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AIR-AUGMENTED COMBUSTION OF BORON AND BORON-METAL COMPOUNDS

Henry T.-S. Hsia
United Technology Center

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United States Air Force
Air Force Systems Command
Air Force Rocket Propulsion Laboratory
Edwards, California 93523

UTC 2385-SAR

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FOREWORD

This report covers research performed during the period 15 May 1970 through 15 November 1970 and is submitted by the author 15 January 1971. This report contains no classified information extracted from other classified documents.

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Edwards AFB, CA 93523

This technical report has been reviewed and is approved.

Alan W. McPeak, Captain, USAF
Project Engineer, Liquid Rocket Division
Air Force Rocket Propulsion Laboratory

ABSTRACT

Under Contract No. AF04(611)-70-C-0065, United Technology Center has completed the first 6 months of a 12-month program to investigate the ignition delay times, burn times or rates and combustion efficiencies of doped and undoped boron and compounds of boron with aluminum, magnesium, and lithium. A literature survey has been conducted for information on the properties and combustion of aluminum, magnesium and lithium borides. An optical burner apparatus built under a previous Air Force contract, AF04 (611)-11544, has been modified and calibrated for the present investigation. Eight borides, which have been obtained or prepared for this program, were analyzed for purity on the basis of chemical, spectrographic, or X-ray data, and are ready for test.

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SECTION I

INTRODUCTION AND SUMMARY

With the current development of air-augmented rocket and Scramjet systems much interest has arisen in the use of solid fuel particles as high-energy additives to the liquid or solid primary propellants. Boron has outstanding potential as an additive to propellants because of its high volumetric heat of combustion with oxygen. However, this potential can only be realized if efficient combustion of the boron with oxygen in air is attained in the ramburner over the desired wide range of flight altitudes and Mach numbers. Work to date has shown a direct relationship between ramburner pressure and boron combustion efficiency: low ramburner pressure leads to poor performance. Previous work sponsored by the Air Force has suggested that the use of catalytic dopants, for example, a coating of LiF deposited on the boron particle surface may facilitate combustion by lowering the particle ignition temperature even at low pressures. Another approach is to replace elemental boron with a boron compound or alloy such as AlB_x, MgB_x or LiB_x. The objective of this program is to evaluate the merits of using such compounds of boron and dopants. The program involves three closely related phases:

A. Phase I: A literature survey for available information from both U.S. and foreign sources on compounds or alloys of boron will be conducted. Selected physical properties and compositions of each compound, alloy or mixture are determined as needed.

B. Phase II: Combustion testing of the compounds and discrete mixtures selected in Phase I is to be accomplished in this phase. The combustion testing is conducted in the optical burner apparatus constructed at UTC under Contract AF04(611)-11544. Photography and chemical analysis of the residues are the primary data gathering methods.

C. Phase III: This phase consists of the data reduction, presentation and recommendations derived as a result of the work accomplished under Phases I and II.

This report summarizes the work accomplished in Phase I and a portion of Phase II. In Phase I, the available literature on aluminum, magnesium, and lithium borides, which is mostly of foreign origin, was reviewed; synopses of the pertinent information are given herein. Eight borides which have been obtained or prepared for the program were analyzed for purity on the basis of chemical, spectrographic, or X-ray data. In Phase II, the burner apparatus has been modified and calibrated for operation with a CO-O_2-air system at 5, 10, 15, 25, and 40 psia and at 1700° and 2000°K. Particles of boron, MgB_2, and LiB_2 were added in some demonstration test runs. Traces of burning particles showed fairly straight trajectories which allow the ignition and burning times to be determined. The parametric testing of various sizes of elemental boron and of all the borides obtained is about to be carried out under various pressure and temperature conditions.

SECTION II

TECHNICAL DISCUSSION

It is well known that several of the low atomic weight metals are excellent rocket fuels. Heats of combustion data (table I) indicate that when heat evolved per unit weight of metal oxide is taken as a measure of metal fuel value, boron, aluminum, lithium, and magnesium are better fuels than carbon and hydrogen. In a volume-limited vehicle system, boron appears most attractive because of its high heat of combustion per unit volume. However, in practice boron in powder form has been found to be more difficult to burn than other metal powders. This can be attributed(1)* to the fact that the boiling point of boron oxide lies below that of boron itself. Thus, combustion must take place on the surface of the metal particle. On the other hand, the boiling points of the oxides of aluminum, lithium, and magnesium lie above that of each respective metal, so that the metal burns in the vapor phase. Thus it has been shown both theoretically and experimentally that boron differs considerably from other light metals in its combustion properties.

1. BACKGROUND

Ignition of metal fuel particles can take place only when they have been heated to their ignition temperature. Initially, heat is supplied primarily by convection, and the heating time is proportional to the square of the particle diameter. As the particle temperature increases, heating by surface reactions becomes important; the heating rate accelerates and becomes proportional to the particle diameter. Most of the total time to ignition is spent in the slow convective heating regime, and this ignition delay time is usually roughly proportional to the particle diameter squared.

The particle temperature history is given by the solution of the following equation(2)

$$\frac{d\,T_p}{dt} = \frac{6}{\rho_p C_p d}\left[\frac{k_g\,Nu}{d}\left(T_g - T_p\right) - \sigma\,\epsilon\,T_p^4\right] \qquad (1)$$

where k_g denotes the thermal conductivity of the gas, Nu the Nusselt number, ρ_p the density, C_p the heat capacity, T_p the

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*Parenthetical superscript numbers denote references appearing on page 35.

