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AFRPL-TR-67-242

SECONDARY COMBUSTION OF PENTABORANE-HYDRAZINE  
EXHAUST IN AIR

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S. D. Rosenberg, R. E. Yates, and R. C. Adrian  
Aerojet-General Corporation

TECHNICAL REPORT AFRPL-TR-67-242

August 1967

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AIR FORCE ROCKET PROPULSION LABORATORY  
Research and Technology Division  
Air Force Systems Command  
United States Air Force  
Edwards, California

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AIR FORCE ROCKET PROPULSION LABORATORY  
Research and Technology Division  
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United States Air Force  
Edwards, California

Report AFRPL-TR-67-242

FOREWORD

This progress report (Aerojet Report No. 1134-81-1), covering the period from 1 May through 31 July 1967, is submitted in partial fulfillment of Contract F04611-67-C-0106.

This investigation is being conducted by the Fuels and Combustion Research Section of the Advanced Propulsion Research Department, Research and Technology Operations, Aerojet-General Corporation, Sacramento, California. The Air Force monitor for the program is A. McPeak, Lt., USAF/RPCL.

The work described herein was performed by S. D. Rosenberg, R. E. Yates and R. C. Adrian. This report was written by the program staff.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ABSTRACT

The design of the first of two liquid micromotors has been completed. This micromotor will be used for the determination of characteristic velocity and chamber temperature and for analysis of the exhaust products. The preparation of the test site has begun and the fabrication and installation of the micromotor and auxiliary equipment have been initiated.

A tentative test plan has been developed for the study of the combustion characteristics in air of the exhaust products of the pentaborane-hydrazine system.

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SECTION I

INTRODUCTION

Air-augmented rockets offer significant improvement in specific impulse over conventional rockets. The improvement is realized through two important mechanisms: first, through addition of the air mass to the exhaust stream and, second, by achieving additional combustion of the primary rocket exhaust when the primary rocket is operated in an under-oxidized condition. Therefore, primary propellant systems which produce exhaust products that may be oxidized further in air are attractive for air-augmentation applications.

The pentaborane-hydrazine propellant system is especially attractive in that the exhaust of this system consists chiefly of hydrogen, boron nitride, and boron. If significant combustion of these exhaust products can be achieved in air, a system of exceptional performance may be realized.

The objective of this program is to establish the combustion characteristics in air of the exhaust products of the pentaborane-hydrazine system. A study of the combustion will be conducted using two liquid micromotors. The test variables which will be investigated include the following:

1. Temperature and pressure of the secondary air, simulating both low altitude/moderate Mach number, 2.5, and high altitude/high Mach number, 4.0.
2. Air-to-propellant-weight flow ratios in the range 8:1 to 40:1.
3. Primary propellant mixture ratios ( $N_2H_4/B_5H_9$ ) in the range 1.27 to 0.6.
4. Secondary combustion chambers (not more than three) of different diameters and lengths.
5. Composition of secondary air, i.e., air or nitrogen.

Test measurements which will be required include the following:

1. Propellant and air flow rates.
2. Air inlet temperature and pressure.
3. Primary and secondary chamber pressures.
4. Total thrust.
5. The extent of conversion of the boron nitride and boron to boron oxides, by collection and analysis of the exhaust products.

I, Introduction (cont.)

6. Spectral gas-temperature and other optical measurements in the secondary chamber.

Characteristic velocity, chamber temperature and specific impulse will be calculated based on these test measurements, and a combustion model will be developed.

SECTION II

SUMMARY

The technical effort on this program is divided into three distinct phases. The work accomplished on each of these phases during the first quarter of the program are reported below.

A. PHASE I: DESIGN, FABRICATION, AND INSTALLATION OF  
MICROMOTOR FACILITIES

1. Micromotor "A"

The site selected for the experimental test program is in the Research Physics Laboratory of the Advanced Propulsion Research Department. The test bay and auxiliary facilities are being installed currently.

The designs of the air-heating system and the combustor components have been completed. Fabrication and installation of the air-heater are in progress. Fabrication of the combustor components is currently underway. These components include the primary propellant and igniter injectors, the water-cooled primary combustion chamber and nozzle, the augmenting-air injector, the water-cooled secondary chamber and replaceable nozzles.

2. Exhaust Sampling System

The design of the exhaust sampling system is nearing completion. The exhaust duct, with provision for liquid-argon injection and exhaust sampling, is currently being fabricated. The design of the dust-collector is under consideration.

3. Spectral Equipment

The assembly of the equipment for spectral temperature determination is almost complete. Modifications of existing equipment and the fabrication of additional components are complete with two exceptions: the light-source intensity monitors and the ring mounting which supports the light-sources.

The complex refractive index of BN, required for particle-cloud temperature determination, has been obtained from data supplied by Dr. W. W. Lozier and by N. J. Norante.

A computer program for the determination of temperatures from the spectral data has been developed.

II, A, Phase I: Design, Fabrication, and Installation of  
Micromotor Facilities (cont.)

4. Micromotor "B"

The thrust combustor is not scheduled for use until later in the program. Acquisition of materials and components for the thrust combustor and stand has been initiated.

B. PHASE II: DETERMINATION OF COMBUSTION CHARACTERISTICS IN AIR  
OF EXHAUST PRODUCTS OF PENTABORANE-HYDRAZINE SYSTEM

Phase II is concerned with the engine test evaluation of the air-augmented pentaborane-hydrazine system. A tentative test plan has been developed to provide the requisite data. Fifty-two tests are planned with Micromotor A. In the course of these tests, the temperature profile in the secondary chamber will be measured, the exhaust products will be analyzed, and the characteristic velocity will be determined under a variety of conditions.

Micromotor B will be used to conduct 23 tests under similar conditions to determine the total thrust and specific impulse. Characteristic velocities will be determined for comparison with the Micromotor A results.

C. PHASE III: INTERPRETATION OF MICROMOTOR TEST RESULTS

Phase III is concerned with the development of a theoretical model of the combustion process or processes. Correlation between the various experimental parameters will be sought through theoretical chemical and physical considerations.

SECTION III

TECHNICAL DISCUSSION

The program is divided into three phases: Phase I, Design, Fabrication, and Installation of Laboratory Micromotor Facilities; Phase II, Determination of the Combustion Characteristics in Air of the Exhaust Products from the Pentaborane-Hydrazine System; and Phase III, Interpretation of Micromotor Test Results. The work accomplished during the period 1 May to 31 July 1967 is discussed below.

A. PHASE I: DESIGN, FABRICATION, AND INSTALLATION OF LABORATORY MICROMOTOR FACILITIES

Phase I is concerned with the design, fabrication, and installation of two liquid micromotors, "A" and "B." Micromotor A will be used for the determination of characteristic velocity,  $c^*$ ; for the determination of exhaust product composition, both gaseous and solid; and for the measurement of gas and particle temperatures in the secondary chamber. Micromotor B will be used for the measurement of total thrust and for the determination of characteristic velocity and specific impulse,  $I_{sp}$ .

1. Test Site

The test site for the experimental combustion studies is in the Research Physics Laboratory of the Advanced Propulsion Research Department. The test bay is being prepared for the installation of Micromotor A. The stand to be used to support the combustor and auxiliary apparatus is currently being modified.

2. Secondary-Air Heating System

Careful consideration has been given to the design of the secondary-air heating system. The use of a pebble-bed heat exchanger, preheated by means of the combustion of LPG-air, was originally suggested for this purpose. However, the large power supply (400 kw) available in the Research Physics Laboratory is adequate to preheat the augmenting air required by the test program. Therefore, an electrical heating system has been designed and is being constructed and installed in the test bay. A schematic of the heater is shown in Figure 1.

An analysis of the electrical heating system was made and the following conclusions were reached:

a. 400 kw will provide 22,768 Btu/min. This is sufficient energy to bring 1.0 lb/sec of air to 1477°F from 50°F or to raise 1.355 lb air/sec through a  $\Delta T$  of 1180°F. Maximum required conditions may be reached by preheating the air reservoir to a temperature of 320°F.

III, A, Phase I: Design Fabrication, and Installation of Laboratory Micromotor Facilities (cont.)

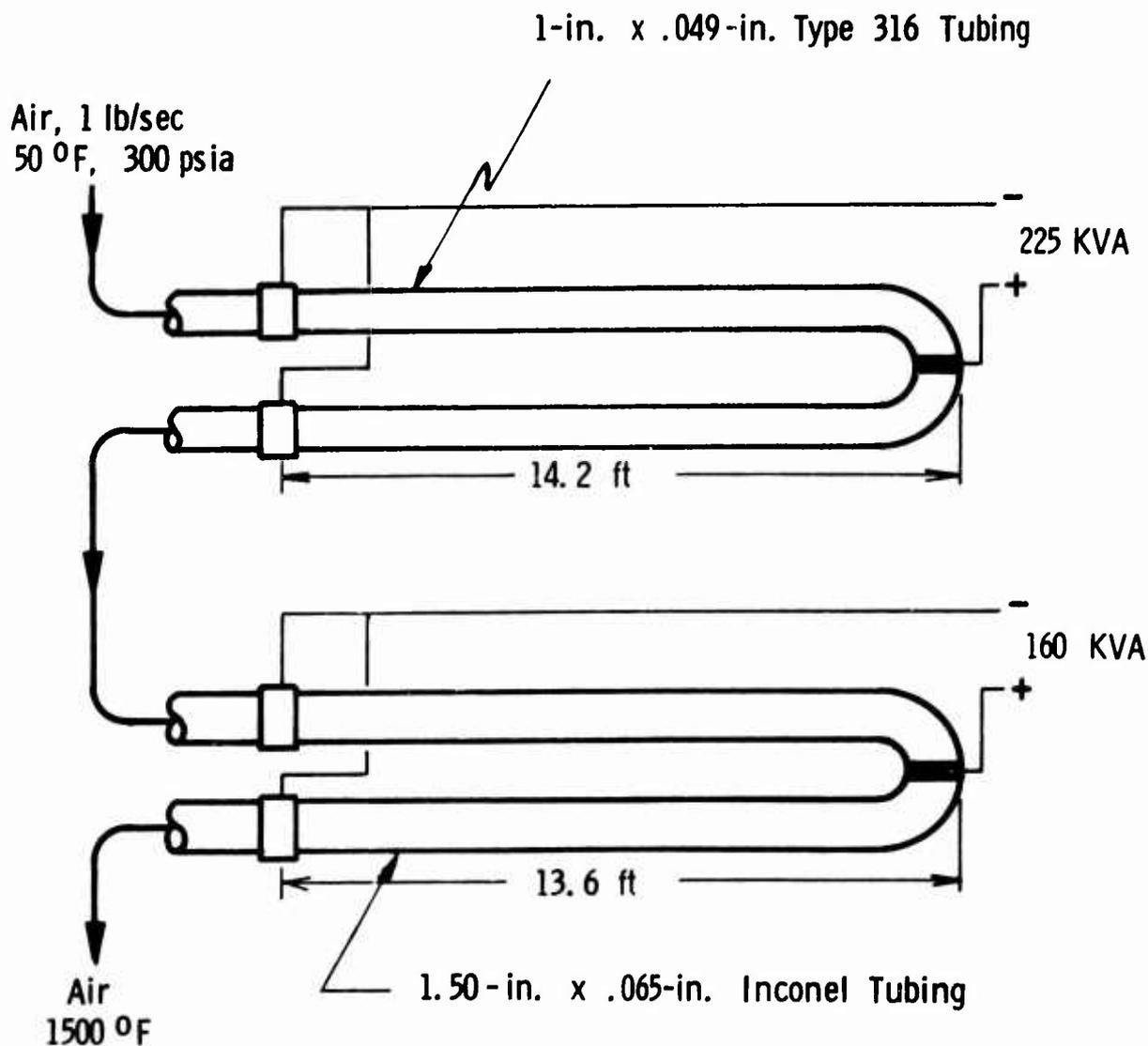


FIGURE 1. SCHEMATIC OF AIR HEATER

b. Pressure drop through the tubing will be less than 40 psi at the high air velocities required, 225 to 500 ft/sec.

c. A two-increment heater will be used; the first increment consists of 28 ft of 1-in.-dia x 0.049 Type 316 stainless steel and the second increment consists of 27 ft of 1-1/2-in.-dia x 0.065 Inconel tubing. The electrical properties of these tubes plus the secondary-air temperature requirements represent power requirements of 3000 amps at 75 volts and 3000 amps at 53 volts, respectively. Heat-transfer coefficients of the tube walls are on the order of 200 and 155 Btu/hr ft<sup>2</sup>, respectively.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory Micromotor Facilities (cont.)

d. Heater weight will be approximately 45 lb.

e. Cost may be reduced somewhat compared with the pebble-bed heater, although the required purchase of high-temperature-resistant tubing may offset other cost reductions.

