H. J. Unger

Knowledge of the performance of rockets requires carefully documented research of their exhaust gases. This is being done, in a high-velocity wind tunnel developed at APL, by infrared spectroscopic analysis of the composition and temperature of gases flowing from a burning solid-propellant rocket. This method of testing under severe environmental conditions uses a specially modified spectrometer and associated recording equipment so ruggedly constructed and mounted as to maintain the requisite optical alignment.

Development of
INFRARED SPECTROMETER
for Rocket Gas Analysis

A high-velocity wind tunnel using a solid-propellant rocket as a source of gas was developed several years ago in the Fluid Mechanics Group of the Research Center by F. K. Hill and H. A. Wallskog. This type of rocket was used because it was a convenient source of high-temperature gas for studying the dynamics of high-speed gas flow through the supersonic portions of a nozzle. Associated with this effort has been a program to develop apparatus and a technique for determining rocket exhaust gas composition without disturbing the gas flow. The usual probe method is not satisfactory since, when a sampling probe is introduced into the stream, the temperature and pressure increase and new conditions exist, so that the sample actually taken does not have the same composition it had in the free stream. Of particular interest is to establish at what position in the nozzle the chemical reactions begin to lag behind the expansion process. Experimental departure from equilibrium theory can be expected at about 1500°K and 100 psia, i.e., very close to the throat of the nozzle for the present rockets.

Since three of the exhaust gas components (CO, CO_2, and H_2O) are active in the infrared region without serious overlapping of their bands, it was believed practical to use infrared spectroscopy to determine the gas composition; it was also hoped that temperature determinations could be made in this way. Rugged equipment that will withstand the vibration of the rocket has now been developed for this application, and some quantitative results have been obtained.

The Rocket

The rocket grain used is a double-base solid-propellant (cellulose nitrate dissolved in nitroglycerin) developed and proof-tested by the Allegany Ballistics Laboratory. The gases produced

during burning are typically those common to most high-impulse rockets, namely, CO, CO_2, H_2, N_2, and H_2O. (The absorption bands of a number of the oxides of nitrogen have been observed during and after the tests.) The combustion chamber pressure and temperature have been found to be approximately 1100 psi and 2500°K, respectively. With end-burning, a 25-lb charge lasts 10 sec and gives relatively constant flow conditions for 9 sec. The composition of the product gases is assumed to be governed at high temperatures and pressures by the water-gas reaction $CO + H_2O \rightleftharpoons CO_2 + H_2 + 9.6$ kcal.

Equipment Development

A diagram of the rocket gas generator (enclosing the solid propellant), the expansion nozzle, tunnel, and associated test equipment is shown in Fig. 1. The combustion chamber orifice, which is the throat of the nozzle, is 0.63 in. in diameter. The nozzle has a conical expansion up to 4 in. where the cylindrical test section is attached, followed by a converging-diverging diffuser. The nozzle is made of molybdenum and is water-cooled to minimize erosion and wall-temperature effects.

One of the chief obstacles to applying infrared spectrometer techniques to a study of rocket exhaust gases is the vibration set up when the rocket is in operation. The sound level in the test building reaches the order of 150 db, and the resulting vibrations are sufficient to shake the building and its foundations; any instru-

mentation must, therefore, be well shock-mounted. The test cell is constructed of reinforced concrete and is both fire- and fragment-proof. The side of the cell opposite the tunnel exhaust is open and the surrounding area is protected by an earthen parapet. The recording equipment is housed in a separate building for the safety of personnel and also for isolation from the vibration.

There is no commercial infrared spectrometer that is sufficiently rugged to operate in this environment. It was necessary, therefore, to modify considerably a conventional instrument, in this case a Perkin-Elmer Mod. 83 Monochromator, so that it could withstand the test conditions. A signal-to-noise ratio of 100 was deemed to be necessary. On each side of the tunnel is a massive table on tracks. On these tables are the light source, the collimating system, the light chopper, wavelength sweeping mechanism, and detector. The arrangement of the scanning spectrometer system and recording equipment is shown in Fig. 2. The instruments are now so ruggedly mounted that they can be transported and assembled in test position in a few minutes.

