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A STUDY OF RADIATIVE PROPERTIES AND COMPOSITION OF THE TURBINE EXHAUST PRODUCTS IN THE F-1 ENGINE

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FOREWORD

This report was prepared in fulfillment of the requirements of Contract No. NASw-16, Task VII. The author wishes to thank the Bravo 2A test stand personnel for their cooperation during this program.

ABSTRACT

Measurements of the spectral radiance and absorption properties of the F-1 turbine exhaust are described. Also reported are the results of gas-particle sampling which determined the relative concentrations of the exhaust gases as well as the size distribution of the carbon particles in the turbine exhaust.

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INTRODUCTION AND SUMMARY

An important requirement in the design of space vehicles is the prediction of the thermal radiation from the rocket exhaust plume to the external vehicle components and principally to the vehicle boattail section. An overconservative estimate of this radiation results in overdesigned components at the expense of payload, cost, and simplicity, whereas a marginal estimate can result in abortion of the mission. Plume radiation may be determined experimentally by direct measurement, or theoretically, if temperature, pressure, and species distributions are known throughout the plume, and the spectral absorption coefficients of the species are known.

In the case of the F-1 engine, a theoretical analysis of the plume radiation is complicated by the fact that the turbine exhaust gases are discharged into the nozzle section of the thrust chamber. The turbine exhaust is cooler than the thrust chamber exhaust and is very rich in carbon, and therefore will absorb radiation from the hotter thrust chamber exhaust gases. Thus it is important to establish the radiative properties of the turbine exhaust products of the F-1 engine.

To accomplish this a spectral radiometer was utilized in an emission-absorption arrangement to provide radiative data in the 1 to 5.5 micron spectral range. In addition, samples of the turbine exhaust products were collected and analyzed to determine the concentration of the emitting species and the size distribution of the carbon particles.

The predominant emitting species in the turbine exhaust was found to be the solid carbon particles. The emission spectra of the exhaust products was a continuum and closely resembled that of an 800 degree kelvin blackbody. The carbon particles were found to have diameters smaller than

1000 Å with the peak of the size distribution being between 200 Å and 400 Å. The percentage of solid carbon in the exhaust duct sample was determined, and a particle number density was calculated. This percentage was considerably greater than that determined for samples collected from the exhausterator of an F-1 engine.

GAS-PARTICLE SAMPLING

APPARATUS AND PROCEDURE

The experimental measurements were made on Bravo 2A test stand at Rocketdyne's Santa Susana Field Laboratory, on which the F-1 turbo-pump system is tested. After passing through the turbine, the gas generator exhaust is discharged into a 23 inch diameter duct. Figure 1 shows the arrangement of the gas generator, turbine and exhaust duct. To perform the gas-particle sampling and spectroscopic measurements, a section of the exhaust duct was constructed which contained ports that allowed the insertion of a sampling probe and optical probes for viewing the exhaust radiation. A sampling probe was designed specifically to collect a gas-particle sample from this section of the duct.

The purpose of sampling the F-1 turbine exhaust products was to determine the relative concentration of the radiating species and the size distribution of the soot particles present. Therefore it was essential that an unbiased gas-particle sample be collected from the exhaust duct. In subsonic flow, which is the condition in the turbine exhaust duct, this can be accomplished only by isokinetic sampling; i.e., equal flow velocities in the proble entrance region and in the free stream. The sampling probe inlet was designed to achieve such flow under the conditions existing in the duct while withstanding the thermal and bending stresses resulting from the flowing gases.

Since the ratio of the free stream static pressure to the pressure in the sample container is initially greater than the critical value, sonic flow will be established in the probe. Isokinetic flow is accomplished

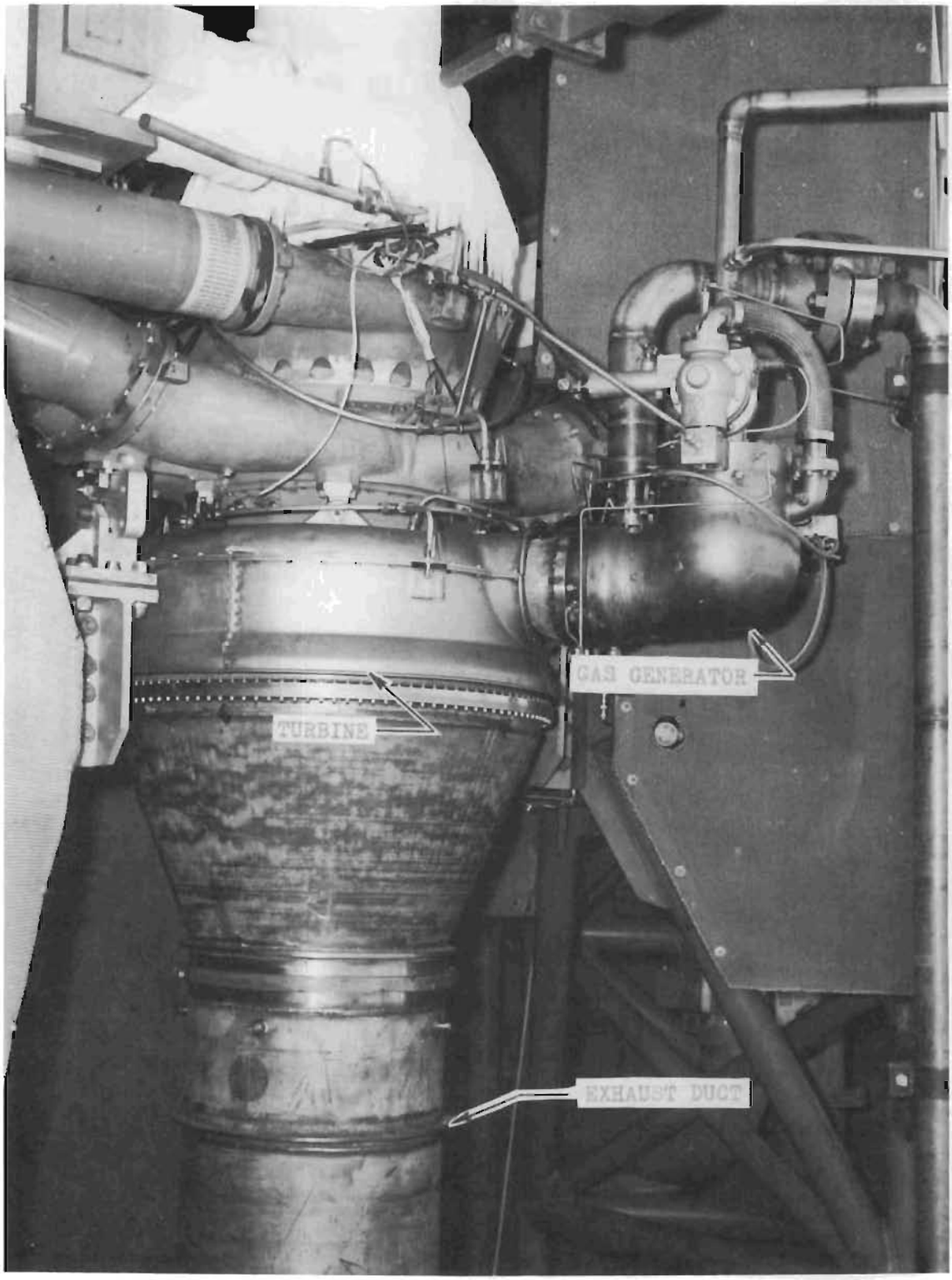

Figure 1. F-1 Turbopump and Gas Generator Installed on Test Stand

by incorporating a converging-diverging section at the probe inlet with properly chosen inlet and throat diameters. Once the flow is established at the beginning of the sampling period, constant conditions at the probe entrance will continue until the pressure in the sampling tank has reached very nearly the free stream total pressure. Thus extended periods of isokinetic sampling are available.

The cantilevered probe is fabricated of concentric tubes with the sample passing through the inner tube and cooling water between the inner and outer tubes. A drawing of the probe is shown in Figure 2.