There are such additional benefits as the following: heating will be instantaneous, with no hot body complicating work in the combustor area; little or no preheat will be required; and there will be no heat limitation on run duration. A high-temperature valve may not be needed; this valve could present a major problem.

3. Micromotor A

The design of the combustor components for Micromotor A has been completed. These components include the primary propellant and igniter injectors, the jacketed, primary combustion chamber and nozzle, augmenting-air injector, and the jacketed, secondary combustion chamber and replaceable nozzles. These components are being fabricated currently. A sketch of the assembled, two-stage combustor is shown in Figure 2.

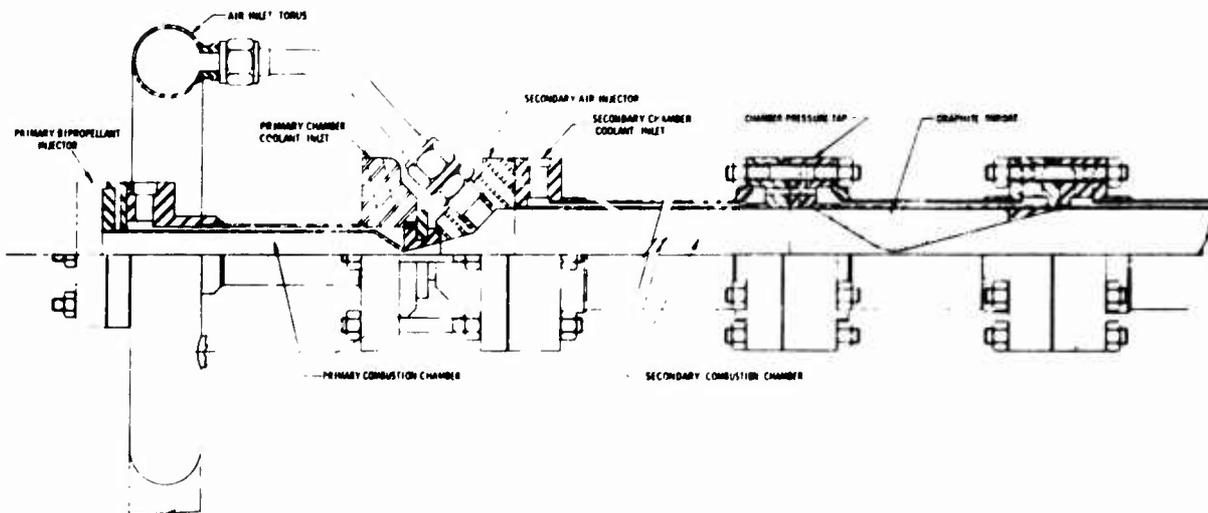


FIGURE 2. MICROMOTOR A ENGINE ASSEMBLY, AA MOD 1

The primary combustor is similar to the Aerojet liquid-liquid combustor used on previous programs. The addition of the secondary chamber plus a high degree of instrumentation make this unit substantially more complex than those previously used, however.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory Micromotor Facilities (cont.)

An uncooled injector has been designed for the primary chamber. Initially, a modified triplet configuration fabricated from stainless steel will be employed. A similar unit has been used previously for this bipropellant system and provided relatively efficient combustion. A pentad spray injector will be used as a backup unit. Ignition will be achieved by means of a time-sequenced injection of a liquid oxidizer, i.e.,  $N_2O_4$ , because the basic bipropellant combination is not hypergolic.

The primary chamber is approximately 6 in. long (injector to throat) and 0.90 in. in diameter. The stainless steel nozzle (0.125-in.-dia throat) and the primary chamber are enclosed within a water-cooling jacket which will provide heat loss data.

Air flow to the secondary chamber will be controlled by a sonic nozzle ahead of a toroid manifold. Three tubes connect the manifold to replaceable nozzles in the air injector. The nozzles will be selected to provide an inlet velocity of Mach 0.4.

The secondary chamber, shown simply as a jacketed tube in Figure 2, is a relatively complex component of the micromotor. Provision has been made for a series of thermocouples along the length of the chamber to provide temperature-profile measurements. Provision has been made also for sets of optical windows through which the spectral temperatures will be measured. Figure 3 is a detailed sketch showing the manner in which these ports are assembled.

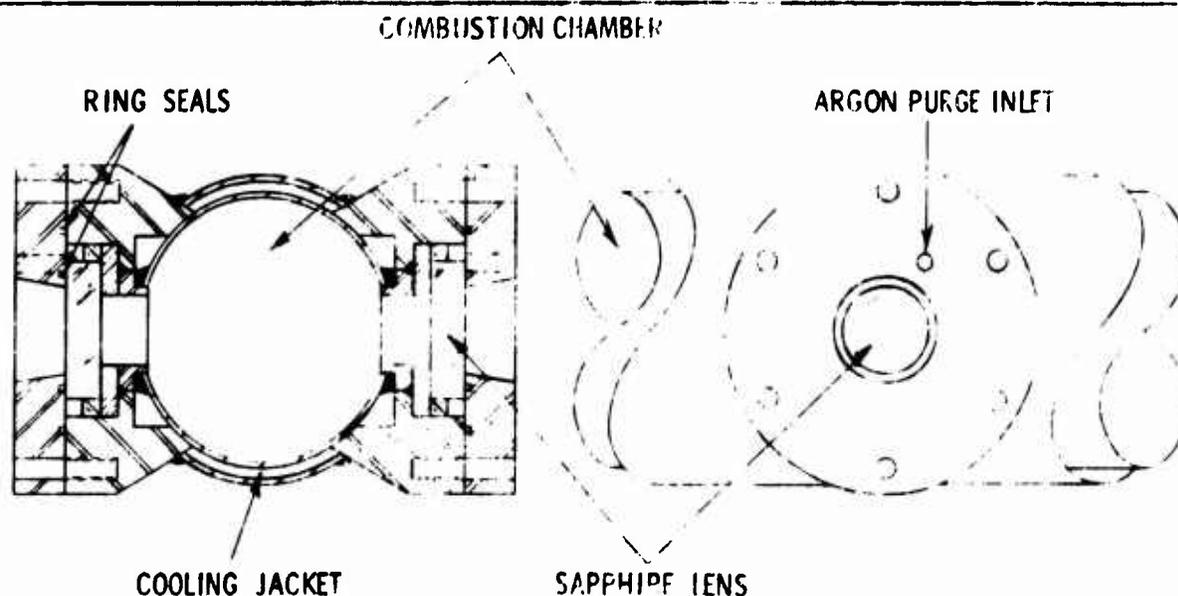


FIGURE 3. OPTICAL PORTS IN THE SECONDARY CHAMBER OF MICROMOTOR A

III, A, Phase I: Design, Fabrication, and Installation of Laboratory  
Micromotor Facilities (cont.)

Replaceable graphite nozzles will be attached to the secondary combustor tube by means of flanges. The wide range of test conditions requires the use of several different throat areas; the use of a flanged connection facilitates the removal of the nozzles for interchange and measurement of post-run throat-diameters.

Graphite has been chosen for the nozzle material because of its superior high-temperature qualities and because its lubricity tends to resist the adhesion of liquid and solid combustion products. In the high air-to-propellant regime, the erosive oxidation of the nozzle may become a problem. Should this occur, the substitution of boron nitride nozzles is expected to eliminate the problem.

4. Exhaust Sampling Equipment

The design of the exhaust sampling system is in progress currently. The design of the exhaust duct has been completed. Figure 4 is a sketch of the water-cooled duct showing the liquid-argon injection and exhaust sample taps. The exhaust filtration unit is being designed at the present time. The type of dust collection system to be used will be selected and the appropriate equipment will be ordered.

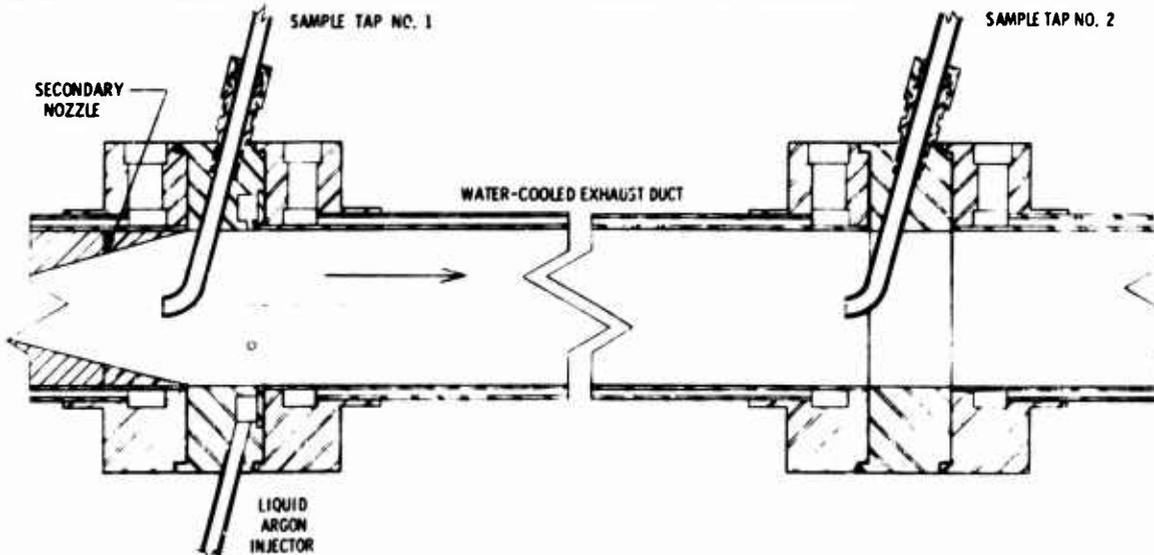


FIGURE 4. WATER-COOLED EXHAUST DUCT

Provision has been made for the injection, if necessary, of liquid argon into the exhaust duct for rapid quenching of the exhaust products. This operation is not intended for normal cooling but only to prevent post-oxidation. The need for argon cooling will not be definitely established until preliminary firings have been made.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory  
Micromotor Facilities (cont.)