TABLE I

PROPERTIES OF FUELS

Fuel	Density g/cm^3	Molecular Weight	Density / Molecular Weight	Heat of Combustion / Unit Weight of Oxide kcal/g	Heat of Combustion / Unit Weight of Fuel kcal/g	Heat of Combustion / Unit Volume of Fuel $kcal/cm^3$
Boron	2.37	10.82	0.231	3.02	14.0	33.2
Aluminum	2.70	26.97	0.100	3.93	7.4	20.0
Magnesium	1.74	24.32	0.0716	3.56	5.900	10.30
Lithium	0.53	6.94	0.0763	4.43	9.540	5.05
Carbon	2.25	12.01	0.1875	2.14	7.830	17.63
Hydrogen	0.063	2.02	0.0312	3.21	28.900	1.82

particle temperature, T_g the gas temperature, d the diameter, σ the Stefan-Boltzmann constant, and ϵ the emissivity of the particle.

The equation shows that a high value of Nu and a low value of $\rho_p C_p$ lead to rapid heating of the particle; this is true for lithium, magnesium, and aluminum. Aluminum has an ignition temperature similar to that of boron, and those of magnesium and lithium are considerably lower. Thus, the ignition delay of these three metals will be shorter than that of boron. Compounds or alloys of these metals with boron will also have a different heatup profile and lower ignition delay time than pure boron.

Previous studies have indicated that three different controlling mechanisms are involved in determining the combustion time of metal particles. Boron apparently burns by the diffusion of the oxidizing species to the particle surface, followed by surface reaction and diffusion of the gaseous combustion products away from the surface.[3,4] This sequence occurs because the vapor pressure of boron oxide exceeds that of boron at the combustion temperature. The combustion rate in this case is limited by the rate of diffusion of the oxidizer through the combustion products. A theory developed by Spalding[5] indicates that the burning time is proportional to the square of the initial particle diameter, is independent of pressure, and depends only slightly on temperature.

Belyaev[6] has recently made a successful correlation of aluminum particle burning rates in fuel-rich gases, assuming that water and carbon dioxide are equally effective oxidants. If there is more than one oxidizing species, j, in the gas, Macek and Semple[2] suggested a generalized expression to calculate the burning time, t, of a metal particle with original diameter, d, as

$$\frac{1}{t} = \sum_j \frac{1}{t_j} = \frac{8\delta}{(\rho_p/M)\, d^2} \sum_j \frac{\beta_j P_j}{\gamma_j} \tag{2}$$

where ρ_p/M denotes the molar density of the metal particle given in Table I, and δ the ratio of flame to particle diameter ($\delta > 1$ for vapor phase combustion, e.g., 2.7 for aluminum; $\delta = 1$ for surface burning, e.g., boron). $\beta = D/RT_g$ where D is the diffusion coefficient, R the gas constant, and T_g the gas temperature. $P_j = P \ln \frac{1}{1-X}$, where X is the mole fraction, P the static pressure, and γ the stoichiometric fuel-oxidant coefficient (e.g., 3/4 for the reaction of boron or aluminum with oxygen).

When the diffusion contribution of carbon dioxide is included, the calculated burning times in dry gases agree with the experiment to within 10% to 20%. Typical burning times for boron were found to be 12 to 15 msec and 20 to 25 msec for 35μ and 44μ particles, respectively. The burning times decreased slightly with increasing gas temperature.

A shock tube study was conducted by Uda[7] to determine the ignition limit of clouds of boron particles in air. The boron samples, consisting of 30μ to 50μ agglomerates (1μ to 2μ primary particles) and 0.015μ particles, were ignited in the high-temperature region behind the reflected shock wave. The 30μ to 50μ agglomerated particles ignited at a reflected shock temperature of about 1,900°K at 1-atm pressure. The ignition temperature decreased steadily with increasing pressure, to about 1,400°K at 20 atm. Ignition of the 0.015μ particles appeared to be insensitive to pressure, and the ignition temperature stayed constant at 1,150°K. For a constant reflected shock pressure, the ignition temperature decreased with decreasing particle size. The ignition delay time of the 0.015μ particles decreased as the reflected shock temperature increased. It was less than 1 msec at 1,140°K and decreased to less than 0.1 msec above 1,400°K.

The studies of boron combustion thus indicate that ignition and burning are sensitive to pressure and temperature conditions, particle size, type of oxidizing environment, and particle concentration. As indicated by equations 1 and 2, the properties of other metals such as lithium, magnesium, and aluminum, if used in conjunction with boron, will contribute to shorter ignition delay and burning times. The shorter burning time is due mainly to the fact that these metal particles burn by a vapor phase mechanism. It seems to be logical to consider compounds or mixtures of boron and these other metals as candidate fuels.

In evaluating boron-rich solid propellants for air-augmented systems, Sims, Lee, and Gonzales[8] replaced boron with boron compounds, including ZrB_2, B_4C, TiB_2, AlB_{12}, and MgB_2. Some promising data were obtained, but the exploratory investigation was too limited to provide systematic results.

In another approach, some experimental results indicate that the ignition temperature of powdered boron in oxygen can be remarkedly decreased by the addition of doping impurities[9] to the metal. LiF is one of the promising dopants, which probably increases the diffusion of boron ions through the oxide surface layer or increases the oxygen diffusion through the oxide film. The ignition temperature of the 1% LiF doped boron was reduced by 160°C.

In a recent air-augmentation combustion study, Rosenberg, et al.[10] deposited LiF on the surface of boron particles and found that the combustion rate of these products was increased.