Figure 3 is a diagram showing the experimental arrangement used for the collection of gas-particle samples. The sample probe was connected to a 12 liter sample tank through a 1/2-inch pneumatically actuated ball valve. The sample tank has been described in detail elsewhere (Ref. 1). A gaseous nitrogen purge was applied to the sample line during the test firing except for the time when the sample was being collected. The purge was turned off approximately one second before the sample valve was opened to allow time for the purge pressure in the line to decay. Prior to each test the sample tank was evacuated and filled with helium to a pressure slightly above one atmosphere. The small positive pressure inside the tank ensured that no air leaked into the tank between the time it was evacuated and the time the analysis was performed. Carbon particle samples were collected on three electron-microscope viewing grids suspended in the tank. For carbon particle size determination, sample times (i.e., the length of time the sample valve was open) of the order of 0.5 seconds were required to reduce agglomeration of particles on the grids. Since longer times were required to collect sufficient gas for analysis, the carbon particle and gas samples were collected on separate tests. Figure 4 is a photograph of the sample system installed on the test stand.

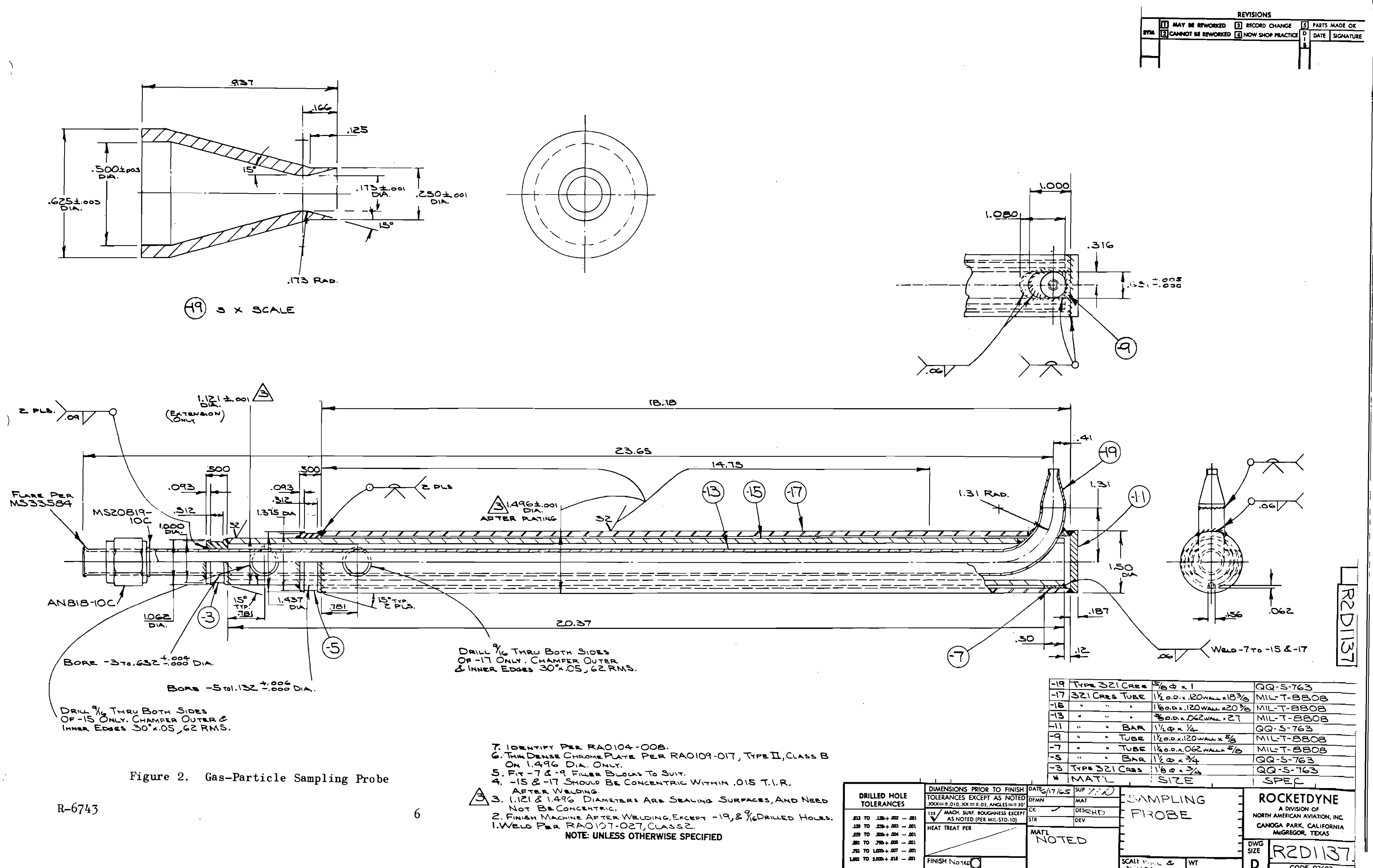

Figure 2. Gas-Particle Sampling Probe

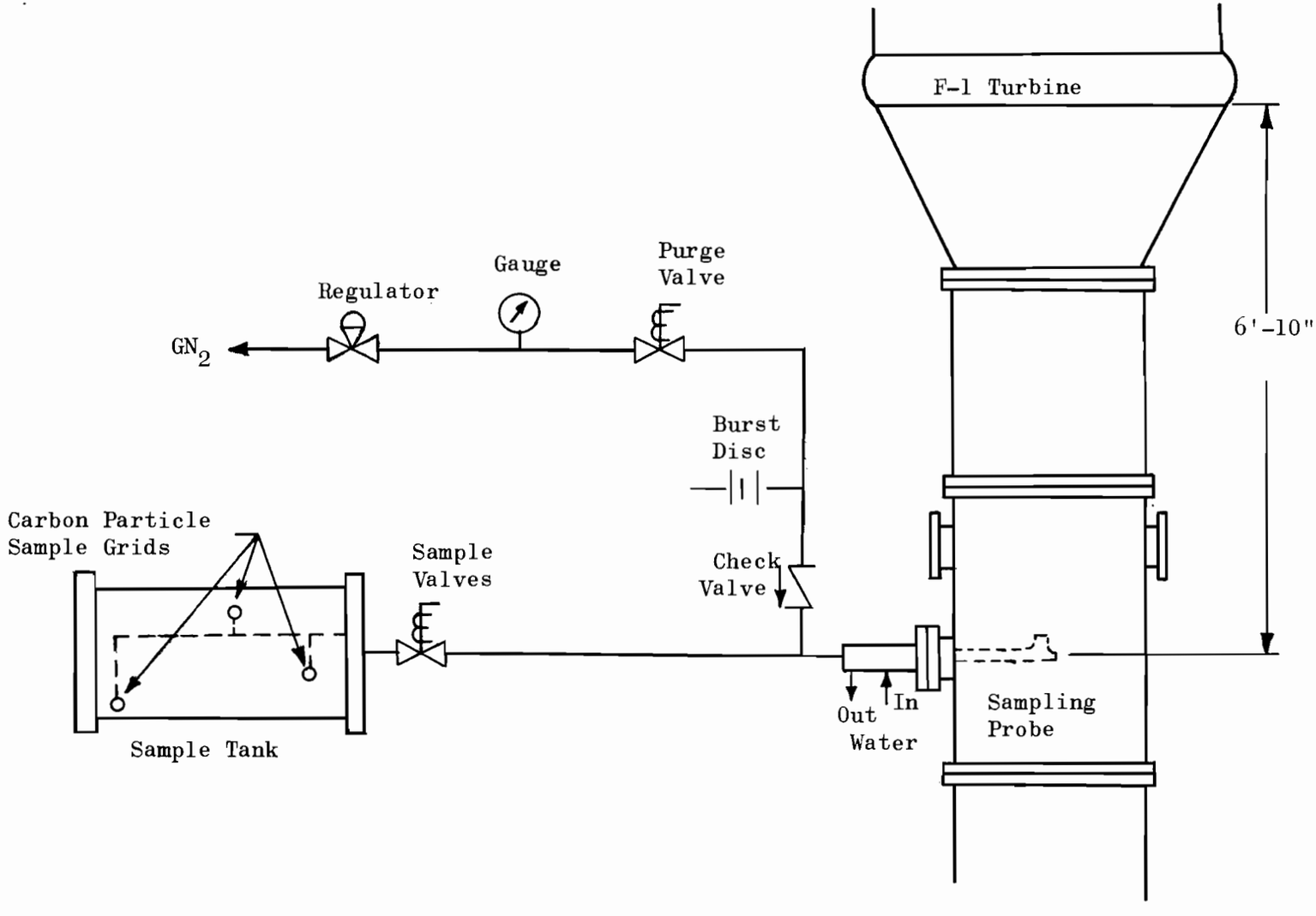

Figure 3. Schematic Diagram of the Experimental Arrangement Used for the Collection of Gas-Particle Samples