Auxiliary samples, taken at three different points in the exhaust duct from the secondary nozzle, will be drawn through Millipore filters to provide both solid and gaseous exhaust samples. These sample draw-off operations will be timed to coincide with the main sample collection. The occurrence of post-oxidation in the exhaust duct should become apparent from analyses of the samples; differences in the composition of the exhaust at the three sample-taps may be the result of post-oxidation.

Design calculations have been made for the exhaust filtration system. The high maximum exhaust rate, 29 cu ft/sec at 400°F, necessitates a large filter area. Therefore, a reduction of the exhaust temperature to approximately 120 to 150°F is required to achieve a practical filter size. The exhaust rate will vary over a wide range, and a compartmented filter may be the best solution to this problem. The least possible collecting area is desired in order to get more accurate material balances for the combustion experiments; thus, the coldest practical exhaust temperature is required. A low exhaust temperature also tends to minimize post-oxidation of the combustion products.

5. Spectral Equipment

The assembly of the spectral equipment is almost complete. Modification of existing equipment and fabrication of additional components are complete, except for the light-source intensity monitors and the ring mounting which supports the light sources. Transport of the equipment to the test site and installation will be undertaken as required.

The principal objective of the spectrometric measurements is to obtain the static gas temperature and the optical depth of the particle cloud at three axial stations in the secondary combustor. The ultimate objective of these measurements is to infer the extent of combustion of the primary propellant exhaust occurring at each axial station, so that the effect of specific parameters on the overall performance of the system can be evaluated. The progression of combustion manifests itself as a decrease in the mass fraction of boron nitride and as an increase in the static stream temperature, both of which can be determined from the measured values of spectral transmittance\* and radiance.

The experimental program will be directed toward obtaining (1) the spectral transmittance and radiance at the spectrum line center of the first line of the sodium-D doublet, 5890 Å and (2) the spectral transmission and radiance associated with the continuum emission of the particle cloud at a wavelength of 5880 Å. These measurements will be taken at three axial stations in the secondary combustor, across the flow centerline.

\* Words ending in -ittance refer to systems or surfaces, while words ending in -ivity refer to materials, following the suggestion of NBS (Reference 1).

III, A, Phase I: Design, Fabrication, and Installation of Laboratory Micromotor Facilities (cont.)

The principal variable of interest, the gas temperature and its estimate of variance, will be calculated from the data taken at various times during the firing. The optical depth of the particle cloud will be determined from the same data. The optical depth, combined with an estimate of the particle size distribution in the cloud, will serve to define the condensed-phase temperature and mass fraction. From a regression analysis, the uncertainty in both of these parameters will also be determined, based on the uncertainty in the particle size distribution.

A requisite to the precise determination of particle temperature (but relatively unimportant to the determination of gas temperature) is the complex refractive index of boron nitride. A literature survey was undertaken and information requests were sent to several potential sources. A letter and report, received from Dr. W. W. Lozier of Union Carbide Corporation, contained optical transmission data for BN at room temperature and in the visible region. These data, along with information supplied N. J. Norante of the Carborundum Company, have been used to deduce the refractive index of BN both at room temperature and at the high temperatures expected in the secondary chamber.

The computer program employed to reduce the experimental spectral data to the desired temperatures has been written for use on the IBM 1130 computer. A description of the program (PROGRAM TEMP) is presented in the Appendix of this report.

The principal part of the spectral equipment is the spectral comparison pyrometer, which has been described in detail elsewhere (Reference 2). The fundamental components of this device are shown in Figure 5.

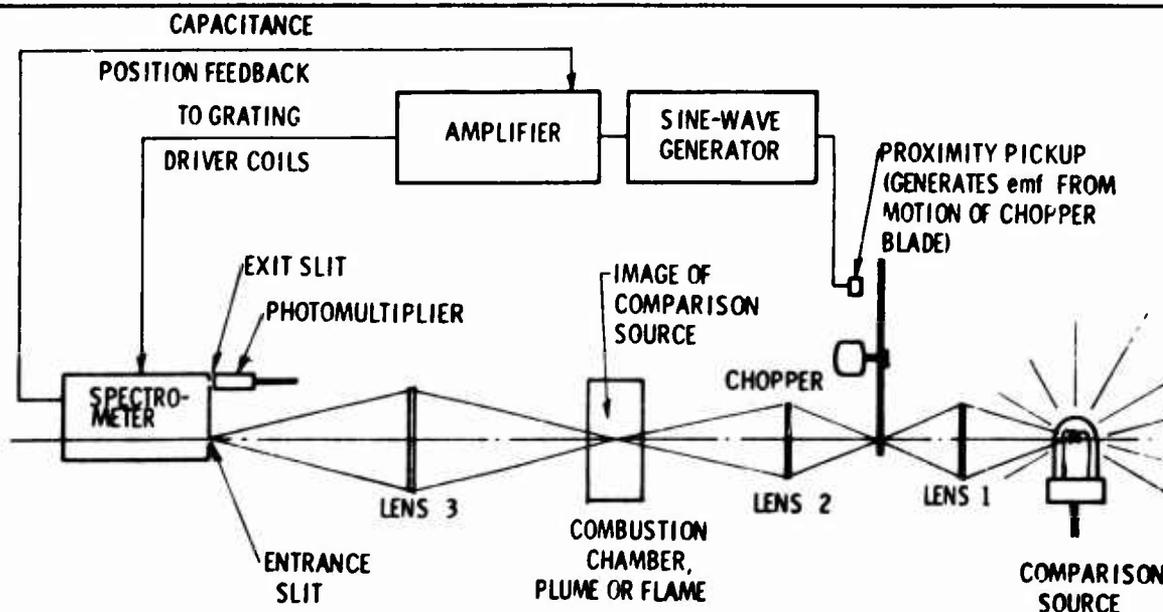


FIGURE 5. OPTICS AND ELECTROMECHANICAL SCHEMATIC OF SPECTRAL COMPARISON PYROMETER

III, A, Phase I: Design, Fabrication, and Installation of Laboratory Micromotor Facilities (cont.)

A reference light source (DC carbon arc), chopper, and associated optics will be used at each of the three axial positions under study. Each of the reference source beams will pass through a set of diametrically opposed windows. The light from each station will be picked up by an optical light guide and passed to an optical sampling scanner which sequentially samples the radiance from each station and focuses it on the entrance slit of the spectrometer.

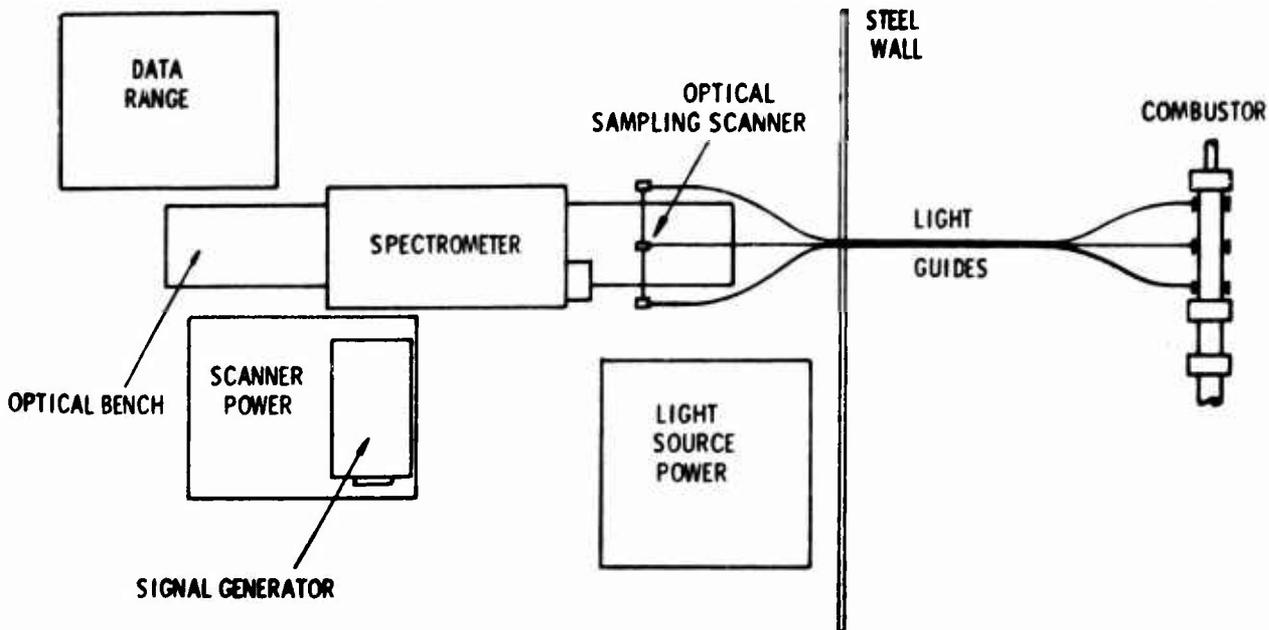


FIGURE 6. SPECTRAL EQUIPMENT LAYOUT

Placement of the apparatus is shown in Figure 6. Because of the potential hazards associated with any engine test experiments, the spectrometer will be protected by the steel wall shown in the figure with the optical light guides passing through a hole in the wall. The three carbon arc lamps and related optics will be positioned by means of mounting rings around the secondary combustion chamber. The spectrometer and optical sampling scanner will be placed on a lathe-bed optical bench at a distance to minimize the length of the optical light guides.

Special components which were required to complete the apparatus include (1) three reference source beam intensity monitors for recording the radiance of each of the carbon arc lamps throughout a run, (2) the scanner power supply to drive the grating within the spectrometer, and (3) the impedance couplers and data ranging equipment to provide signals of low impedance and a range of gains for coupling of all equipment to the data recording equipment.

III, A, Phase I: Design, Fabrication, and Installation of Laboratory  
Micromotor Facilities (cont.)

6. Micromotor B

The second stage of the test program involves the use of Micromotor B for thrust measurements. The design of the thrust combustor will be substantially less complicated than Micromotor A, in that the spectral measurements and exhaust sample collection will not be required and water cooling of the combustion chamber will be eliminated. However, the thrust stand planned will carry much of the auxiliary equipment, such as the air/nitrogen storage tank and heater, propellant tanks, valves, and lines. In this manner more accurate thrust measurements can be made.

Design of the thrust stand and combustor will be initiated later in the program. Experience with Micromotor A will provide necessary and valuable information about the design requirements for Micromotor B.

III, Technical Discussion (cont.)