2. METAL BORIDES

As discussed in the preceding sub-section, the physical and thermochemical properties of the candidate borides or alloys of boron with other metals will control their heat-up, ignition and burning characteristics when they are used as particulate fuel additives in a secondary combustion system, and thus will determine how their performance will compare with that of boron alone. For instance, they may provide an increase of overall fuel density with little loss in energy released. In general, all the metal borides have very high melting points and are known as refractory materials.[11] Since metal borides have not been considered previously as fuel additives, their thermochemical properties are not readily available. The following subsections summarize accessible data, mostly taken from foreign publications.

a. Aluminum Borides

There are five reported and authenticated phases in the aluminum boron system[12]: AlB_2, AlB_{10}, α-AlB_{12}, β-AlB_{12}, γ-AlB_{12}. No information has been found on AlB_6. The three forms of AlB_{12} and AlB_{10} are hard materials with structures similar to boron or boron carbide, whereas AlB_2 is a soft graphite-like material of hexagonal structure. Some of the physical properties of aluminum borides are shown in Table II.

TABLE II

PHYSICAL PROPERTIES OF ALUMINUM BORIDES

Boride	Crystal Structure	Theoretical Density g/cm^3	Melting Point °F
AlB_2	Hexagonal	3.16	3,010±90
AlB_{10}	Orthorhombic	2.54	4,390±90
α-AlB_{12}	Tetragonal	2.58	3,925±90
β-AlB_{12}	Orthorhombic	2.60	4,015±90
γ-AlB_{12}	Orthorhombic	2.56	-

Serebryanskii and Epel'baum[13] reported that the boron-containing specimens were prepared from pure elemental aluminum and boron in a tubular furnace. They give the phase composition in relation to specimen composition and synthesis temperature as shown in table III.

Formation and decomposition processes of aluminum borides were investigated by Atoda et al[14] using Differential Thermal Analysis, X-ray and chemical analysis techniques on samples prepared in an electric furnace. AlB_2 begins to form at 600°C and decomposes into the α-AlB_{12} phase above 920°C. The latter is stable up to at least 1900°C; it decomposes above 1900°C, separating elemental Al.

The energies of combustion of AlB_2 and α-AlB_{12} were measured by Domalski and Armstrong[15] in a bomb calorimeter using flourine as the oxidant. From the data obtained in these experiments the heats of formation of AlB_2 and α-AlB_{12} were calculated as -16 $\pm$3 and -48 $\pm$10 kcal/mol, respectively. The lack of precision in these values is due to uncertainties in the impurity corrections and in the heats of formation of the combustion products.

b. Magnesium Borides

The magnesium-boron system displays a wide range of mutual solubility: MgB_2 will dissolve in magnesium; on the other hand, if MgB_2 is heated above 300°C, it will lose magnesium progressively to form MgB_4, MgB_6 and MgB_{12}.[11] The magnesium borides[16] react with free oxygen, MgB_2 at 580°C and and MgB_4 at 400°C, but the reactions are not complete at 1100°C. MgB_2 reacts with water and with HCl at 15°C to produce 97% hydrogen and 3% boranes; MgB_4 reacts only with boiling HCl while the other borides do not react at all.

The heat of formation of MgB_{12} was estimated as -34.4 kcal/mol.[17] Information on the heats of formation of other magnesium borides has not yet been found.

c. Lithium Borides

Information on lithium borides is scarce. Markovskii and Kondrashev[18] reported that as a result of the electrolysis of lithium borate, a product was obtained containing 82.9% B and 9.4% Li, probably a mixture of elemental boron and LiB_6. No other lithium borides are mentioned in the open literature.

TABLE III

PHASE COMPOSITION OF ALUMINUM BORIDES

<table>
<tr><th colspan="2">Original composition</th><th colspan="10">Synthesis temperature, °C</th></tr>
<tr><th>% B</th><th>% Al</th><th>650°</th><th>700°</th><th>800°</th><th>900°</th><th>950°</th><th>1000°</th><th>1100°</th><th>1200°</th><th>1300°</th><th>1400°</th></tr>
<tr><td>28.9</td><td>71.1</td><td colspan="4">AlB_2, Al</td><td rowspan="2">AlB_2
Al</td><td colspan="5" rowspan="6">α-AlB_{12}+Al</td></tr>
<tr><td>44.9</td><td>55.1</td><td colspan="2" rowspan="7">AlB_2+Al</td><td colspan="2" rowspan="7">AlB_2</td></tr>
<tr><td>55.0</td><td>45.0</td><td rowspan="6">α-AlB_{12}</td></tr>
<tr><td>61.9</td><td>38.1</td></tr>
<tr><td>70.9</td><td>29.1</td></tr>
<tr><td>76.5</td><td>23.5</td></tr>
<tr><td>80.3</td><td>19.7</td><td colspan="5" rowspan="2">α-AlB_{12}</td></tr>
<tr><td>82.5</td><td>17.5</td></tr>
</table>

d. Estimated Heat Release of Borides

In the absence of information on the heats of formation of most of the borides considered in this program, the heat release from the reaction of the borides with oxygen was calculated on the basis of heat release data on each of the two component elements. The results are compared to pure boron in Table IV.

From the viewpoint of volumetric heat release, the lithium borides appear to be the best fuel additives among the metal borides, followed by the aluminum and the magnesium borides.

e. Analysis of Test Samples

All the nine (9) compounds specified in the program, i.e. AlB_2, AlB_6, AlB_{12}, MgB_2, MgB_6, MgB_{12}, LiB_2, LiB_6 and LiB_{12}, were obtained in the form of chemical compounds except AlB_6. No information could be found in the literature on AlB_6 and it probably does not exist as a compound. The other compounds are either available commercially or were specially synthesized for this program. The purity of each boride was determined from chemical, spectrographic or X-ray diffraction analyses as summarized in table V.

The MgB_6 obtained shows a medium pattern of MgB_2 and a weak pattern of MgB_{12}; and the LiB_6 shows a strong pattern of LiB_{12} and a weak pattern of LiB_2. It is likely that MgB_6 and LiB_6 are unstable and temperature dependent; although formed in the synthesis process at high temperature, they may be transformed into other borides during the cooling period.