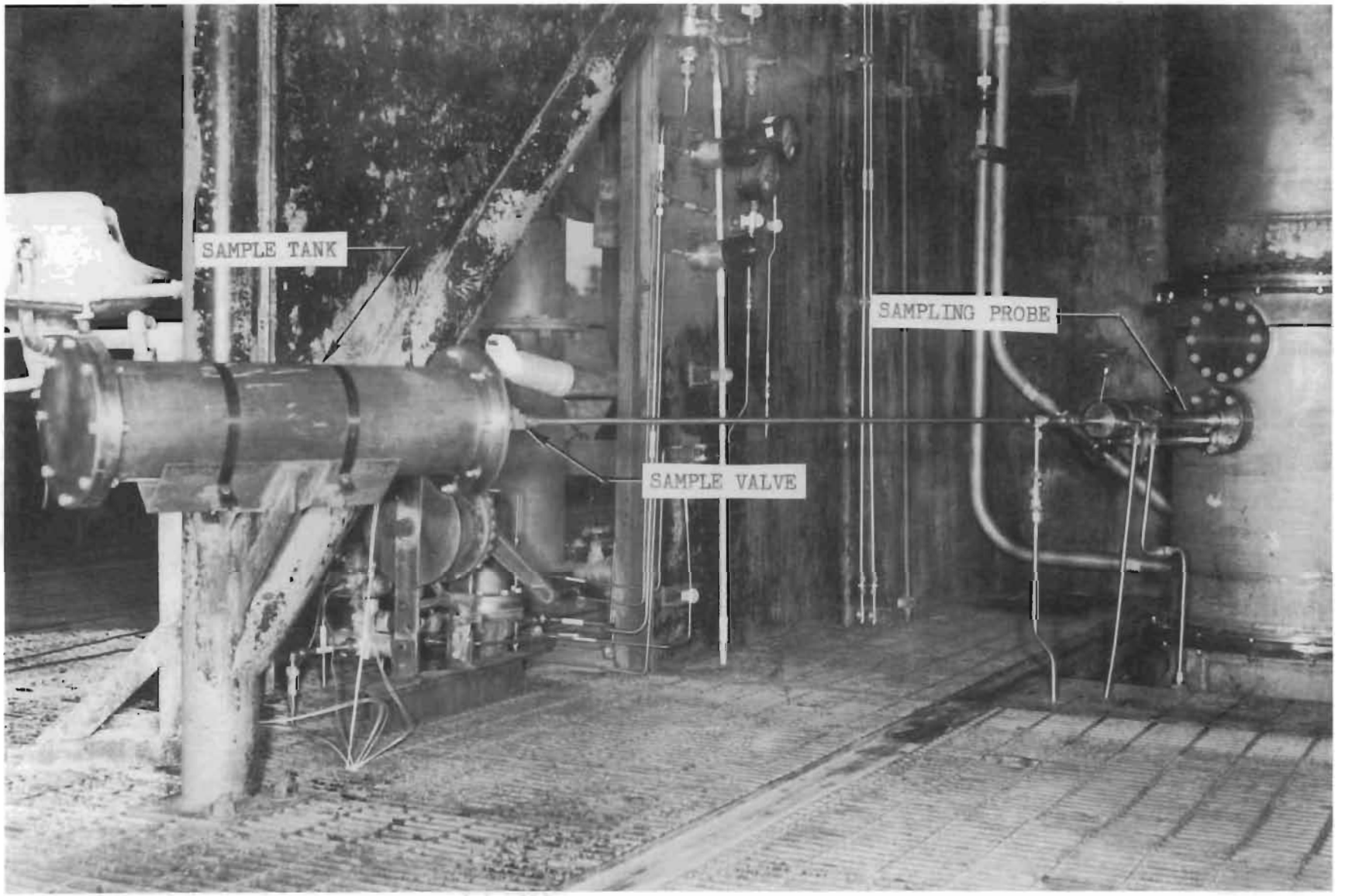

Figure 4. Gas-Particle Sampling System Installed on the Test Stand

DATA REDUCTION

The species present in the gas sample and their mole percentages were determined by mass spectrometer analysis. The liquid analysis for Run No. 28 through 37 consisted only of separating the water from the remainder of the liquids and weighing it. For Run No. 095 the liquids were analyzed by mass spectrometry. The solids were collected and weighed, and a carbon-hydrogen analysis was performed. Only the weight of carbon and hydrogen can be found by this process. The remainder of the solids was assumed to be oxygen, since this is the major additonal species present in the propellants of the gas generator.

The carbon particle size distributions were determined from electron micrographs of the sample grids by the Sloan Equivalent Circle Technique (Ref. 2). This technique consists of counting the number of particles in a particular size increment. Size differentiation with this technique was limited to 200 Å incremental steps. The total number of particles counted on each sample grid was approximately 1000.

RESULTS

Gas Analysis

Gas samples were collected from seven tests of the F-1 turbopump. The samples were collected at various immersion depths in the exhaust duct ranging from the center to a distance of 5/16-inches from the edge. The mole percentages of the gases found in the sample are given in Table 1. Also shown are the values predicted from performance calculations for shifting equilibrium conditions. The gas generator chamber pressure and mixture ratio are also given.

TABLE 1

SUMMARY OF GAS SAMPLING RESULTS

	Run No.							
	032	029	028	030	037	036	095	Predicted
Start Time of Sampling (sec. after ignition)	15	10	15	15	15	15	15	-
Duration of Sample (sec)	1.0	1.0	0.5	1.0	1.5	1.5	3.0	-
Radial Position (inches from center)	0	1.5	3.5	5.5	9.5	11	0	-
Chamber Pressure (psia)	928	951	977	929	872	963	931	900
Gas Generator Mixture Ratio	0.424	0.438	0.440	0.426	0.422	0.432	0.427	0.420
Sample Mixture Ratio	0.433	0.437	0.394	0.362	0.398	0.488	0.408	0.420
Hydrogen/Carbon Molar Ratio	2.338	2.064	2.023	1.935	2.082	2.158	2.028	1.953
Average Molecular Weight of Sample Gases (grams/mole)	21.40	25.23	26.59	26.12	23.86	23.82	24.70	11.69
Static Pressure in Duct (psia)	41.9	42.1	43.5	41.9	42.6	42.5	42.7	50.0
	Mole Percent							
H_2O	2.00	0.37	0.89	0.98	0.93	0.70	8.74	16.96
CO	28.80	29.82	29.28	30.75	30.09	31.85	28.45	9.57
CO_2	4.42	4.58	3.39	4.24	4.79	4.17	3.90	5.55
H_2	26.29	21.43	18.64	22.48	26.13	21.96	17.25	52.65
O_2	-	-	-	-	-	-	0.87	-
CH_4	18.35	19.46	18.83	15.08	15.82	20.90	15.78	15.27
C_2H_4	7.56	10.27	12.80	7.72	5.12	7.22	8.77	-
C_2H_6	4.50	4.63	4.05	4.69	4.78	5.68	4.77	-

TABLE 1

(Concluded)

	Run No.							Predicted
	032	029	028	030	037	036	095	
C_3H_4	0.44	0.36	1.18	0.76	0.72	–	0.19	–
C_3H_6	3.50	3.88	1.79	4.31	3.98	2.55	4.77	–
C_3H_8	1.34	0.33	1.70	1.03	1.85	1.01	1.37	–
C_4H_8	1.78	1.03	4.03	1.80	1.79	2.14	1.66	–
C_4H_{10}	0.41	–	–	–	0.33	–	–	–
C_5H_{10}	–	–	–	–	–	–	0.58	–
C_6H_6	0.61	3.85	3.42	5.82	3.29	1.81	1.92	–
C_6H_{12}	–	–	–	0.36	–	–	–	–
$C_6H_5CH_3$	–	–	–	–	0.36	–	0.47	–
Carbon (weight percent)	–	–	–	–	–	–	4.51	42.57

The sample mixture ratios reported in the table were obtained by dividing the total weight of oxygen found in the sample tank by the total weight of carbon plus hydrogen. As can be seen from the table, they agree fairly well with the mixture ratio of the gas generator determined from the propellant flowrate measurements.

The mass spectrometer analysis of the liquids from Run No. 095 showed the presence of water, benzene (C_6H_6), toluene (C_2H_8), and cyclohexene (C_6H_{10}). The mole percentages were 75.3, 16.5, 4.0 and 4.2 respectively. Since the majority of the organic liquids was benzene, the organic liquid in the samples from the other tests on which the complete liquid analysis was not performed was assumed to be benzene. The liquids present in the sample tank were assumed to be gases at the time the sample was collected, so the values reported in Table 1 include those quantities found in the liquids.