B. PHASE II: DETERMINATION OF COMBUSTION CHARACTERISTICS IN AIR OF EXHAUST PRODUCTS OF PENTABORANE-HYDRAZINE SYSTEM

Phase II is concerned with the engine test evaluation of the air-augmented pentaborane-hydrazine system. Fifty-two tests are planned with Micromotor A and 23 tests are planned with Micromotor B. A wide range of test conditions will be investigated during the test phase, including:

1. Primary propellant mixture ratio--1.27, 0.9, and 0.6.
2. Primary chamber pressure--425 psia, 300 psia.
3. Air-to-propellant ratio--8:1, 16:1, and 40:1.
4. Secondary chamber pressure--200 psia, 50 psia.
5. Secondary air temperature--800°F, 1500°F.

Test measurements will include the following:

1. Propellant and air flow rates.
2. Air inlet temperature and pressure.
3. Pressure in the primary and secondary chambers.
4. Total thrust.
5. Percent conversion of boron and boron nitride to boron oxide(s) by collection and analysis of final exhaust products.
6. Optical measurements in the secondary chamber (gas-temperature determination is required, particle-temperature determination is desired).

Characteristic velocity, chamber temperature, and specific impulse will be calculated based on these test measurements.

The tentative test program planned for Micromotor A is outlined in Table I. Throughout the testing program, combustion efficiencies based on the calculation of characteristic velocity will be determined.

The initial tests will be directed primarily toward determining (1) the extent of combustion of boron and boron nitride in the combustor and (2) whether post-oxidation of these materials occurs. If conversion of these materials is not achieved, a larger secondary chamber will be installed.

III, B, Phase II: Determination of Combustion Characteristics in Air  
of Exhaust Products of Pentaborane-Hydrazine System (cont.)

Temperature profile studies will be initiated using thermocouples installed in the secondary chamber. In the placement of the thermocouples, consideration will be given to the mixing patterns of the air and primary exhaust streams, so that reliable interpretations can be made from the data. Spectral measurements will be made also, to test the design of the optical ports. A suitable window design is required in subsequent tests.

Emphasis in the experiments in the main body of the testing program will be on studying the effects of the various operating parameters on the performance characteristics of the air-augmented system. The efficiency of boron and boron nitride conversion to the oxides, as indicated by  $c^*$  determinations, will be substantiated by analyses of the combustion products of selected runs.

The tentative test program using Micromotor B is presented in Table II. These tests are devoted to the measurement of thrust under the operating conditions previously studied for Micromotor A. From these data, specific impulse calculations will be made. In addition to the thrust and specific impulse determinations, the  $c^*$  values will be determined for comparison with the results obtained earlier in Micromotor A.

TABLE I  
TENTATIVE TEST PROGRAM WITH MICROMOTOR A

Test No.	Test Parameters				Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N <sub>2</sub> )-to-Propellant Ratio	Primary Propellant Mixture Ratio	
1	800	200	8/1	1.27	The medium-sized secondary chamber (1.9-in. dia and 14.0-in. length) will be used in Tests 1 through 6. The study of two particularly important factors (post-oxidation and conversion of B and BN to oxygenated species in the secondary chamber) will be emphasized in these first tests. Both phenomena will be studied by analysis of the solids in the secondary exhaust. If conversion does occur satisfactorily, the medium-sized secondary chamber will be used in the tests which follow. If conversion is not effected, the large-sized secondary chamber (2.9-in. dia and 60.0-in. length) will be used. A combustion efficiency based on c* will be determined for these runs. A major decision point will be reached at conclusion of Run 6.
2	800	200	16/1	1.27	
3	800	200	40/1	1.27	
4*	800	200	8/1	1.27	
5	800	200	8/1	1.27	
6	800	200	16/1	1.27	

TABLE I (cont.)

Test No.	Test Parameters				Remarks	
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N <sub>2</sub> )-to-Propellant Ratio	Primary Propellant Mixture Ratio		
7	1500	50	8/1	1.27	These runs will again emphasize the study of post-oxidation and oxidation of boron species in secondary chamber. If oxidation of conversion of the boron species does occur satisfactorily, the medium-sized secondary chamber will continue to be used in the tests which follow. If not, the larger-sized chamber will be used. C* determinations will also be carried out. A major decision point will be reached at conclusion of Run 10.	
8	1500	50	16/1	1.27		
9	1500	50	40/1	1.27		
10*	1500	50	8/1	1.27		
11	800	200	8/1	1.27		The objectives of Runs 11 through 16 are (1) to obtain a temperature profile along the longitudinal axis of the secondary chamber and (2) to check out spectral techniques for temperature measurements. Twelve thermocouples and a single pair of sapphire windows, i.e., one spectral analysis site, will be installed on secondary chamber for this purpose. C* determinations will also be carried out. A major decision point will be reached at conclusion of Run 16.
12	800	200	16/1	1.27		
13	800	200	40/1	1.27		
14*	800	200	8/1	1.27		
15	1500	50	8/1	1.27		
16	1500	50	16/1	1.27		

TABLE I (cont.)

Test No.	Test Parameters			Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N <sub>2</sub> )-to-Propellant Ratio	
17	800	200	8/1	Emphasis in these runs will be placed on obtaining spectral data at three different locations of the secondary chamber; one site in the fore part of the chamber, a second intermediate site, and th. third location in the aft part of the chamber. The three sites will be monitored simultaneously. Run 23 will be identical to Runs 17 and 18 except that nitrogen rather than air will be used. Runs 24 through 26 provide tests for the high Mach number simulation. Runs 27 through 29 provide tests for the low Mach number simulation plus a fuel-rich primary propellant combination. Spectral data will be obtained at each of three sites in each of these runs. C* determinations will be made for each run.
18	800	200	8/1	
19	800	200	16/1	
20	800	200	16/1	
21	800	200	40/1	
22	800	200	40/1	
23*	800	200	8/1	
24	1500	50	8/1	
25	1500	50	16/1	
26	1500	50	40/1	
27	800	200	8/1	
28	800	200	16/1	
29	800	200	40/1	

TABLE I (cont.)

Test No.	Test Parameters			Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N <sub>2</sub> ) - to-Propellant Ratio	
30	800	200	8/1	The objective of this series of 11 runs, Runs 30 through 40, is to obtain performance data at propellant mixture ratios which are less than stoichiometric, e.g., MR = 0.9 and 0.6. Combustion efficiencies based on c* will be determined for each run.
31	800	200	16/1	
32	800	200	40/1	
33*	800	200	8/1	
34*	800	200	8/1	
35	1500	50	8/1	
36	1500	50	16/1	
37	1500	50	40/1	
38	800	200	8/1	
39	800	200	16/1	
40	800	200	40/1	

TABLE I (cont.)

Test No.	Test Parameters				Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N <sub>2</sub> ) - to-Propellant Ratio	Primary Propellant Mixture Ratio	
41	800	200	8/1	1.27	A primary nozzle having no diverging section will be used in Runs 41 through 46; the same secondary chamber used in the previous runs will be employed. This design may provide the best gas stream mixing and the highest primary exhaust temperature. The effect of these potentially beneficial parameters upon combustion efficiency (based on c*) is of interest.
42	800	200	16/1	1.27	
43	800	200	40/1	1.27	
44*	800	200	8/1	1.27	
45	800	200	16/1	0.6	
46	800	200	16/1	0.9	
47	800	200	8/1	1.27	Runs 47 through 52 will be conducted using the smallest of the three secondary chambers, i.e., the one having a 1.15-in. dia and 3.9-in. length. The results of this series of runs, as interpreted from combustion efficiency (c*), will provide useful design data for future programs.
48	800	200	16/1	1.27	
49	800	200	8/1	1.27	
50	800	200	16/1	1.27	
51	1500	50	8/1	1.27	
52	1500	50	16/1	1.27	

\*Nitrogen will be used as the secondary gas in these runs.

TABLE II  
TENTATIVE TEST PROGRAM WITH MICROMOTOR B

Test No.	Test Parameters				Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N <sub>2</sub> ) - to-Propellant Ratio	Primary Propellant Mixture Ratio	
1	800	200	8/1	1.27	The primary objective of Runs 1 through 3 is to demonstrate whether the performance (based on c*) realized with Micromotor B is the same as with Micromotor A. The experimental conditions associated with Runs 1 through 3 are identical with those of Runs 1 through 3 made with Micromotor A. Micromotor B will be instrumented for thrust measurement and have the same design for the primary and secondary combustion chambers as Micromotor A. Micromotor B will also be checked out for thrust-measurement-use in these first runs.
2	800	200	16/1	1.27	
3	800	200	40/1	1.27	
4	800	200	8/1	1.27	
5	800	200	8/1	1.27	
6*	800	200	8/1	1.27	
7	800	200	16/1	1.27	
8	800	200	16/1	1.27	
9	800	200	40/1	1.27	
10	800	200	40/1	1.27	

TABLE II (cont.)

Test No.	Test Parameters			Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air (or N <sub>2</sub> )-to-Propellant Ratio	
11	1500	50	8/1	Runs 11 through 13 continue the pattern set by Runs 4 through 10. The secondary air temperature and the secondary chamber pressure are different for the two sets of runs, however. The same objectives are sought, i.e., thrust data primarily and c* data secondarily.
12	1500	50	16/1	
13	1500	50	40/1	
14	800	200	8/1	Runs 14 through 16 are the same as Runs 4 through 9 except that the propellant mixture ratio is lowered from 1.27 to 0.9.
15	800	200	16/1	
16	800	200	40/1	
17	800	200	8/1	Runs 17 through 19 are identical to Runs 4 through 9 except that the propellant mixture ratio is lowered from 1.27 to 0.6.
18	800	200	16/1	
19	800	200	40/1	

TABLE II (cont.)

Test No.	Test Parameters				Remarks
	Secondary Air (or N <sub>2</sub> ) Temperature (°F)	Secondary Chamber Pressure (psia)	Air(or N <sub>2</sub> )-to-Propellant Ratio	Primary Propellant Mixture Ratio	
20	800	200	8/1	1.27	Runs 20 through 23 will be conducted using a primary nozzle having no diverging section. The same secondary chamber used in the previous runs will be employed. This design may provide the best gas stream mixing and the highest primary exhaust temperatures. Their effect upon thrust is of interest. These tests will be conducted only if the similar tests with Micromotor A, Tests 41 through 46, indicate that they are of interest. Other tests will be substituted if the non-expansion nozzle is deleterious.
21	800	200	16/1	1.27	
22	800	200	40/1	1.27	
23	1500	50	16/1	1.27	

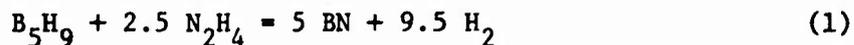
Nitrogen will be used as the secondary gas in these runs.

## III, Technical Discussion (cont.)

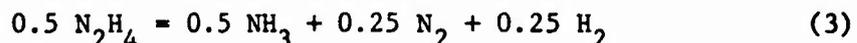
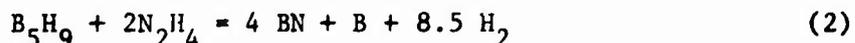
## C. PHASE III: INTERPRETATION OF MICROMOTOR TEST RESULTS

This phase of the program is concerned with the development of a theoretical model of the combustion process or processes. Correlation between the various experimental parameters will be sought through theoretical chemical and physical considerations.

The combustion process which occurs in the primary chamber has been the subject of extensive study both at Aerojet and elsewhere (Reference 3). The theoretical reaction which yields the highest specific impulse and which is thermodynamically favored is represented by equation (1).