Scanning electron beam micrographs were taken of all the borides at 300, 1000 and 3000 magnification. Micrographs of an elemental boron were also taken for reference. In the following micrographs the borides appear as agglomerates of amorphous particles of various sizes (Figure 1, 2 and 3).

3. EXPERIMENTS

The major components of the test facility are the optical burner apparatus, a gas supply system, an optical system for high speed photography, a device for exhaust residue sampling, a control console and sequencer for remote control of ignition, flow valves, camera and particle sampling, plus electronic recording equipment monitoring pressures and temperatures. The general arrangement of the test setup is shown in Figures 4 and 5.

TABLE IV

ESTIMATED HEAT RELEASE OF BORIDES RELATIVE TO BORON

	B	AlB_2	AlB_6	AlB_{12}	MgB_2	MgB_6	MgB_{12}	LiB_2	LiB_6	LiB_{12}
Heat release per unit weight of fuel relative to boron	1.0	.798	.895	.942	.598	.780	.871	.730	.895	.944
Volumetric heat release relative to boron	1.0	.740	.860	.918	.697	.840	.911	.918	.968	.982

TABLE V

ANALYSIS OF BORIDES

Borides	Wet Chemical Analysis	Spectrographic Analysis[b]	X-Ray Analysis
AlB_2 (55.2/44.4)[a]	Al 55.2% B 43.9% C 0.18% H 0.002% N 0.18% O 0.61%		AlB_2 Medium weak pattern AlB_{12} Trace Al_2O_3 Trace Al Medium pattern
AlB_{12} (17.1/82.9)	Al 18-20% B 78-81% Fe 0.05% Si 0.2% C 0.8% Mg 0.5% Zr 0.1%		AlB_{12} α-phase good pattern Al_2O_3 5 weak lines of -phase
MgB_2 (52.9/47.1)	Mg 52.6%	Si 0.01-0.1% Mn 0.03-0.3% Cu 0.003-0.3% Fe 0.03-0.3% Pb 0.003-0.03% Al 0.01-0.01%	MgB_2 Strong pattern MgB_4 Trace MgO Trace
MgB_6 (27.3/72.7)	Mg 26.97%	Si 0.01-0.1% Mn 0.03-0.3% Cu 0.003-0.3% Fe 0.03-0.3% Pb 0.003-0.03% Al 0.01-0.01%	MgB_2 Medium pattern[c] MgB_{12} Weak pattern MgO Trace
MgB_{12} (15.8/84.2)	Mg 15.25%	Si 0.01-0.1% Mn 0.03-0.3% Cu 0.003-0.3% Fe 0.03-0.3% Pb 0.003-0.03% Al 0.01-0.01%	MgB_{12} Strong pattern MgB_2 Trace
LiB_2 (24.3/75.7)	Li 24.1%	Si 0.01-0.1% Mn 0.03-0.3% Cu 0.003-0.3% Fe 0.03-0.3% Pb 0.003-0.03% Al 0.01-0.01%	Perfect pattern
LiB_6 (9.8/90.2)	Li 9.79%	Si 0.01-0.1% Mn 0.03-0.3% Cu 0.003-0.3% Fe 0.03-0.3% Pb 0.003-0.03% Al 0.01-0.01%	LiB_{12} Strong pattern[d] LiB_2 Weak pattern
LiB_{12} (5.1/94.9)	Li 5.2%	Si 0.01-0.1% Mn 0.03-0.3% Cu 0.003-0.3% Fe 0.03-0.3% Pb 0.003-0.03% Al 0.01-0.01%	Perfect pattern

Note:
(a) Number in parenthesis is the weight ratios, metal to boron
(b) All the same as same source of ray materials were used
(c) No MgB_6 detected although chemistry was perfect
(d) No AlB_6 detected although chemistry was perfect