The first six gas samples that were collected did not contain a measurable amount of solid carbon in the sample tank. For the seventh test (Run No. 095) the sampling inlet valve was moved to the opposite end of the sample line, adjacent to the sampling probe. The solids in the line as well as the solids deposited on the walls of the sampling probe were collected and weighed. Again no appreciable amount of solids was found in the tank, but a total of 0.727 grams of carbon was found in the line and probe. This corresponds to 4.51 weight percent of the total sample. The total sample weight (gas plus solid) was 16.05 grams.

The hydrogen/carbon molar ratio of the sample was calculated for comparison with the hydrogen/carbon ratio for RP-1 fuel, which is nominally 1.935. The ratios calculated from the sample analysis were all very close to this value.

Pressure measurements were made during each test at the exit of the turbine. Previous measurements in the exhaust duct at the position where the samples were collected indicated a pressure drop of 13 psi from the turbine exit to the sampling port in the duct. This pressure differential was subtracted from the pressure measured at the exit of the turbine for each test and is reported in Table 1.

Carbon Particle Size Distribution

The carbon particle size distribution was determined from the sample grids from two tests, Run No. 033 and 034. A representative micrograph of a grid from each of these tests is shown in Fig. 5 and 6. The size distribution of the particles from these two tests is shown graphically in Fig. 7. As can be seen from the graphs, the maximum particle diameter is 1000 Å from test 033 and 800 Å from test 034. In both cases the greatest number of particles is in the 200-400 Å range.

Inspection of the electron micrographs of the sample grids from Run No. 033 indicated there was particle agglomeration and particle coating by hydrocarbon contaminants. This could explain the higher counts in the larger size range on Run No. 033. The sample grids from Run No. 034 appeared to be much cleaner, and consequently the frequency distribution curve is more narrow in range than that from Run No. 033. Thus, the distribution curve from Run No. 034 is probably more representative of the actual conditions in the F-1 turbine exhaust. These size distributions are similar to those found in the exhaust of a model F-1 engine and in low pressure hydrocarbon flames (Ref. 1, 3).