However, analyses of the combustion products, both gaseous and solid, and experimental performance tests indicate that this optimum process does not occur. Rather, the reactions which most satisfactorily account for the observed combustion products and performance are



The secondary-combustion process in air will involve the combustion of both gaseous and solid, particulate material. This secondary process can be considered to occur in four distinct stages: (a) the mixing of air with the primary exhaust stream, (b) the ignition of the combustible gases, (c) the surface reaction of the particles, whereby their temperature is raised to ignition, and (d) the combustion of the boron nitride-boron in the vapor phase surrounding the particle or at the particle surface.

The mixing of the primary exhaust with air is accomplished by turbulent eddy diffusion followed by molecular diffusion. The turbulent eddy diffusion brings about the intermixing of the two streams on a sufficiently fine scale to permit the molecular diffusion to occur rapidly. Therefore, the efficiency of the mixing process is highly dependent on the physical configuration of the flowing streams and on the transport properties of the flows. Within the constraints of practical design considerations, the air inlet and primary exhaust ports have been designed to provide large velocity differences between the two streams and a large angle between their centerlines. These factors are considered to be especially important in the promotion of turbulence.

III, C, Phase III: Interpretation of Micromotor Test Results (cont.)

The combustible gases in the primary exhaust ignite as they mix with the air. These gases, chiefly hydrogen and ammonia, have relatively wide flammability limits and low ignition temperatures. Hence, the combustion of these gases is expected to occur rapidly and completely.

A particle can be brought to its ignition temperature in two different ways: (1) the transfer of heat from the gas surrounding the particle or (2) by surface chemical reaction of the particle with the surrounding gas. Heat transferred to the surface of the particle by either mechanism must exceed the rate of dissipation of the energy from the surface.

Both particle size and concentration are factors in this heat balance. A smaller particle has high surface-to-volume ratio, which results in a high rate of heat production per unit volume and a low cooling rate. When particle concentration is high, more of the heat radiated from a given particle will be used to heat neighboring particles.

Surface oxidation of the particles can lead to the formation of a protective oxide layer. If such a layer is formed, the result may be detrimental to particle ignition even though the particle temperature may be increased. However, if the oxide is sufficiently volatile to vaporize and expose unreacted surface, then ignition can be accomplished.

Similarly, the ultimate combustion of the particles is highly dependent on the surface condition of the particle. If the active particle surface is continually renewed by the volatilization of the oxide, then the rate of combustion is controlled by the diffusion of oxygen to the surface in the heterogeneous system. On the other hand, if the oxide does not vaporize at a significant rate, then the combustion may be inhibited.

Homogeneous gas-phase reactions occur rapidly and efficiently; consequently, in systems where the temperature is sufficiently high to vaporize the material of the particle, as well as the combustion products, the maximum rate of combustion is achieved.

The conditions which will be encountered in the secondary chamber will vary over a wide range. The primary propellant ratio will be varied over the range from pentaborane-rich to stoichiometric. Consequently, the boron content of the solid exhaust will vary appreciably. Also, the air-to-propellant ratio will be varied over a wide range, as will the air inlet temperature and pressure, giving rise to large variations in chamber temperatures.

The variation in chamber conditions may result in significant changes in the modes of ignition and combustion of the solid material. Temperature profiles, studied both spectroscopically and with thermocouples,

III, C, Phase III: Interpretation of Micromotor Test Results(cont.)

and chemical analysis of the combustion products, will be of value in discerning the prevailing mechanisms. These observations, combined with the  $c^*$  efficiencies and  $I_{sp}$  determinations will permit the establishment of the combustion model.

SECTION IV

FUTURE WORK

A. PHASE I: DESIGN, FABRICATION, AND INSTALLATION OF MICROMOTOR FACILITIES

1. Micromotor "A"

The preparation of the test bay and auxiliary facilities will be completed. The fabrication of the combustor components and the installation of the micromotor facilities will be completed.

2. Exhaust Sampling System

The design, fabrication, and installation of the exhaust sampling system, including the water-cooled ducts, and the dust-collection system, will be completed.

3. Spectral Equipment

The assembly and installation of the equipment for spectral temperature measurements will be completed.

4. Micromotor "B"

The design and fabrication of components of the thrust stand and combustor will be initiated as the design requirements are established.

B. PHASE II: DETERMINATION OF COMBUSTION CHARACTERISTICS IN AIR OF EXHAUST PRODUCTS OF PENTABORANE-HYDRAZINE SYSTEM

The testing program outlined in Table 1 is scheduled to commence on 18 September 1967 and the program outlined in Table 2 is scheduled to commence on 1 February 1968.

C. PHASE III: INTERPRETATION OF MICROMOTOR TEST RESULTS

This phase of the program is scheduled to commence on 18 September 1967, when the installation of Micromotor A has been completed and the testing program has been initiated.

REFERENCES

1. W. N. Harrison, Paper No. 1 of Measurement of Thermal Radiation Properties of Solids, J. C. Richmond, Editor of Symposium, Dayton, Ohio, September 1962.
2. S. F. Colucci and J. M. Adams, Flame Temperature Measurement of Metalized Propellant (U), Final Report on Contract AF 04(611)-10545, Report No. AFRPL-TR-66-203, September 1966 (Confidential).
3. Proceedings of the Pentaborane-Hydrazine Combustion Conference, Edwards Air Force Base, August 16-17, 1960.

APPENDIX

PROGRAM TEMP--A COMPUTATIONAL SCHEME IN  
FORTRAN IV FOR DETERMINATION OF GAS AND  
PARTICLE TEMPERATURE FROM SPECTROMETRIC DATA

I. GENERAL DESCRIPTION

Program TEMP is a machine program written in Fortran IV language for use either with the IBM 360, 7094 or 1130 machines. Input data is placed on 80 column punched cards. Output is adaptable to 8-1/2 x 11 in. paper.

The program receives calibration data related to the spectral response of some sort of detector used for the spectrometric measurements. Detector constants (called "TUBE CONSTANT") are determined over any spectral range and signal strength, the number of total data points being limited to 100, at a maximum of 10 wavelengths.

From spectrometric data taken within the continuum of the flame and at specific spectrum line centers, the temperature of both the gas and particle cloud within the flame is calculated from Planck's Law.

II. COMPUTATIONAL SCHEMES

The main program is divided into several computational schemes, identified by the comment card which corresponds to the following headings (refer to Table I).

TABLE I

```

C      PROGRAM TEMP - A COMPUTATIONAL SCHEME IN FORTRAN IV
C      FOR DETERMINATION OF GAS AND PARTICLE TEMPERATURES
C      FROM SPECTROMETRIC DATA.
C
C      EXTERNAL TWF1
C      DIMENSION TA(15),FLA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),
C      IELD(10)
C      DIMENSION AK(100),E(100)
C      COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2
C      AKTF(X3)=(A+B*(X3-EB))/GAIN
C
C      FORMAT STATEMENTS
C
C      100 FORMAT(11)
C      110 FORMAT(8F10.0)
C      120 FORMAT(4I5)
C      130 FORMAT(2F10.0,110,5F10.0)
C      140 FORMAT( 27H0  MEAN PARTICLE VOLUME = E12.5, 7H CU CM /
C      127H0  NUMBER CONCENTRATION = E12.5,11H PER CU CM )
C      150 FORMAT(F10.0,110)
C      160 FURMAT(34H0  EQUATION FOR TUBE CONSTANT AT F6.4, 9H MICRONS )
C      170 FORMAT( 16H0  K(E) = E12.5, 3H + E12.5, 6H (E - E12.5, 1H))
C      180 FORMAT(15H0  RUN TIME = F8.3,6H SECS )
C      190 FORMAT( 37H0  WITH VARIANCE OF ESTIMATE = E12.5 /
C      1 37H  POPULATION VARIANCE = E12.5 /
C      2 17H  FTEST = F7.3, 8H HAVING 13,14H DEG OF FRDM. )
C      200 FORMAT(25H0  SOURCE TEMPERATURE = F9.3)
C      210 FORMAT(E20.5,5F10.0)
C      220 FORMAT(4E20.5)
C      230 FORMAT(5F10.0,20X,110)
C      240 FURMAT(22H0  FLAME THICKNESS = E12.5, 4H CM )
C      250 FORMAT(63H0  ---*--
C      1----- )
C      260 FORMAT(22H0  PARTICLE EMISS. = F7.4,8H, REF = F7.4, 4H AT F6.4,
C      1 9H MICRONS / 22H  PARTICLE EMISS. = F7.4,8H, REF = F7.4,4H AT
C      2F6.4,9H MICRONS /21H  GAS EMISSIVITY = F7.4,4H AT F6.4,9H MICRONTEMP
C      35 )
C      270 FORMAT(63H0  *****EFFECTIVE FLAME THICKNESS USED (MULT. SCATTERINTEMP
C      1G)***** /22H  XNO*GS1*ST = E12.5 )

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280 FORMAT(4E15.5/4E15.5)
290 FORMAT(21H0 #PARTICLE TEMP. = F7.2, 1-H, (0.5 TEMP. = F7.2)
300 FORMAT(64H0 #PARTICLE TEMPERATURE EFFECTS NEGLECTED-----
1-----)
310 FORMAT(72H0)
1 PARTICLE EMISS. = F7.4,15H, GAS EMISS. = F7.4,4H AT F6.4,9H MICRONS /22H
2NS )
320 FORMAT(72H0----- /35H -----)
1-----
2-----*
330 FORMAT(11H0 TIME = F8.3,5H SECS )
340 FORMAT(72H /72H
1
2
3
350 FORMAT(5E10.5,F10.0)
360 FORMAT(7F10.0,110)
370 FORMAT( 32H0 TRANSVERSE - OPTICALLY THICK )
380 FORMAT( 32H0 TRANSVERSE - OPTICALLY THIN )
390 FORMAT(F8.1,3E21.5)
400 FORMAT (3H0A 2F9.2,14)
410 FORMAT (3H0B 2F9.2,14)
420 FORMAT ( 25H0 I ELD(I) TW2(I) )
430 FORMAT (13,2X,F6.4,E14.5)
440 FORMAT ( 340C 2E11.4/3E11.4/4E11.4 )
450 FORMAT(3H0D 5E12.5)
460 FORMAT( 32H GAIN RATIO, RUN/CAL. = F8.5)
C READ DATA FOR TABLES OF EMISSIVITY VS. TEMP, WAVELENGTH
READ (5,120)J1,II
READ(5,110) (TA(I),I=1,J1)
READ(5,110)(ELA(I),I=1,11)
READ (5,110) ((EPSI(I,J),I=1,11),J=1,J1)
C
C I INDEX REFERS TO LAMBDA, J INDEX REFERS TO TEMPERATURE.
C EPSILONS SHOULD BE PUNCHED IN THE FOLLOWING MANNER -
C EPS(LAM(1),T(1)), EPS(LAM(2),T(1)),...,EPS(LAM(I),T(1)),
C EPS(LAM(1),T(2)), EPS(LAM(2),T(2)),...
C
C READ WINDOW TRANSMISSIVITY (CLEAN)
READ (5,120)J2
C (LA) (5,110)(TM(I),I=1,J2)
C
C READ (5,130) (7,ELR,K0,ERR,CORV

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C C2 = THE CONSTANT IN THE PLANCK RELATION.
C ELR = THE WAVELENGTH AT WHICH BRIGHTNESS TEMP. IS MEASURED.
C K0 = NO. OF ALLOWED ITERATIONS IN DETR. OF TRUE TEMPERATURE.
C ERR = ALLOWED REL. ERROR IN TRUE TEMP. OF REF. SOURCE
C
C READ (5,110) EL1,EL2
C 470 READ (5,340)
C JJJ=1
C PRINT HEADING
C
C WRITE (6,340)
C READ (5,100) INDI
C
C INDICATOR CODE
C
C IND1
C 1 READ NEW CALIBRATION DATA, CALC. AND PRINT TABLES, CALC.
C AND PRINT TEMPERATURES
C 2 CONTINUE TO READ AND PRINT CALIBRATION AT VARIOUS LAMBDA
C 3 READ ONLY PRE-, POSTRUN CALIBRATION, CALC., PRINT TEMP.
C 4 PRINT EVERYTHING, INCLUDING CHECKOUT VALUES
C 5 CALL EXIT
C IND
C 0 READ MORE TEMPERATURE DATA CARDS
C 1 READ NEW CASE, SAME EMISSIVITY TABLES
C IND3
C 1 BRIGHTNESS TEMPERATURE IN DEGREES FAHRENHEIT
C 2 BRIGHTNESS TEMPERATURE IN DEGREES CENTRIGRADE
C 3 BRIGHTNESS TEMPERATURE IN DEGREES KELVIN
C
C READ (5,350) VBAR,GAI,GS1,GF2,GS2,CHI
C GO TO (480,480,690,480,870),IND1
C *****
C CALCULATION OF DETECTOR CONSTANTS
C
C READ WAVELENGTH VALUE FOR PHOTOTUBE CALIBRATION POINTS
C 480 READ(5,130)ELC
C J5=1
C IND4=1
C GAIN=1.0
C I=1
C READ DATA FROM PRELIMINARY PHOTOTUBE CALIBRATION. THIS CALIBRATION
TEMP 86
TEMP 87
TEMP 88
TEMP 89
TEMP 90
TEMP 91
TEMP 92
TEMP 93
TEMP 94
TEMP 95
TEMP 96
TEMP 97
TEMP 98
TEMP 99
TEMP 100
TEMP 101
TEMP 102
TEMP 103
TEMP 104
TEMP 105
TEMP 106
TEMP 107
TEMP 108
TEMP 109
TEMP 110
TEMP 111
TEMP 112
TEMP 113
TEMP 114
TEMP 115
TEMP 116
TEMP 117
TEMP 118
TEMP 119
TEMP 120
TEMP 121
TEMP 122
TEMP 123
TEMP 124
TEMP 125
TEMP 126
TEMP 127
TEMP 128
TEMP 129

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C ACCOMPLISHED WITH REFERENCE LIGHT SOURCE POSITIONED CLOSE ENOUGH
C TO SPECTROMETER TO GIVE OUTPUT EMF GREATER THAN ANY EMF GENERATED
C DURING THE RUN.
C ONE OR MORE EMF VALUE REQUIRED FOR EACH BRIGHTNESS TEMP AT THE
C WAVELENGTH READ IN ABOVE. ONE BLANK CARD REQUIRED TO READ IN NEW
C BRIGHTNESS TEMP. TWO BLANK CARDS REQUIRED AT END OF THIS DATA.
C T2 = BRIGHTNESS TEMPERATURE.
C 490 READ (5,150)TR,IND3
C
C IF(TB)630,630,500
500 GO TO (510,520,530),IND3
510 TX=TB
    TB=(TB+459.6)/1.8
    GO TO 540
520 TX=(TB+273.12)*1.8-459.6
    TB=TB+273.12
    GO TO 540
530 TX=TB*1.8-459.6
540 T1=TR
    K1=0
550 T2=C2/(FLR*ALOG(1.0+EPS(FLR,T1))*( EXP(C2/(ELR*TR))-1.0))
    GO TO (570,570,560,570),IND1
560 WRITE (6,400)T1,T2,K1
570 K1=K1+1
    IF(ABS((T1-T2)/T1)-ERR)600,600,580
580 IF(K1-K0)590,600,600
590 T1=T2
    GO TO 550
600 T5=T2
    GO TO (610,700),IND4
C
C READ EMFS, E1, AT GIVEN TR. EQUATION CALCULATED
C
C 610 READ (5,110) F1
    IF(E1)490,490,620
620 E(I)=E1
    AN(I)=EPS(ELC,T5)*TWF1(ELC)**2*K1(ELC,T5)/E1
    I=I+1
    GO TO 610
C
C REINITIALIZE
C 630 JJ=I-1
    EN=JJ
    OXY=0.0