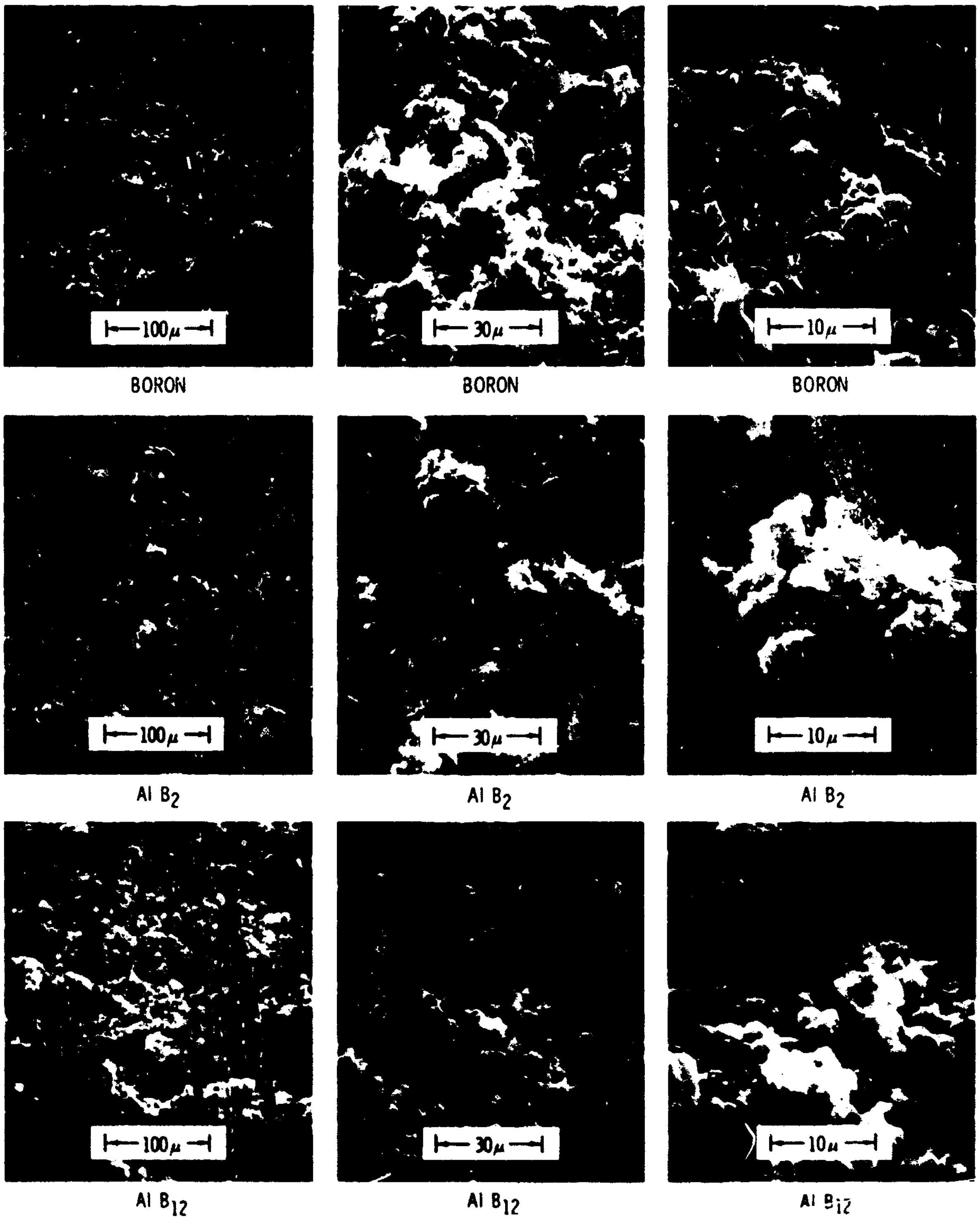

Figure 1. Scanning Electron Micrographs of Boron (325 mesh) and Aluminum Boride (AlB_2-200 mesh, AlB_{12}-325 mesh) Powders

01496

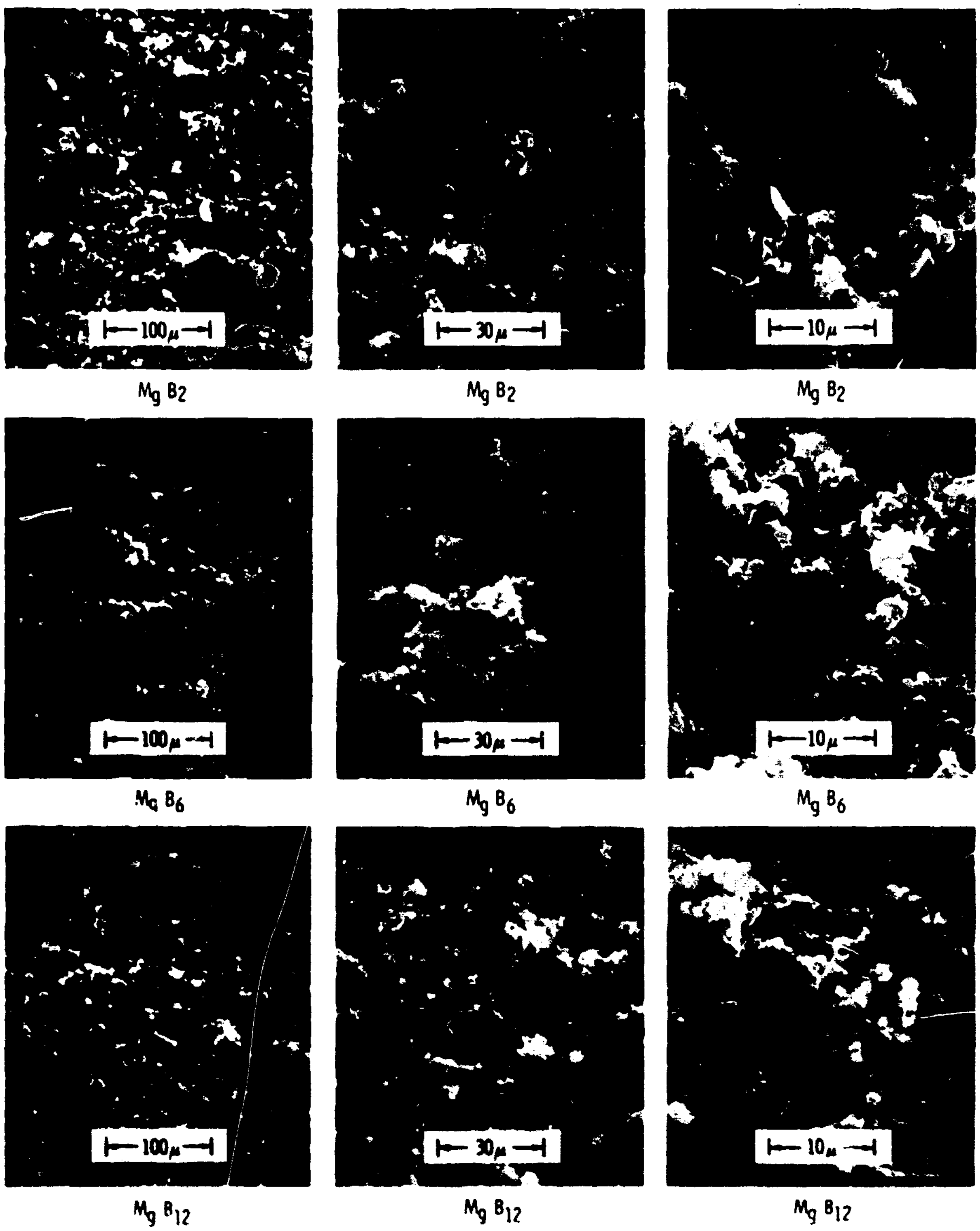

Figure 2. Scanning Electron Micrographs of Magnesium Boride Powders (MgB_2-200 mesh, MgB_6 and MgB_{12} -325 mesh)