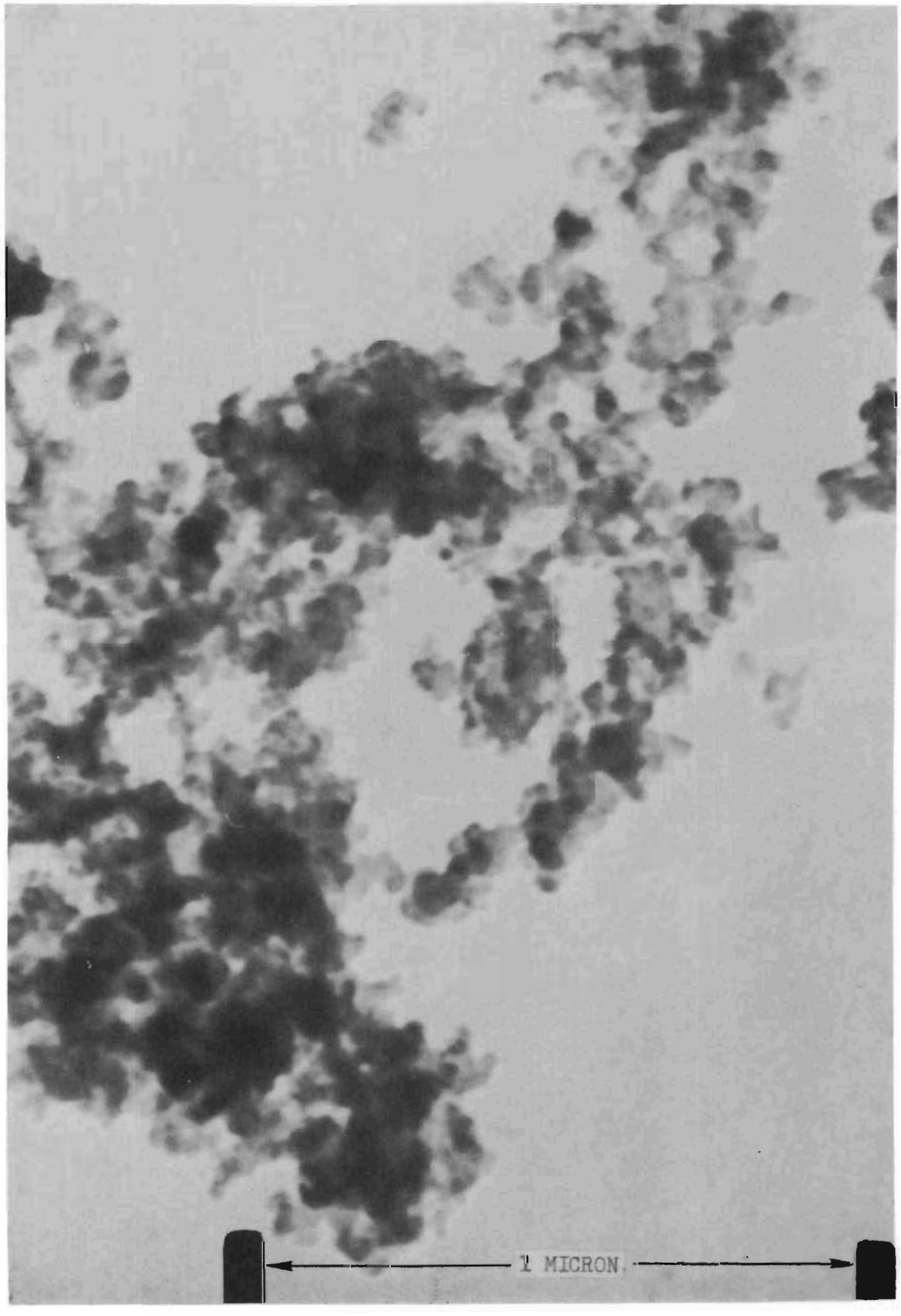

Figure 5. Electron Micrograph of Sample Grid From Run No. 033

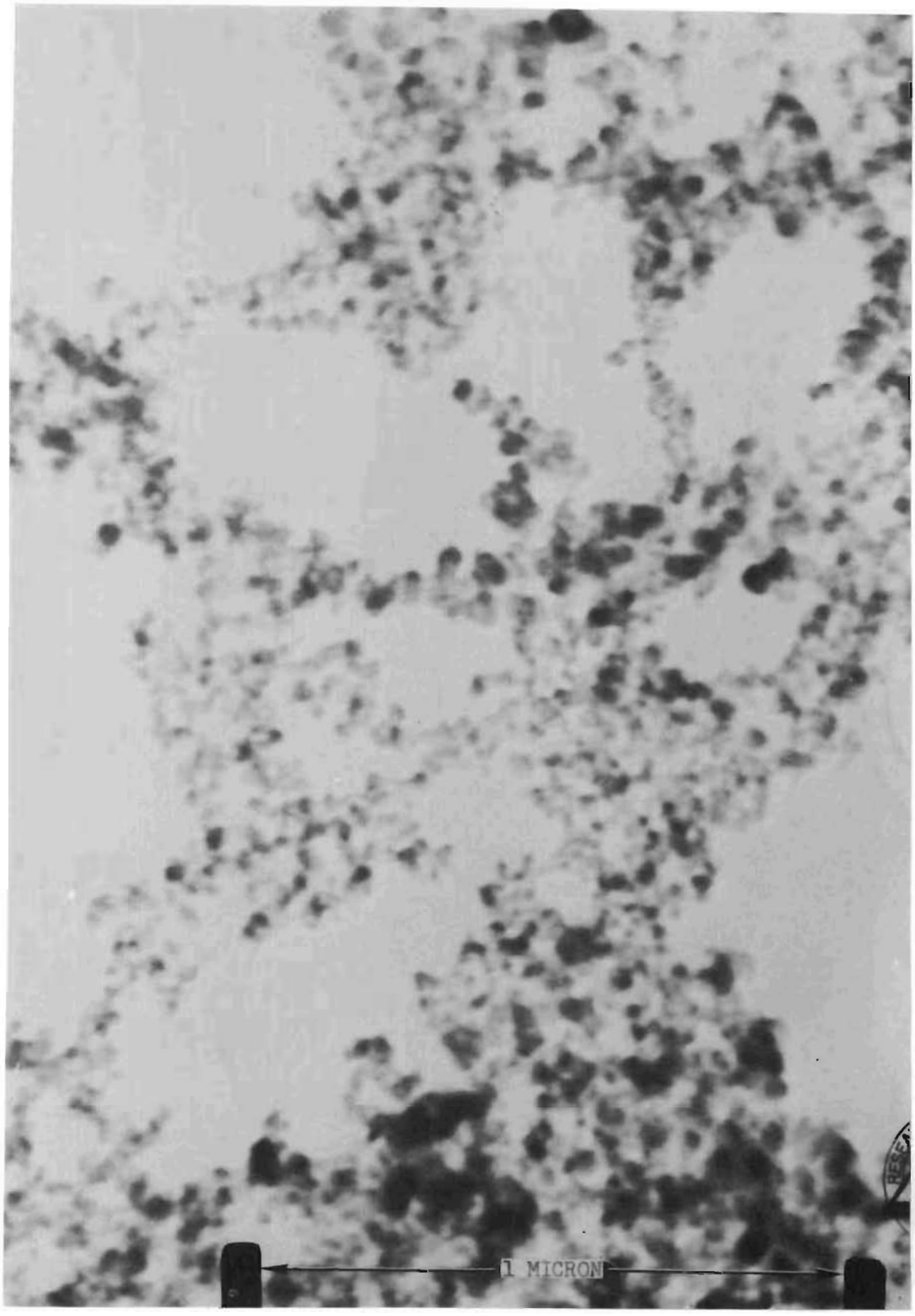

Figure 6. Electron Micrograph of Sample Grid From Run No. 034

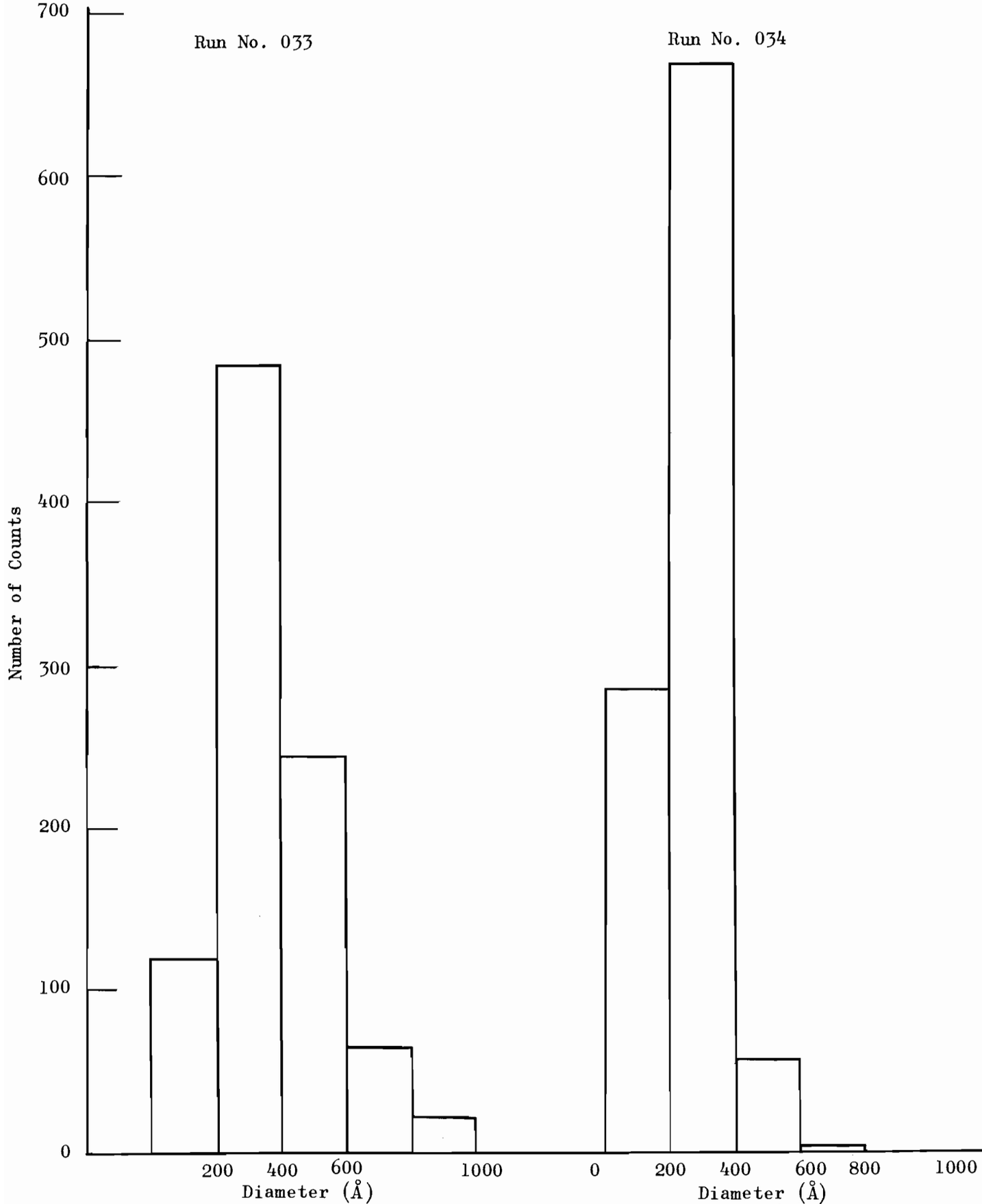

Figure 7. Size Distribution of Particles From Run No. 033 and 034

The particle number density in the exhaust may be calculated from the results of the analysis of the sample from Run No. 095. The number of particles in the sample is given by

$$n_p = \frac{m_p}{\rho_p \bar{V}_p}$$

where m_p is the total mass of the particles collected, ρ_p is the density of the particles, and $\bar{V}_p$ is the average volume of the individual particles. The average volume is found (assuming spherical particles) from the size distribution curve of Run No. 034 to be 15.1×10^{-18} cm^3. The value of m_p is the total mass of solid carbon found in the sample, and ρ_p is the density of graphite.

To obtain particle number density, this value of n_p must be related to the volume occupied by the sample when it was in the exhaust. Assuming the volume occupied by the solid material in the exhaust is negligible compared to that of the gases, the sample volume used for particle number density calculation is the mass of the gas in the sample divided by its density in the exhaust. The density is caluclated using the perfect gas law.

$$nR_oT = pV$$

$$= p \frac{m_g}{\rho g}$$

$$\rho_g R_o T = p \frac{m_g}{n}$$

$$\rho_g R_o T = p\bar{M}_g$$

or

$$\rho_g = \frac{p\bar{M}_g}{R_o T}$$

$\bar{M}_g$ is the average molecular weight of the sample gases and is found from the sample analyses. The pressure, p, is the measured pressure in the duct given in Table 1. The temperature used is that determined from performance calculations for this pressure and is equal to 780°K. R_o is the universal gas constant. The sample volume in the exhaust is then the total mass of the gases m_g divided by this density or $V = m_g/\rho_g$. The particle number density can then be determined by $N = n_p/V$. The particle density calculated by this method for Run No. 095 is $N = 2.34 \times 10^{12}$ particles/cm^3.

RADIOMETRIC MEASUREMENTS

APPARATUS AND PROCEDURE

The spectral radiometer was designed specifically to measure the apparent spectral radiance of rocket exhausts in the near infrared spectral region. It consists basically of a prism monochromator equipped with both a lead sulfide and lead selenide photoconductive detector, a set of entrance optics, and an internal blackbody calibration standard.