```

TEMP 130  
TEMP 131  
TEMP 132  
TEMP 133  
TEMP 134  
TEMP 135  
TEMP 136  
TEMP 137  
TEMP 138  
TEMP 139  
TEMP 140  
TEMP 141  
TEMP 142  
TEMP 143  
TEMP 144  
TEMP 145  
TEMP 146  
TEMP 147  
TEMP 148  
TEMP 149  
TEMP 150  
TEMP 151  
TEMP 152  
TEMP 153  
TEMP 154  
TEMP 155  
TEMP 156  
TEMP 157  
TEMP 158  
TEMP 159  
TEMP 160  
TEMP 161  
TEMP 162  
TEMP 163  
TEMP 164  
TEMP 165  
TEMP 166  
TEMP 167  
TEMP 168  
TEMP 169  
TEMP 170  
TEMP 171  
TEMP 172  
TEMP 173

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```

SY=0.0
SX=0.0
SX2=0.0
DO 640 I=1,JJ
  SXY=SXY+AK(I)*E(I)
  SY=SY+AK(I)
  SX2=SX2+E(I)**2
  SX=SX+E(I)
  A=SY/EN
  EB=SX/EN
  IF(EN*SX2-SX**2)660,650,660
640 R=0.0
  GO TO 670
650 B=(EN*SXY-SX*SY)/(EN*SX2-SX**2)
660 SP2=0.0
  SE2=0.0
  DO 680 I=1,JJ
    SE2=SE2+((A+B*(E(I)-EB)-AK(I))**2)/(EN-2.)
680 SP2=SP2+((AK(I)-A)**2)/(EN-1.)
  FTST=SP2/SE2
C
C PRINT TUBE CONSTANT EQUATION
  WRITE (6,160) ELC
  WRITE (6,170) A,B,EB
  WRITE (6,190) SE2,SP2,FTST,JJ
  GO TO (690,480,690,690,690),INDI
C READ REFERENCE SOURCE CONDITION PRIOR TO RUN. ESTABLISH
C GAIN CHANGE FROM CALIBRATION CONDITION
690 IND4=2
700 SUME1=0.0
  I=0
710 READ(5,110) E1
  IF (E1) 730,730,720
720 SUME1=SUME1+E1
  I=I+1
  EN=I
  GO TO 710
730 AVE1=SUME1/EN
  GAIN=AVE1*AKTF(AVE1)/(RI(ELC,TS)*EPS(ELC,TS)*TWFL(ELC)**2)
  WRITE(6,460) GAIN
  *****
  CALCULATION OF REFERENCE SOURCE AND WINDOW CONDITIONS DURING RUN
C
C
C
TEMP 174
TEMP 175
TEMP 176
TEMP 177
TEMP 178
TEMP 179
TEMP 180
TEMP 181
TEMP 182
TEMP 183
TEMP 184
TEMP 185
TEMP 186
TEMP 187
TEMP 188
TEMP 189
TEMP 190
TEMP 191
TEMP 192
TEMP 193
TEMP 194
TEMP 195
TEMP 196
TEMP 197
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TEMP 203
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TEMP 205
TEMP 206
TEMP 207
TEMP 208
TEMP 209
TEMP 210
TEMP 211
TEMP 212
TEMP 213
TEMP 214
TEMP 215
TEMP 216
TEMP 217

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C READ REFERENCE POINT TO ESTABLISH REF. SOURCE TEMP DURING RUN
740 READ(5,130) ELPP,ELD
    T1=3000.
    K2=0
750 T2=C2/(FLP*ALOG(1.+FPS(FLP,T1)/(FLP**5.*F10P*AKTF(F10P))))
    GO TO (770,770,770,760,770),INDI
C
C CHECKOUT PRINT
760 WRITE (6,410) T1,T2,K2
770 IF(ABS((T2-T1)/T1)-ERR)800,800,780
780 K2=K2+1
    IF(K2-K0)790,800,800
790 T1=T2
    GO TO 750
800 TS=T2
C
C PRINT SOURCE TEMPERATURE DURING RUN
    WRITE (6,200) TS
C
C READ POST-FIRE REFERENCE POINTS TO ESTABLISH CHANGE OF TRANSMISS-
    IVITY DURING RUN, TR = RUN TIME
    T*2(I)=TRANSMISSIVITY AT END OF RUN AT WAVELENGTH ELPP(I).
    REINITIALIZE
    I=1
    READ (5,110) TR
    WRITE (6,180) TR
810 READ (5,110)ELOPP,ELPP
C
    IF(ELOPP)870,870,820
820 T*2(I)=(F10PP*AKTF(F10PP)/(FPS(FLPP,TS)*RI(FLPP,TS)))**.5
    ELD(I)=ELPP
    GO TO (830,830,860,830,830),INDI
830 GO TO (840,850),J5
840 WRITE (6,420)
    J5=2
850 TTT=TW2(I)
C
C PRINT POST FIRE TRANSMISSIVITY
    WRITE(6,430) I,ELPP,TTT
860 I=I+1
    GO TO 810
C
C *****
C CALCULATION OF GAS AND PARTICLE CLOUD TEMPERATURES AND
C SPECTRAL EMITTANCE