01497

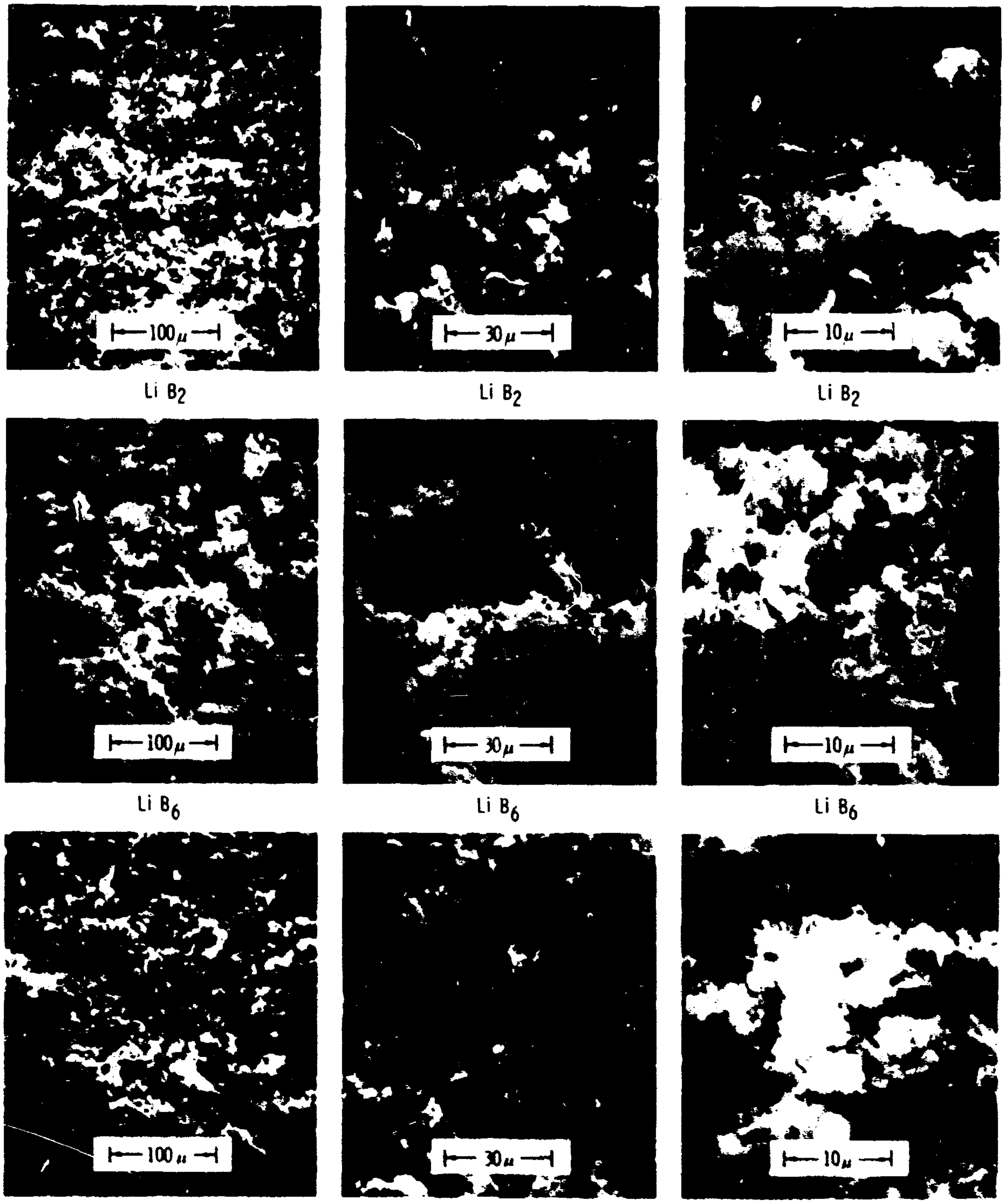

Figure 3. Scanning Electron Micrographs of Lithium Boride Powders (325 mesh)

