008	16

Table 2 Measured species concentrations (O/F = 1.62)

Component	Measured no. density, cm^{-3}	Mole fraction of major species
H_2O	2.97×10^{12}	0.153
N_2/CO	9.90×10^{12}	0.511
H_2	1.50×10^{12}	0.077
CO_2	1.63×10^{12}	0.084
OH	Trace	
H	1.27×10^{12}	0.066
O_2	7.59×10^{11}	0.039
NO	4.24×10^{10}	0.0022
O	6.95×10^{10}	0.0036

Table 3 Identified mass numbers in MMH/N_2O_4 exhaust

Specie	Mass no.	Specie	Mass no.
H^+	1	NO^+, CH_3NH^+	30
$H_2{}^+$	2	$NHNH_2{}^+$	31
He^+	4	$O_2{}^+$	32
C^+	12	U	35
CH^+	13	$[H_2O]_2^+$	36
N^+	14	U	37
$CH_3{}^+, NH^+$	15	$C_3H_2{}^+$	38
O^+, NH_2^+	16	$C_3H_3{}^+$	39
$NH_3{}^+, OH^+$	17	$CN_2{}^+$	40
H_2O^+	18	$CHN_2{}^+$	41
H_2O^+	19	$CH_2N_2{}^+$	42
U	20	$CH_3N_2{}^+$	43
$CO_2{}^{++}$	22	$CO_2{}^+, CH_3N_2H^+$	44
U	24	CH_3NHNH^+	45
CN^+	26	$NO_2{}^+, CH_3NHNH_2{}^+$	46
CNH^+	27	$C_4H_2{}^+$	50
$N_2{}^+, CO^+$	28	$C_4H_4{}^+$	52
$N_2{}^+, CO^+$	29	U	53

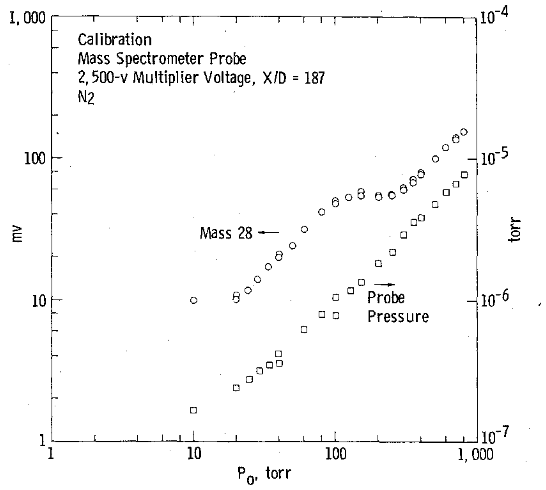

Fig. 6 Nitrogen calibration.

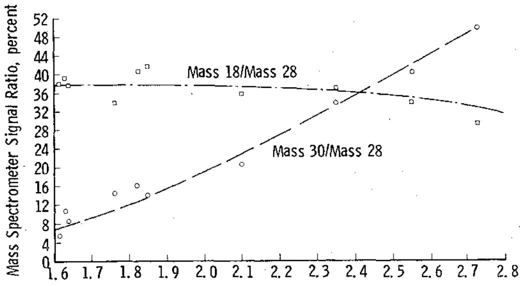

Fig. 7 Variation of species with O/F ratio.

The major species present in an equilibrium MMH/N_2O_4 exhaust plume were calculated using the Gordon-McBride computer program[13] for an O/F ratio of 1.60, with the assumption of frozen flow at the throat. These values are listed in Table 1. An absolute measurement of the constituency of the 1-lb_f-thrust engine exhaust was attempted with the mass spectrometer probe for several O/F ratios, including the engine design value of 1.60 and the stoichiometric value of 2.50. The O/F ratio was varied by controlling the fuel tank feed pressure, and thus, except for small flow-rate changes due to combustion chamber pressure fluctuations, the oxidizer flow rate was the same for all runs. Figure 7 represents the variation of signal from a combustion product, H_2O (mass 18), and an oxidizer product, NO (mass 30), as functions of O/F ratio. The signals are normalized with respect to the mass 28 signal for each run to minimize effects due to variations in spectrometer behavior. The mass 28 peak was chosen since combined nitrogen/carbon-monoxide densities were calculated to vary only a few percent over the O/F range investigated. Although significant scatter is evident, the combustion product signal tends to drop slightly with increasing O/F ratio while the oxidizer product increases significantly. The slight drop in mass 18 to mass 28 ratio at higher O/F ratios is due to the decrease in available fuel to support combustion. The mass 30 to mass 28 signal increases with O/F due to the increased amount of N_2O_4 available for cracking.