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TEMP 218  
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TEMP 220  
TEMP 221  
TEMP 222  
TEMP 223  
TEMP 224  
TEMP 225  
TEMP 226  
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TEMP 254  
TEMP 255  
TEMP 256  
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TEMP 259  
TEMP 260  
TEMP 261

```

C 870 READ (5,360) TI,E11,E12,E21,E22,RHOL,RHOG,IND
      XNO=CHI*RHOG/((CHI*RHOG+(1.-CHI)*RHUL)*VBAR)
      WRITE (6,140) VBAR,XNO
      IND2=IND+1
      CALL TRANS (TI,TR,TWF1,EL1,EL2,TAU1,TAU2)
      ST = THICKNESS OF THE FLAME, CM.
      ST=-(ALOG((E11*AKTF(E11))-E12*AKTF(E12)))/(TAU1**2.*EPS(EL1,TS))*
      IRI(EL1,TS))/(XNO*(GAI+GSI))
      COMP=XNO*GSI*ST
      Z=ST
      WRITE (6,320) JJJ
      IND6=1
      WRITE (6,330) TI
      WRITE (6,250)
      880 WRITE (6,240) ST
      CALCULATE EMISSIVITY OF PARTICLE CLOUD
      EPSPI=1.-EXP(-XNO*GAI*ST)
      REFP1=1.-EXP(-XNO*GSI*ST)
      CALCULATE PARTICLE TEMPERATURE
      TP=C2/(EL1*ALOG(1.+TAU1*EPSPI/(EL1**5.*E12*AKTF(E12))))
      EPSP2=1.-EXP(-XNO*GA2*ST)
      REFP2=1.-EXP(-XNO*GS2*ST)
      CALCULATE SPECTRAL ABSORPTION COEFFICIENTS.
      GAG=-ALOG((E21*AKTF(E21))-E22*AKTF(E22))/(TAU1**2*EPS(EL2,TS))*IRI(EL
      12,TS))/Z-XNO*(GA2+GS2)
      EPSG=1.-EXP(-GAG*ST)
      CALCULATE GAS TEMPERATURE
      ABB=1.-((1.-EPSP2)*(1.-EPSG)
      CEE2=XNO*GA2+GAG
      CEE3=(XNO*GA2/GAG)*IRI(EL2,TP)
      CEE=1.+1./(EL2**5.*(E22*AKTF(E22)*CEE2/(GAG*TAU2*ABB)-(CEE3))
      TG=C2/(EL2*ALOG(CEE))
      PRINT ALL TEMPERATURES
      WRITE (6,260) EPSPI,REFP1,EL1,EPSP2,REFP2,EL2,EPSPG,EL2
      WRITE(6,370)
      WRITE (6,290) TP,TG

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TEMP 262  
TEMP 263  
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TEMP 305

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TEMP 349

TP=C2/(EL1*ALOG(1.+TAU1*GA1*(1.-EXP(-XNO*(GAI+GSI)*ST)))/(FL1**5.**
1E12*AKTF(E12))*(GAI+GSI)))
ABB=1.-(1.-EPSG)*(1.-EPSP2)*(1.-REFP2)
CEE2=XNO*(GA2+GS2)+GAG
CEE=1.+1./(EL2**5.*(E22*AKTF(E22)*CEE2/(GAG*TAU2*ABB)-CEE3))
TG=C2/(EL2*ALOG(CEE))
WRITE (6,380)
WRITE (6,290) TP,TG
GO TO (900,900,900,900,890,900),IND1
890 WRITE (6,280) GAI,GA2,GS1,GS2,GAG,CEE2,CEE3,CEE
C
900 GO TO (910,920),IND6
910 IND6=2
ST=COMP*ST
WRITE (6,270) COMP
GO TO 880
C
CALCULATE VARIABLES FOR SAME DATA, NEGLECTING SCATTERING
920 EPSP1=1.0+(E12*AKTF(E12)-E11*AKTF(E11))/(TAU1**2.*EPS(EL1,TS)
1*RI(EL1,TS))
EPSP2=EPSP1*(GA2/GAI)
TP=C2/(EL1*ALOG(1.+EPSP1*TAU1/(EL1**5.*E12*AKTF(E12))))
EPSG=1.0-(E21*AKTF(E21)-E22*AKTF(E22))/(1.-EPSP2)*TAU2**2.
1*EPS(EL2,TS)*RI(EL2,TS))
GAP=-ALOG(1.-EPSP1)
GAG=-ALOG(1.-FPSG)
GO TO (940,940,940,940,940),IND1
940 DD=EPS(EL1,TS)
FF=RI(EL1,TS)
GG=T*FI(EL1)
WRITE (6,450) DD,FF,GG
WRITE (6,440) FI,FR,EL1,E12,EL1,E21,E22,EL2,TAU1,TAU2,GAP,GAG
940 ABB=1.-(1.-EPSG)*(1.-EPSP1)
CEE2=GAP+GAG
CEE3=(GAP/GAG)*RI(EL2,TP)
CEE=1.+1./(FL2**5.*(E22*AKTF(E22)*CEE2/(GAG*TAU2*ABB)-CEE3))
TG=C2/(E12*ALOG(CEE))
WRITE (6,300)
WRITE (6,310) FPSP1,FL1,EPSP2,EPSG,EL2
WRITE (6,290) TP,TG
JJJ=JJJ+1.
GO TO (870,870),IND2
950 END
C
SUBROUTINE OR FUNCTION USED
C
RI(WAVELENGTH,TEMP),THE PLANCK FUNCTION

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C EPS(WAVELENGTH,TEMP.),THE REFERENCE LIGHT SOURCE EMISSIVITY      TEMP 350
C TWFL(WAVELENGTH),THE TRANSMISSIVITY OF THE CLEAN WINDOW          TEMP 351
C TRANS, A SUBROUTINE TO CALCULATE TIME-DEPENDENT WINDOW TRANSMISS. TEMP 352
C FUNCTION RI(EL,T)
C DIMENSION TA(15),ELA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),
C IELD(10)
C COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2
C X=C2/(EL*T)
C IF(X-170.)110,110,100
C 100 RI=0.0
C RETURN
C 110 RI=1.0/(EL*.5.*(EXP(C2/(EL*T))-1.0))
C RETURN
C END
C FUNCTION EPS(EL, T)
C DIMENSION TA(15),ELA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),
C IELD(10)
C COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2
C 100 N=2
C 110 M=2
C 120 IF (EL-ELA(M)) 150,150,130
C 130 M=M+1
C 140 GO TO 120
C 150 IF (T-TA(N)) 180,180,160
C 160 N=N+1
C 170 GO TO 150
C 180 EPS1=EPSI(M-1,N-1)+((T-TA(N-1))/(TA(N)-TA(N-1)))*(EPSI(M-1,N)-
C 1EPSI(M-1,N-1))
C 190 EPS2=EPSI(M,N-1)+((T-TA(N-1))/(TA(N)-TA(N-1)))*(EPSI(M,N)-EPSI
C 1(M,N-1))
C 200 EPS=EPS1+((EL-ELA(M-1))/(ELA(M)-ELA(M-1)))*(EPS2-EPS1)
C RETURN
C END
C FUNCTION TWFL(EL)
C DIMENSION TA(15),ELA(40),EPSI(40,15),TW1(10),TW2(10),ELB(10),
C IELD(10)
C COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2
C M=2
C 100 IF(EL-ELR(M))120,120,110
C 110 M=M+1
C GO TO 100
C 120 TWFL= TW1(M-1)+(EL-FLR(M-1))*(TW1(M)-TW1(M-1))/(ELB(M)-ELR(M-1))
C RETURN
C END