To make adequate optical and spectroscopic measurements in a nozzle, it is necessary to have observation ports of relatively constant transmission characteristics. The problem of "dirty" gas which blackens everything it reaches has been solved by recessing the window and flushing its inner surface with an inert gas such as nitrogen. If a sufficient gas flow is used to bal
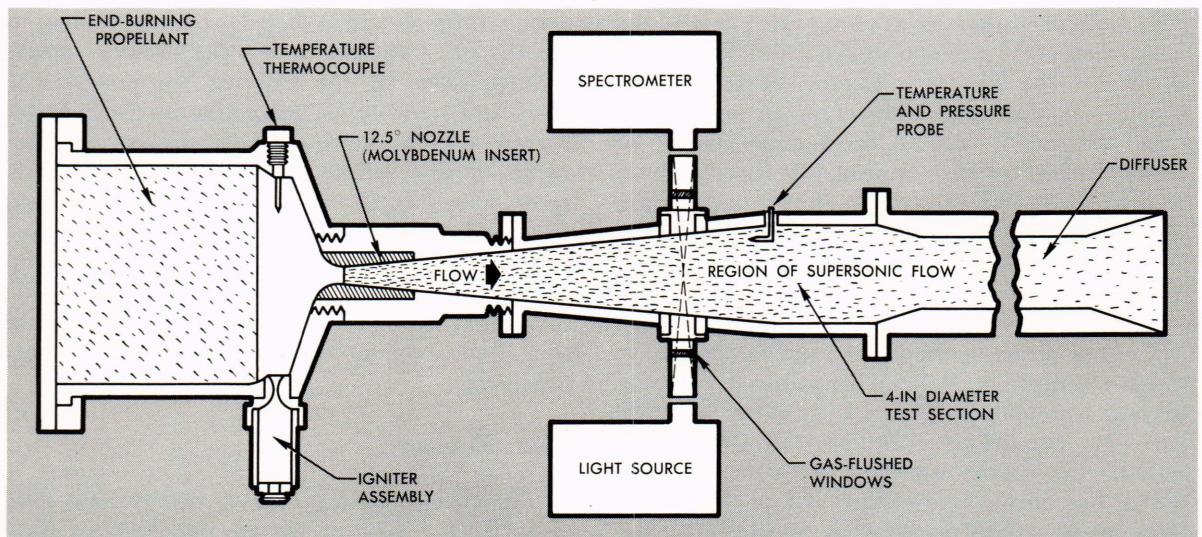

Fig. 1—Diagram of the high-temperature rocket tunnel showing arrangement of equipment for conducting spectroscopic analysis as well as for pressure and temperature measurements in the gas stream.
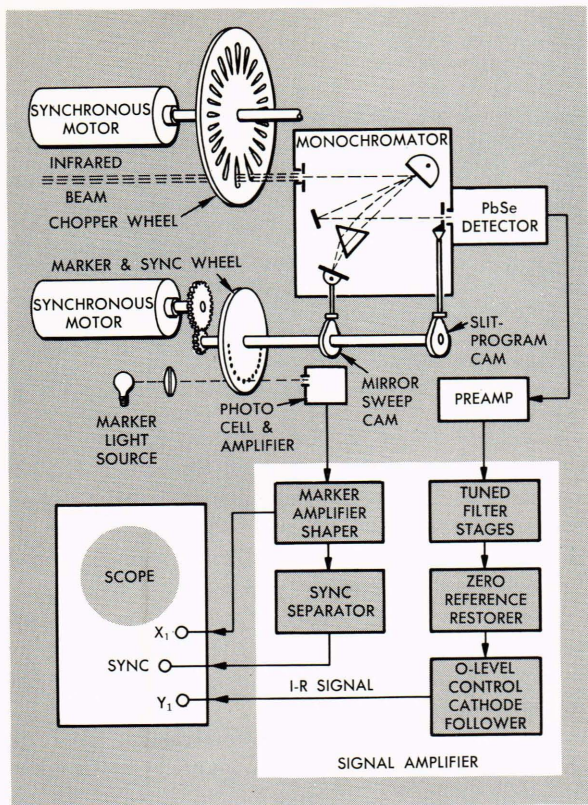
Fig. 2—Schematic diagram of the fast-scanning infrared spectrometer.

ance the nozzle pressure at the wall, no soot enters the side tube supporting the window. This flushing method has been so successful that optical windows of even such fragile, crystalline materials as rock salt and calcium fluoride have been used without damage, and twenty-five successive tests have been run in which the change in transmission factor of the cell windows was less than 1%.

The spectral region in the infrared in which CO, CO_2, and H_2O have fundamental vibration bands (at 4.25, 4.73, and 6.09μ, respectively) is suited to rapid scanning (0.7 sec per spectrum). Two high-speed detectors have been used successfully: lead selenide (PbSe) and gold-doped germanium (Au-Ge). At the liquid-nitrogen temperature (76°K) to which they are cooled, the time constant of the detectors is of the order of 10^{-6} sec. Therefore, high-speed light choppers may be used, and the advantages of AC amplifiers may be explored. Visual observations of the spectra are made on a 21-in. oscilloscope screen while recording is accomplished with a 5-in. oscilloscope and a 35-mm continuous-drive camera.
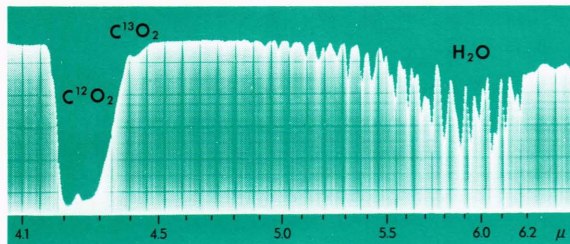

Fig. 3—Spectrogram of the atmospheric absorption in the 120-in. path of the spectrometer. Carbon 13 occurs in about 1.1% of atmospheric CO_2. Time sweep increases from right to left; total sweep time is 0.83 sec.