Table 2 presents the measured values of major species number densities at an O/F ratio of 1.62. Use of the mass spectrometer calibrations, measured cracking patterns, and tabulated ionization cross sections[11] were employed in the compilation of Table 2. A correction for nonlinear multiplier response was also included. A comparison of Table 2 and Table 1 reveals that the combustion was less than complete, since the measured H_2O concentration was much smaller than that for equilibrium (even if one were to consider equilibrium or nonequilibrium variations in the nozzle).

This supports the poor combustion efficiency (0.83) reported for the engine by the Marquardt Corporation, since the small H_2O concentration indicated less than the maximum enthalpic change had occurred. The water dimer signal was investigated to estimate nucleation effects upon the water concentration, but the signal levels were too low to explain significant water monomer depletion. In addition, the predicted water condensation onset point was twice the *X/D* value of the probe location in the plume, assuming the scaling laws used for Apollo[14,15] and other AEDC[16] studies are applicable. The electron beam system which was employed to assist in the calibration of the mass spectrometer probe was also used to measure water and hydrogen number densities in the plume. Extrapolated to the mass spectrometer axial location, the electron beam determined the plume number densities to be 5.23×10^{12} cm^{-3} for water and 2.02×10^{12} cm^{-3} for hydrogen. These values are slightly higher than the mass spectrometer values, but the ratios between the two species for both instruments basically agree. More precise mass spectrometer probe calibrations are necessary to obtain better quantitative data. Nonetheless, the major species data do indicate the ability of the probe to make quantitative major species measurements in a rocket exhaust plume.

Minor Species

In order to obtain minor species measurements it was necessary that the mass spectrometer gain be set much higher than what had been useful in making major species measurements. This resulted in losing some of the major species data for particular runs due to excessive signal levels. If necessary, this loss of data could be avoided through the use of a mass switching technique, but time for perfection of this technique was unavailable. Practically all mass numbers from mass 12 to 53 were resolved in the mass spectra when the mass spectrometer swept the mass range from 1 to 55 amu. This emphasizes the complicated spectra of such a rocket exhaust and the large dynamic range of the mass spectrometer. Table 3 presents a list of the principal ions identified in the spectra. Quantitative interpretation of the data was not attempted since calibrations were nonexistent and species cracking effects were so extensive. The identification of all peaks is difficult, but most unidentified peaks in Table 3 (designated by a U) can be attributed to cracked vacuum-pump oil present in the vacuum chamber. The helium listed was due to a small leak in the gaseous helium refrigeration system. It should be noted that the spectra is of sufficient quality to allow relative comparison of minor species for different operating conditions, although quantitative evaluation of an individual peak would be extremely difficult.

Summary and Conclusions

A conical cryogenically cooled mass spectrameter probe which utilized a molecular beam skimmer, CO_2 cryosorption pumping, and a quadrupole mass spectrometer was evaluated by directly sampling the exhaust plume of a 1-lb$_f$-thrust bipropellant (MMH/N_2O_4) rocket engine at a location 63 nozzle exit diameters downstream of the nozzle exit. The following concluding observations are made:

1) The probe-pumping system is capable of maintaining the high-vacuum conditions necessary for mass spectrometer operation.

2) Acceptable instrument response time and sensitivity are obtainable, the hostile environment not significantly affecting the mass spectrometer sensitivity.

3) Reasonable mass spectra of the rocket exhaust constituents can be obtained with quantitative measurement of major species.

4) Minor constituents can be determined by use of the probe with relative comparisons being possible in some instances. Quantitative measurement is not realistic with the present system.

The most serious hindrance to quantitative measurements with the present probe resulted from the lack of reliable and extensive calibrations. These data could be obtained, however, through the extensive use of sonic orifice calibration experiments similar to those discussed in this article. The major probe limitation was the inability to function in very high impact pressure regimes, such as would be present for a probe placed within a reasonable distance (dictated by test chamber size) of a large rocket engine. A correction for this shortcoming is obtainable through probe redesign to insure maximum coolant flow rates and increased pumping for the system.

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