```

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SUBROUTINE TRANS (T,S,J,A,B,X,Y)
DIMENSION TA(15),ELA(40),EPSI(40,15),TA1(10),TW2(10),ELB(10),
iELD(10)
COMMON TA,ELA,EPSI,TW1,TW2,ELB,ELD,C2
V=A
J=1
M=2
100 IF(V-FLD(M))130,130,120
110 IF(V-FLD(M))130,130,120
120 M=M+1
GO TO 110
130 TW2T = TW2(M-1)+(V-ELD(M-1), S: W2(M)-TW2(M-1))/(ELD(M)-ELD(M-1))
AA=(1./5.)*U(V)/TW2T -1.)
W= U(V)/(1.+AA*T)
GO TO (140,150),J
140 X=W
V=B
J=2
GO TO 100
150 Y=W
RETURN
END

```

TRANS 1  
 TRANS 2  
 TRANS 3  
 TRANS 4  
 TRANS 5  
 TRANS 6  
 TRANS 7  
 TRANS 8  
 TRANS 9  
 TRANS 10  
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 TRANS 12  
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 TRANS 16  
 TRANS 17  
 TRANS 18  
 TRANS 19  
 TRANS 20  
 TRANS 21

II, Computational Schemes (cont.)

A. CALCULATION OF DETECTOR CONSTANTS

After having read into storage the emissivity tables for the reference source being used in the calibration, the program will then accept data which relates signal strength (e.g., galvanometer deflection, inches) to reference source intensity (e.g., brightness temperature). After having calculated the detector constants which relate measured signal strength to radiance (or temperature), the program prints out an equation for the relationship together with statistical indicators by which to assess the validity of the relationship.

B. CALCULATION OF REFERENCE SOURCE AND WINDOW CONDITIONS DURING RUN

The reference source temperature is determined from the measured signal from the reference source just prior to flame introduction. Data on reference source intensity just after flame extinguishment is also introduced as input at this point in the routine, together with the run time. To account for any spectral nonuniformity in window transmissivity, the post-test data can include up to 10 wavelength data, each being associated with a corresponding source intensity. Any transient change in window transmissivity or reference source radiance is accounted for subsequently in the calculations of temperature from the spectrometric data, with the assumption that such changes occurred linearly with time between the pre- and post-run data points (i.e., during the "run time").

C. CALCULATION OF GAS AND PARTICLE CLOUD TEMPERATURES AND SPECTRAL EMITTANCE

The spectrometric data, in the form of galvanometer deflections, are introduced here. Data on gas and condensed phase density are used together with previously stored data on particle absorption and scattering cross sections to calculate the particle number density (or concentration) and other physical properties of the particle cloud as required. If no particulates are present in the flame, the mass fraction of particles, CHI, is set equal to zero on the input.

Several computational options are used to calculate temperatures. The first of these treats the problem of radiation scattering by the particle cloud for the "optically thin"\* condition. This treatment is valid for most common flames having particulate mass fractions up to 0.4 together with a thickness up to 7 centimeters. When conditions on condensed phase mass fraction or thickness simultaneously exceed these values, the results may be invalid.

---

\*This refers to optical characteristic of the cloud for scattering of radiation along the "line of sight;" this case is shown directly under "SCATTERING EFFECTS CONSIDERED," Table II.

II, C, Calculation of Gas and Particle Cloud Temperatures and Spectral Emittance (cont.)

At this condition on optical depth in a direction parallel to the optical axis, two conditions on transverse optical thickness are considered. In the first of these, termed the "TRANSVERSE-OPTICALLY THICK" case, the temperatures are computed for the condition where scattering losses from the flame radiation equal scattering gains, within the optical path. This condition is most frequently valid. In the second condition, termed "TRANSVERSE-OPTICALLY THIN" (see Table II), the results are based on the assumption that there is a net scattering loss of radiation from the flame within the optical path, either because the flame's transverse dimension is extremely small or because there is extreme thermal disequilibrium. In both of the above cases, it is assumed that all the radiation from the reference source, scattered out of the optical path, is permanently lost.

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TABLE II  
SAMPLE OUTPUT, PROGRAM TEMP

RUN NUMBER N-2, NITROGEN, TIME APPROXIMATE  
SODIUM SOLUTION USED TO COAT WALLS ON DOWNSTREAM END OF MIX CHAMBER

EQUATION FOR TUBE CONSTANT AT 0.5890 MICRONS

$$K(E) = 0.73433E-03 + -0.43587E-04 (F - 0.11233E 01)$$

WITH VARIANCE OF ESTIMATE = 0.49151E-10

POPULATION VARIANCE = 0.41460E-09

FTEST = 8.435 HAVING 12 DEG OF FRDM.

GAIN RATIO, RUN/CAL. = 1.00369

SOURCE TEMPERATURE = 2792.472

RUN TIME = 55.000 SECS

computed from EIOP, ELP  
all temperatures in °K

I	ELD(I)	TW2(I)
1	0.5880	0.96636F 00
2	0.5890	0.96705F 00
3	0.5900	0.96067F 00

MEAN PARTICLE VOLUME = 0.10000E-11 CU CM

NUMBER CONCENTRATION = 0.26666E 02 PER CU CM

-----CASE 1-----

TIME = 0.000 SECS

-----SCATTERING EFFECTS CONSIDERED-----

FLAME THICKNESS = 0.12406E 06 CM where particle effects are important, this qty must agree with actual thickness.

PARTICLE EMISS. = 0.0033, REF = 0.0325 AT 0.5880 MICRONS

PARTICLE EMISS. = 0.0033, REF = 0.0325 AT 0.5890 MICRONS

GAS EMISSIVITY = 0.3031 AT 0.5890 MICRONS

TRANSVERSE - OPTICALLY THICK

\*PARTICLE TEMP. 2828.01, GAS TEMP. = 2817.15

considered to be most  
valid under normal  
conditions

TRANSVERSE - OPTICALLY THIN

\*PARTICLE TEMP. = 2833.41, GAS TEMP. = 2822.24

TABLE II (cont.)

\*\*\*\*\*EFFECTIVE FLAME THICKNESS USED (MULT. SCATTERING)\*\*\*\*\*  
XNO\*GSI\*ST = 0.33084E-01

FLAME THICKNESS = 0.41047E 04 CM

PARTICLE EMISS. = 0.0001, REF = 0.0010 AT 0.5880 MICRONS

PARTICLE EMISS. = 0.0001, REF = 0.0010 AT 0.5890 MICRONS

GAS EMISSIVITY = 0.0118 AT 0.5890 MICRONS

TRANSVERSE - OPTICALLY THICK

B.

\*PARTICLE TEMP. = 4660.34, GAS TEMP. = 4491.25

TRANSVERSE - OPTICALLY THIN

\*PARTICLE TEMP. = 4660.87, GAS TEMP. = 4491.71

-----SCATTERING EFFECTS NEGLECTED-----

PARTICLE EMISS. = 0.0357 AT 0.5880 MICRONS

PARTICLE EMISS. = 0.0357, GAS EMISS. = 0.3031 AT 0.5890 MICRONS

\*PARTICLE TEMP. = 2217.68, GAS TEMP. = 2822.18

valid where no particles  
are present in flow stream.

II, C, Calculation of Gas and Particle Cloud Temperatures and Spectral Emittance (cont.)

The above computations are repeated, using an effective flame thickness to account for multiple scattering. The validity of this treatment has not been verified but it is used to serve as a basis of comparison.

Lastly, the data is reduced and temperatures calculated with the assumption that there is no scattering of radiation by the particles. This case leads to an accurate determination of temperature where the particles are pure absorbers or where there are no particles.

Under conditions ordinarily encountered in flames and small rocket motors, either the output directly under the heading "SCATTERING EFFECTS CONSIDERED. . . TRANSVERSE-OPTICALLY THICK" or under the heading "SCATTERING EFFECTS NEGLECTED," (Table II) will be most valid.

II, Computational Schemes (cont.)

D. SUBROUTINES OR FUNCTIONS USED

Subordinate to the main program deck are four subroutines which are used by the main program to perform intermediate calculations and interpolate tabulated information. They are described in the following paragraphs.

1. Function RI(EL, T)

This subroutine calculates the value of the Planck function:

$$R_1(\lambda, T) = \frac{1}{\lambda^5 \exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

2. Function EPS (EL, T)

This subroutine is used to perform the interpolation of the tabulated reference light source emissivity,  $\epsilon(\lambda, T)$ .

3. Function TWF1 (EL)

This subroutine interpolates tabulated pre-run window transmissivity data to obtain the window transmissivity at any specified wavelength.

4. Subroutine TRANS (T,S,U,A,B,X,T)

This subroutine calculates the window transmissivity at the specified time, based upon pre- and post-test transmissivity data. It is assumed that window deposits build up linearly with time.

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III. INPUT INFORMATION

The variables which must be included as input and the required format is shown in Table I. The following list of nomenclature gives a description of each of the input variables, in the order in which they must be read in.

<u>Set Number</u>	<u>Input Variable</u>	<u>Description [Format]</u>
1	*J1, I1	Indicates number of temperature, wavelength data points to be used in reference light source emissivity tables. [2I5.]
1a	*TA(I)	Temperature data point corresponding to identically indexed emissivity data point, °K. Maximum number of points is 15. [8F10.0]
1b	*ELA(I)	Wavelength data point corresponding to identically indexed emissivity data point, micron. Maximum number points is 40. [8F10.0]
1c	*EPSI(I,J)	Reference source emissivity data point at the ith value of wavelength and the jth value of temperature. Emissivity data is read in the order $\epsilon(\lambda_1, T_1)$ , $\epsilon(\lambda_2, T_2)$ , $\epsilon(\lambda_3, T_1)$ . . . $\epsilon(\lambda_{11}, T_1)$ , $\epsilon(\lambda_1, T_2)$ , $\epsilon(\lambda_2, T_2)$ . . . $\epsilon(\lambda_2, T_2)$ . . . $\epsilon(\lambda_{11}, T_{J1})$ . Maximum number of points is 600. [8F10.0]
2	*J2	Indicates number of pre-run window transmissivity data to be read in. [I5]
2a	*TW1(I)	Pre-run window transmissivity at the ith wavelength.
	ELB(I)	The ith wavelength value for TW1(I), microns. [8F10.0]
3	*C2	The Planck constant, 14388 °K. [F10.0]
	ELR	The wavelength in microns at which brightness temperature measurements are taken, usually 0.653 . [F10.0]
	KLO	Number of allowed iterations in the iterations determination of source temperature from measured brightness temperature. Usually taken as 10. [I10]

\*Indicates new input card required at the start of this set. All input variables after each \* are placed on same card up to 8.

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III, Input Information (cont.)

<u>Set Number</u>	<u>Input Variable</u>	<u>Description</u> [Format]
	ERR	Allowed relative error in the true source temperature calculated from the measured brightness temperature, usually taken as 0.000001. [F10.0]
	CONV	Not used in Program 660300.
4	*EL1	Wavelength at which continuum spectral radiance is measured, microns. [F10.0]
	EL2	Wavelength at spectrum line center where radiance is measured, microns. [F10.0]
5	*Heading	Placed on three cards. First column of each card should contain a blank. Any arrangement of letters and numbers may be used in the first 72 columns of three cards. [72H]
6	*IND1	Indicator [I1]
	=1	means: Read detector calibration data at one wavelength, calculate and print temperatures.
	=2	Continue to read calibration data and print tables of detector constants at several wavelengths.
	=3	Suppress printing of detector calibration data, calculate and print temperatures.
	=4	Print all data, including internal checkout sequences.
	=5	Used only when output error cannot be found. Call exit.
7	*VBAR	Number mean particle volume pertaining to particles present within the flow stream, cm <sup>3</sup> . [E10.5]
	GA1	Average absorption cross section of particles for radiation of wavelength EL1, cm <sup>2</sup> . [E10.5]
	GS1	Average scattering cross section for radiation of wavelength EL1, cm <sup>2</sup> . [E10.5]
	GA2	Same as GA1, except for wavelength EL2.
	GS2	Same as GS1, except for wavelength EL2.
	CHI	Mass fraction of particulate matter in flame, gms solids/gms total. [F10.0]

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III, Input Information (cont.)

<u>Set Number</u>	<u>Input Variable</u>	<u>Description</u> [Format]
8	*ELC	The wavelength at which the pre-run reference light source calibration is performed, microns. [F10.0]
9	*TB	Brightness temperature at which the first set of detector signals (E1) is recorded, at the gain setting used during calibration. [F10.0]
	IND3	Indicator, placed in the 20th column of the same card with TB.
	- 1	TB is in degrees Fahrenheit
	- 2	TB is in degrees Centigrade
	- 3	TB is in degrees Kelvin
10	*E1	The recorded detector signal corresponding to TB. Any number of E1 cards can be read in for each value of TB, but no more than 100 values of E1 can be read in for all TB with the same value of ELC. [F10.0]
	*	<u>A blank card placed here</u> indicates that a new value of TB (Set #9) is to be read in followed by the corresponding E1 cards (Set 10). <u>Two blank cards placed here</u> indicates that the detector constant correlation equation is to be calculated and printed. The input proceeds as follows: If IND1=2, the machine will read in a new value of ELC (Set #8) and repeat. If IND1=1, the machine will proceed to the next input card shown below (Set #11).
11	*TB	Brightness temperature at which the detector signal (E1) is recorded at the gain setting used during the run. One only. [F10.0]
	IND3	Indicator (see Set #9)
12	*E1	The recorded detector signal corresponding to TB. Any number of E1 cards can be read in. The arithmetic average of all E1's will be computed and used to determine the gain change between the calibration and run conditions. [F10.0]

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III, Input Information (cont.)

<u>Set Number</u>	<u>Input Variable</u>	<u>Description [Format]</u>
	*	<u>A blank card placed here</u> indicates that all the E1 cards have been read in; the machine will calculate the gain change, print, and proceed to the next input card shown below (Set #13).
13	*E1OP	The measured level of detector signal with the reference light source on in the condition used during the run. This value is used to calculate the true source temperature during the run, and serves as the reference on which all the temperature measurements are based. [F10.0]
	ELP	The wavelength to which E1OP corresponds, microns. [F10.0]
14	*TR	The total run time, seconds [F10.0]
15	#E1OPP	The post-test equivalent of E1OP. [F10.0]
	ELPP	The wavelength to which E1OPP corresponds.
		Note: Although only one card containing both E1OP and ELP can be read, as many as 10 values of E1OPP and ELPP can be read, with both E1OPP and ELPP on one card [2F10.0], since the post-test window transmissivity may be strongly spectrally dependent.
	*	A blank card placed here signifies that all E1OPP have been read in. The machine proceeds to the next input card shown below, set #16.
16	*TI	The time in seconds from the start of the run. This serves as the basis on which window transmissivity is calculated. If no change in window transmissivity occurs, the value of TI is unimportant. [F10.0]
	E11	Measured signal with reference source on, at E11. [F10.0]
	E12	Measured signal with reference source off, at E11. [F10.0]

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III, Input Information (cont.)

<u>Set Number</u>	<u>Input Variable</u>	<u>Description [Format]</u>
E21		Measured signal with reference source on, at EL2. [F10.0]
E22		Measured signal with reference source off, at EL2. [F10.0]
RHOL		Density of condensed phase, gms/cm <sup>3</sup> . [F10.0]
RHOG		Density of gas phase, gms/cm <sup>3</sup> . [F10.0]
IND		Indicator code placed in 80th column.
	= 0	(blank) Read new data card
	= 1	Read new entire case, starting with set number 5, the heading.

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13 ABSTRACT The design of the first of two liquid micromotors, has been completed. This micromotor will be used for the determination of characteristic velocity, chamber temperature and analysis of the exhaust products. The preparation of the test sight has begun and the fabrication and installation of the micromotor and auxiliary equipment has been initiated.  A tentative test plan has been developed for the study of the combustion characteristics in air of the pentaborane-hydrazine system.		

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Pentaborane-Hydrazine Air Augmentation Micromotor Spectral Comparator Pyrometer						

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