The optical arrangement of the spectral radiometer is shown in Fig. 8. The radiation from the exhaust is reflected by two flat mirrors and imaged at a plane intersected by the preslit, which is a small aluminized stripe on an otherwise clear piece of glass. The light passing through the glass is reimaged by a camera, to produce a fiducial photograph. The shadow of the preslit indicates the field of view of the instrument. The radiation reflected by the preslit is reimaged at the monochromator entrance slit. The beam is interrupted by another beam splitting device, a reflecting chopper, located close to the monochromator entrance slit. The reflected radiation is directed onto a thermistor bolometer which measures the total radiation (radiation at all wavelengths) from the exhaust. The bolometer is used only to detect any sudden variations of the radiance of the exhaust with time so that such variations will not be erroneously interpreted as characteristic spectra. The beam entering the monochromator is dispersed by the prism and imaged onto either a lead sulfide or lead selenide detector element. A motor driven detector change mirror permits changing detectors during a run so that the complete wavelength range from 1.0 to 5.5 microns can be covered. The electrical output from the detector is amplified and recorded by a direct writing recorder. A motor

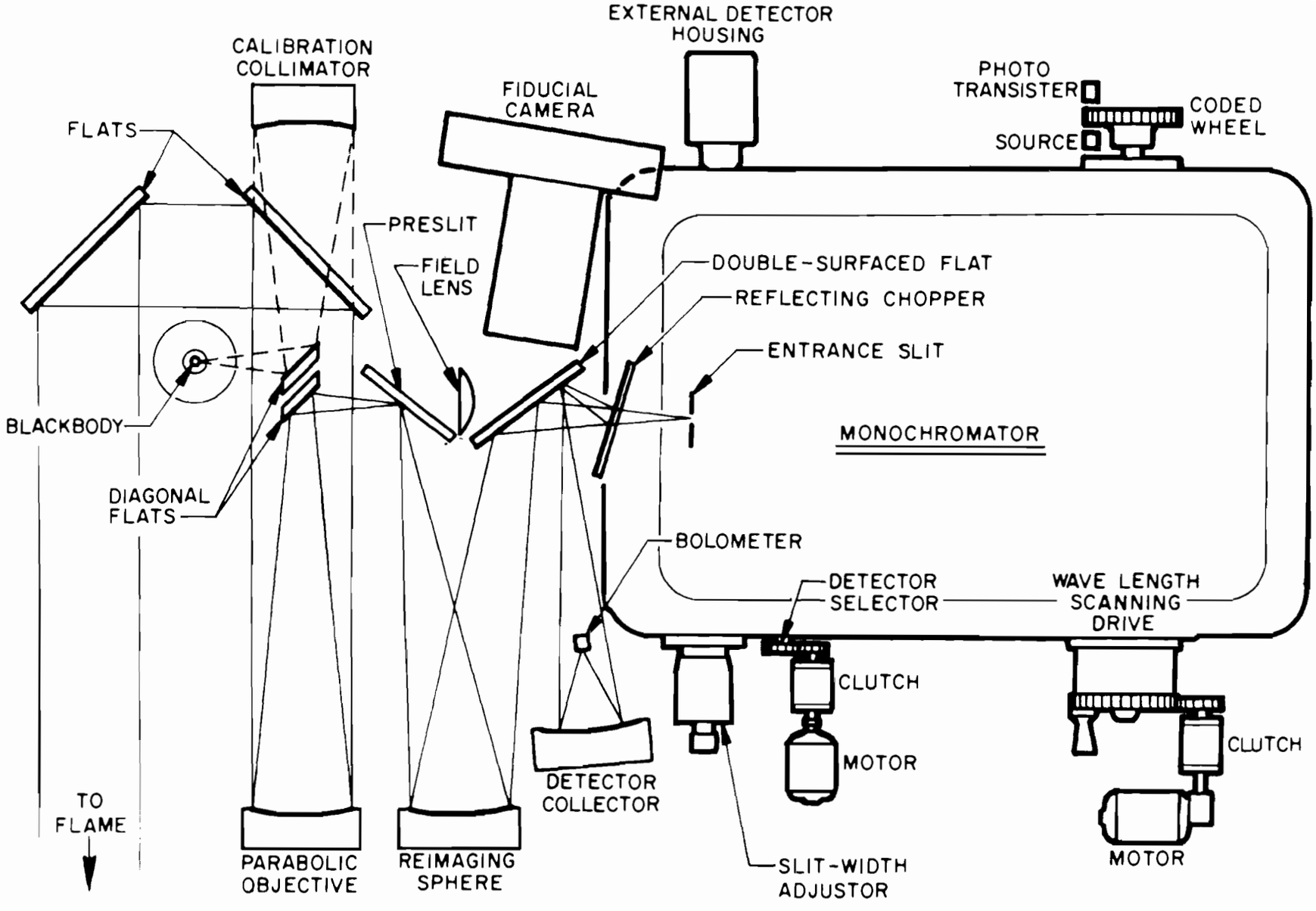

Figure 8. Schematic Diagram of Spectral Radiometer

drive is provided for the remote operation of the wavelength scanning drive. A wavelength record is established by a coded wheel on the wavelength drive shaft which interrupts a light beam to a phototransistor.

An absolute intensity calibration is obtained by removing the second flat mirror in the optical path of the exhaust radiation. This permits the radiation from a blackbody source to enter the optical system with the same number of reflections, thus obviating any need for reflectance corrections. The image of the blackbody aperture fills the preslit and hence the entrance slit of the monochromator. The blackbody radiator is capable of operations at temperatures up to 2000°C (Ref. 4).

Figure 9 is a diagram of the arrangement of the radiometric instrumentation on the test stand. The radiometer was connected to one of the viewing ports by a 4-inch diameter, 8 foot long optical tunnel. The tunnel and radiometer were purged with gaseous nitrogen to reduce atmospheric absorption. A greybody source consisting of an electrically heated flat carbon rod was attached to the flange directly opposite the radiometer. The temperature of the greybody was adjusted so that the radiance from the greybody was approximately twice that of the turbine exhaust. During the test firing a shutter in front of the greybody alternately opened for one complete wavelength scan and then closed for one scan. Thus both emission and absorption measurements were made during the same test. An optical probe (a hollow shaft containing a sapphire window in one end) which was inserted into the exhaust duct was provided for both the radiometer and the greybody source. The immersion depth of each optical probe was adjustable so that various optical pathlengths could be obtained. The low radiance level of the turbine exhaust species necessitated the use of large monochromator slit widths (> 250 microns). Thus the resolution of the spectrometer was reduced.

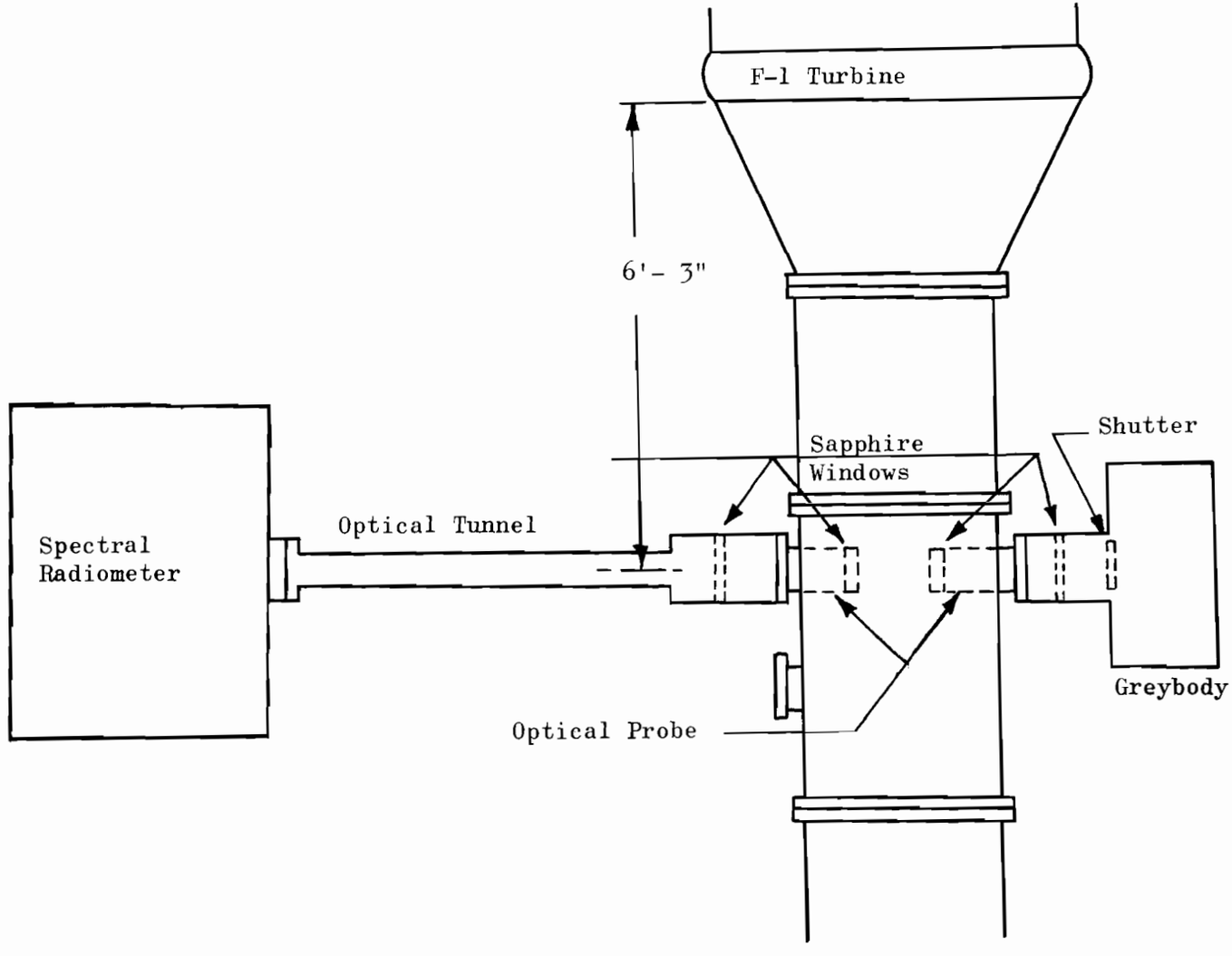

Figure 9. Schematic Diagram of the Experimental Arrangement Used for the Radiometric Measurements