01498

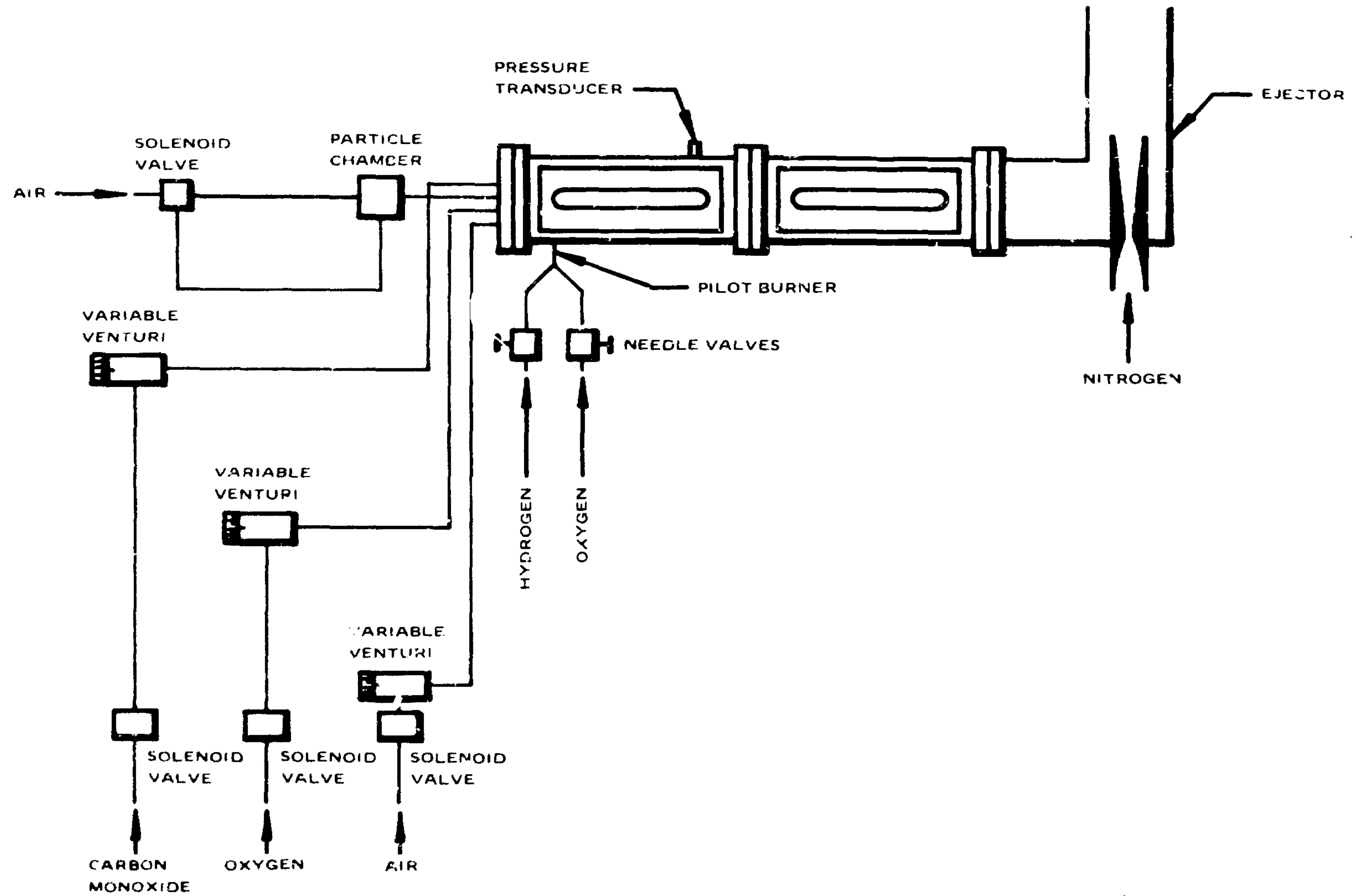

Figure 4. Schematic Diagram of the Test Set-Up

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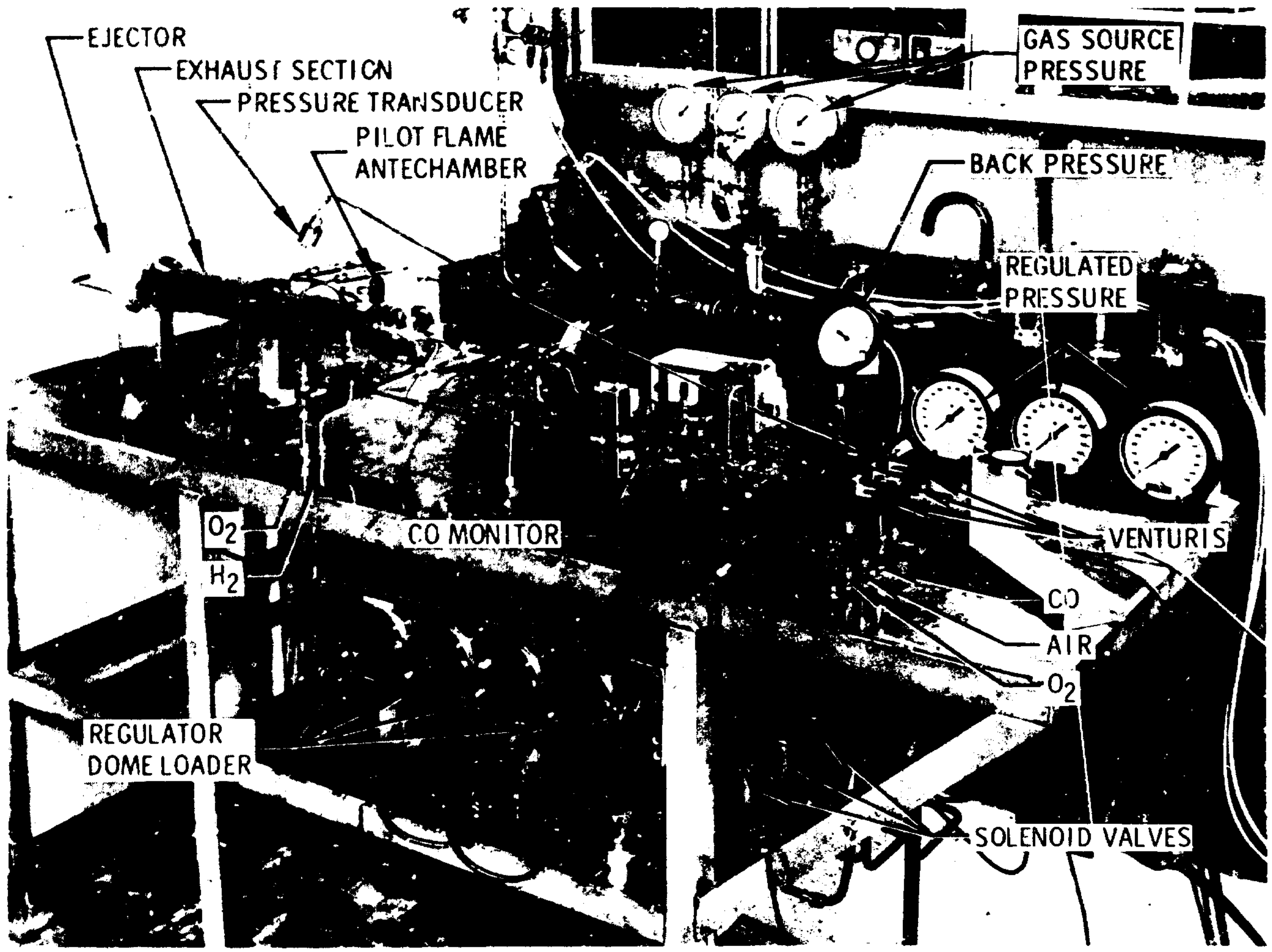