In order to obtain satisfactory analysis of the gases in the absorption cell, all of the light path in the spectrometer must be free from absorbing material. The spectrometer system is therefore enclosed in metal boxes and flushed with air that has been purified by passing it through activated alumina. This method removes all of the CO_2 and most of the H_2O. As a test of the potential sensitivity of this method of analyzing gases, atmospheric absorption over the entire light path of 120 in. was measured first; the results are indicated in Fig. 3. The nominal composition of the air by volume is 0.03% CO_2 and 1.8% H_2O at 50% relative humidity. In addition to showing the fundamental absorption bands of CO_2 and H_2O, this figure also shows the absorption due to the isotopic species CO_2. It is known that C^{13} occurs in 1.1% concentration in ordinary carbon, and the $C^{13}O_2$ bands should be very similar to those of $C^{12}O_2$ but shifted slightly to the long-wavelength side because of the mass difference; this shift may be observed on the spectrogram.

Results

In applying this spectrometric equipment to gases from rocket exhausts, satisfactory results have been obtained. In a typical run, Fig. 4, immediately upon ignition of the rocket it is
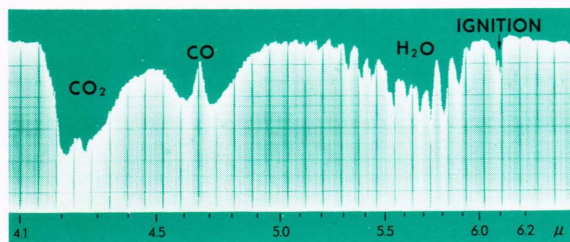

Fig. 4—Spectrogram of the first sweep of the spectrometer at ignition of the propellant.

TABLE I
INFRARED SPECTROMETER RUNS: CONDITIONS AND RESULTS
(Nozzle Angle—12.5°)

TEST NUMBER	STATION DIAMETER (in.)	MEASURED CHAMBER TEMPERATURE (°K)	MEASURED CHAMBER PRESSURE (psia)	STATIC NOZZLE PRESSURE (psia)	CALCULATED MACH NUMBER	TEMPERATURE (°K)		
						THEORETICAL	EXPERIMENTAL	
							T_{CO_2}	T_{CO}
148	2.37	2270	1050	8.22	3.64	918	917	950
150	1.86	2230	1110	14.82	3.29	1050	—	1050
154	2.37	2300	1065	7.95	3.64	918	910	—
156	1.35	2320	1100	37.50	2.68	1328	1345	1300

noticed that there is a transient phenomenon which lasts for approximately 0.01 sec and consists of a momentary decrease in transmission over the entire spectral region, sometimes followed by a short period of emission. This is caused by the luminosity of solid particles burning in the residual oxygen in the tunnel. After this transient, equilibrium is established quickly and the absorption bands for CO_2, CO, and H_2O appear as in Fig. 5, which was taken between 5 and 6 sec after ignition.
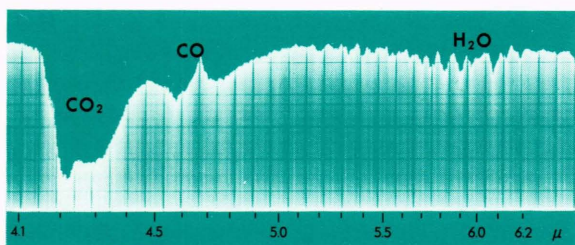

Fig. 5—Spectrogram of the seventh sweep after ignition. The 4.25 μsec CO_2 band is noticeably broadened from that in Fig. 3 owing to the high temperature (1350°K).

In making average gas temperature determinations by this method, use could be made of the separation between the maxima of the P and R branches of the CO_2 and CO absorption bands. In most of the spectrograms obtained thus far, the maxima of the branches appear to be "washed out" (as can be observed in Fig. 4) because of the presence of small amounts of N_2O and NO and some overlapping of bands caused by temperature broadening. However, in some of the spectrograms obtained most recently these branches are quite sharp and have led to the calculation of temperatures that agree reasonably well with the theoretical values. Table I summarizes the temperature calculations from the infrared data.

Several successive tests were made at most of the six stations used to date, and reproducible absorption data were obtained. The absorption path across the nozzle has been varied from 4.0 to 1.35 in. and the corresponding pressure varied from 1.8 to 38 psia. Since the percentage absorption at a particular wavelength is a function of the product of the path length and the density, it turns out that the absorption due to each gas or vapor increases as the stations advance toward the nozzle throat. The observed absorption data are consistent with this.

This exploratory work has shown that the "ruggedized" equipment developed and the techniques employed can be used satisfactorily in the severe environmental conditions present during operation of a rocket motor. The results obtained suggest that this equipment may be useful, when fully developed, in obtaining quantitative analysis and temperature determinations of exhaust gases from rocket propellants.