In order to take meaningful data, it was necessary to keep the window free of carbon deposition during the test. This proved to be the most difficult problem encountered in the entire program, and considerable effort was expended to establish a purge system which would keep the window clean. Several systems were constructed and tested in the exhaust duct during test firings before a successful purge system was developed. The system which performed satisfactorily is shown schematically in Fig. 10. Gaseous nitrogen was injected uniformly around the periphery of the sapphire window into a converging nozzle section designed to give sonic velocities of GN_2 directly in front of the window.

Figure 11 is a photograph of the spectral radiometer installed on the test stand.

DATA REDUCTION

Several wavelength scans of the blackbody at temperatures close to the brightness temperature of the turbine exhuast were made for each test. This specified a recorder pen deflection $D_B(\lambda)$ associated with a radiance value $N_B(\lambda)$ at a particular wavelength, λ. From this information a curve of inverse sensitivity $(N_B(\lambda)/D_B(\lambda))$ vs wavelength (λ) was obtained. The radiance of the turbine exhaust (N_f) was then found from

$$N_f(\lambda) = D_f(\lambda) \left[\frac{N_B(\lambda)}{D_B(\lambda)} \right]$$

A correction due to the attenuation of the two sapphire windows was applied to the exhaust radiance. The radiance of the blackbody source was found from the blackbody tables for a particular temperature. The temperature of the blackbody source was measured with an optical pyrometer which in turn was compared against an NBS certified tungsten ribbon lamp.

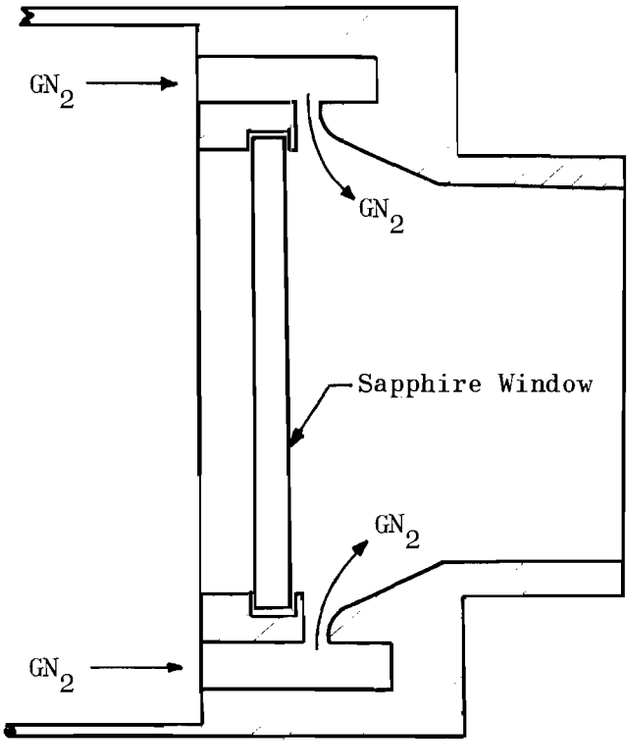

Figure 10. Diagram of the Purge System for Optical Probe

Figure 11. Spectral Radiometer Installed on Test Stand

RESULTS

The spectral radiance of the turbine exhaust is shown in Fig. 12 and 13. Figure 12 shows the radiance measured in the 1.3 to 3.2 micron region (PbS detector), and Fig. 13 the radiance measured in the 1.4 to 5.5 micron region (PbSe detector). As may be seen from the figures, the spectral radiance is very close to that of an 800°K blackbody. The dip in the curve of Fig. 12 around 2.7 μ is due to atmospheric water absorption. It was not possible to purge the system long enough to eliminate all atmospheric absorption.

The peak around 3.3 microns in Fig. 13 is the radiation due to the C-H stretching vibration of the hydrocarbon molecules found in the turbine exhaust (Ref. 5). However it is difficult to attach any physical significance to the fluxuations between 4.8 and 5.5 microns apparent in Fig. 13. The transmission of the sapphire windows is dropping off drastically in this region. The correction for this transmission loss during the data reduction will magnify any small fluxuations present in the raw data. Thus the peaks in this region should not be attributed to emission from any particular species.

Absorption measurements were made over optical pathlengths of 7-1/2-inches and 4-3/4 inches. At these distances the exhaust products absorbed virtually 100 percent of the greybody radiation. An attempt to measure the absorption over a 2-inch pathlength was unsuccessful due to a malfunction of the greybody source during the test. Additional measurements were not possible within the time and funding of this program.

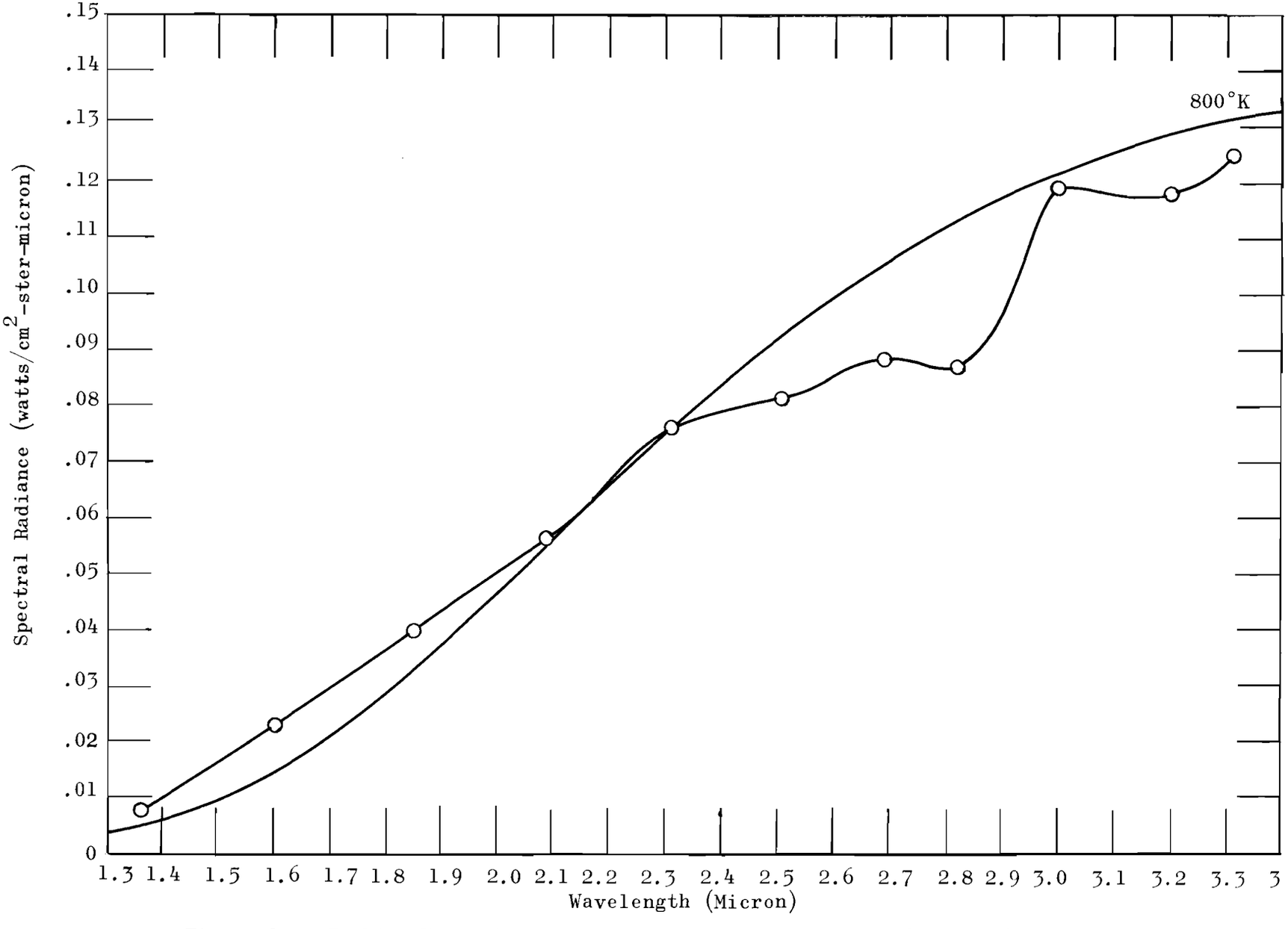

Figure 12. Turbine Exhaust Spectral Radiance Measured With PbS Detector - Run No. 110

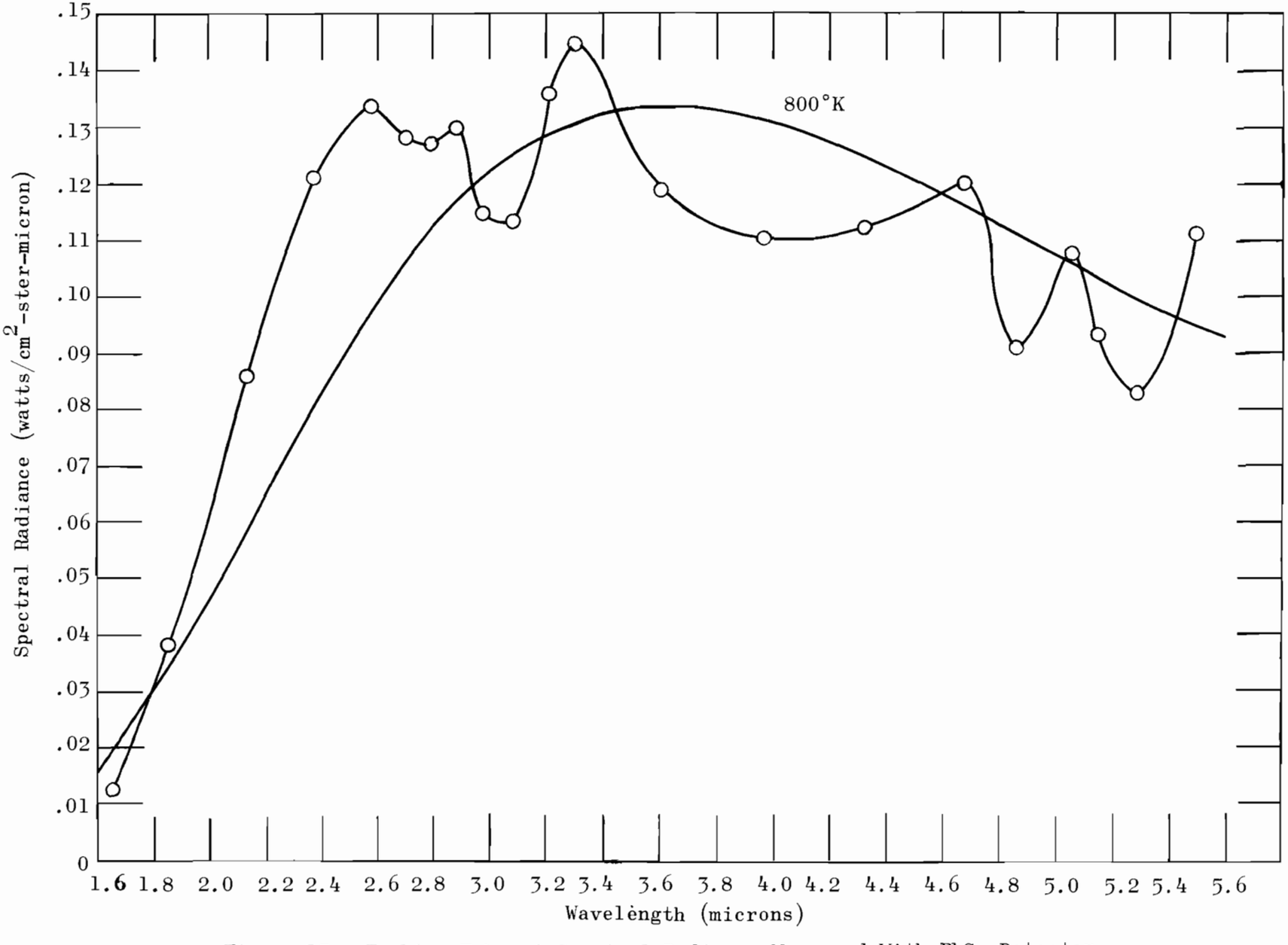

Figure 13. Turbine Exhaust Spectral Radiance Measured With PbSe Detector - Run No. 110

A summary of the important operating parameters of the gas generator and turbine is given in Table 2. The exhaust temperatures and pressures presented were measured by thermocouples and pressure transducers in the exhaust cone directly below the outlet of the turbine. The inlet temperatures and pressures were measured between the gas generator and the inlet to the turbine. Also presented are the mixture ratio, chamber pressure, oxidizer flow, fuel flow, and total flow of the gas generator.

TABLE 2

SUMMARY OF GAS GENERATOR AND TURBOPUMP OPERATING PARAMETERS

Run No.	Date	Time	Mixture Ratio	Chamber Pressure (psia)	Exhaust		Inlet		Fuel Flow (lb/sec)	LOX Flow (lb/sec)	Total Flow (lb/sec)
					T (°F)	P (psia)	T (°F)	P (psia)			
633-028	2-16-66	1450	0.440	977	1358	56.5	1495	922	108.0	47.6	155.6
633-029	2-16-66	1950	0.438	951	1317	55.1	1467	916	108.2	47.4	155.6
633-030	2-21-66	1015	0.426	929	1261	54.9	1440	842	113.2	48.3	161.5
633-032	2-21-66	1930	0.424	928	1272	54.9	1442	857	112.1	47.6	159.7
633-033	2-23-66	2000	0.429	986	1280	56.3	1445	888	110.2	47.4	157.6
633-034	2-23-66	2355	0.430	970	1286	55.2	1467	896	110.2	47.4	157.6
633-035	2-24-66	1050	0.425	951	1256	55.6	1450	873	111.6	47.4	159.0
633-036	2-24-66	1445	0.432	963	1297	55.5	1452	883	110.2	47.6	157.8
633-037	3-1-66	1020	0.422	872	1218	55.6	1433	848	114.9	48.5	163.4
633-095	6-30-66	2400	0.427	931	1304	55.7	1466	878	110.8	47.3	158.1
633-110	8-16-66	2140	0.417	1016	1236	62.1	1437	945	117.8	49.1	166.9

CONCLUSIONS

The predominant emitting species in the F-1 turbine exhaust are the solid carbon particles. These particles have a diameter less than 1000 Å and the majority have diameters between 200 Å and 400 Å. The turbine exhaust radiance is approximately that of an 800°K blackbody which agrees with the temperature predicted by performance calculations.

One can determine the quantity L=Nz for comparison with the work of Stull and Plass (Ref. 6); z is the pathlength and N is the particle density calculated previously. With z = 4-3/4 inches, the shortest pathlength for which an absorption measurement was made, $L = 2.72 \times 10^{13}$ cm^{-2}. Stull and Plass have calculated an emissivity for a carbon particle size distribution similar to that found in the turbine exhaust for various values of L. The peak of the distribution curve is at a diameter of 400 Å. For this distribution and the value of L calculated above, the emissivity is found to be equal to one out to 5 microns. This agrees with the data obtained with a 4-3/4 inch pathlength, which showed complete absorption in this wavelength region.

It should be noted that the 4.51 weight percent of solid carbon found in the sample from Run No. 095 is much greater than that found in samples taken from the exhausterator of an F-1 engine (Ref. 1). Thus the particle number density from the exhausterator of an actual engine should be less than that found in the duct on the turbopump test stands. This is understandable since the total volume occupied by the gases coming from the exhausterator is greater than the volume of the gases in the exhaust duct. Therefore, since the carbon particles are the major absorbing species, the absorption by the exhaust from the exhausterator for a particular pathlength may not be as great as that from the exhaust in the duct.

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