Figure 5. Test Set-Up

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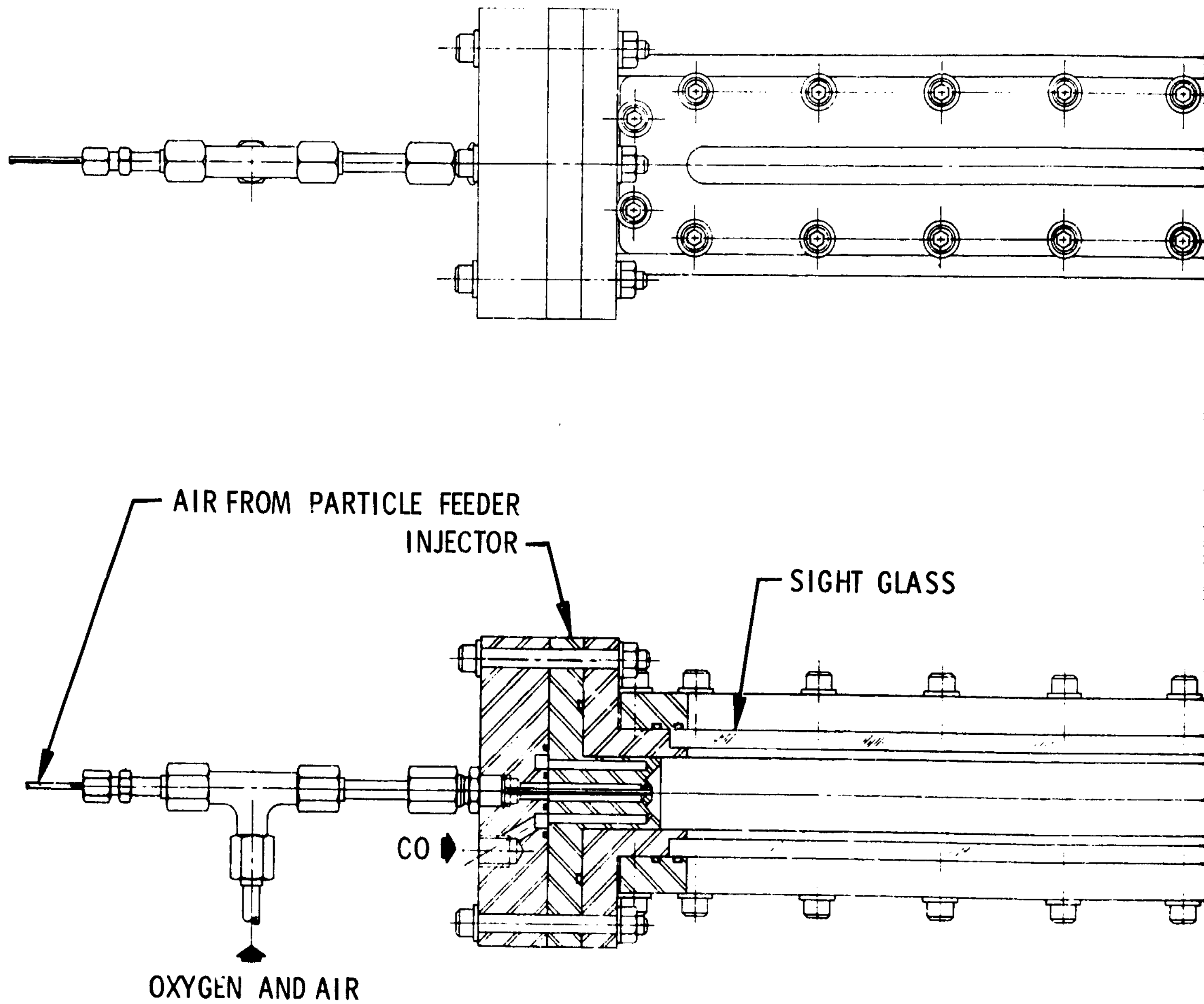
a. Test Apparatus

The major piece test equipment used in this program was constructed at UTC under contract AF04(611)-11544.[19] Several modifications were made to meet the requirements of the current contract; the major ones were (1) use of a CO/O_2 flame instead of a H_2/O_2 flame, to eliminate the effect of the presence of water vapor on the combustion; (2) installation of an ejector system attached to the burner exhaust duct for maintaining low chamber pressure conditions, (3) installation of a thermocouple to monitor the flame temperature and (4) extending the running period to facilitate collection of large amounts of exhaust residue. A large part of the experimental effort in the first six months of the program was devoted to carrying out these modifications and to calibration of the burner.

(1) Optical Burner

The optical burner, shown in Figure 6, consists of a combustion chamber of 1 in. I.D. fitted with a transparent Vycor window operating with carbon monoxide and oxygen. The fuel/oxygen injector consists of a central port, through which the oxygen is admitted, surrounded by six manifolded fuel jets. The fuel inlets end in a series of jets canted 45° to the axis of the burner. These jets impinge on the oxygen jets which are canted outward at 45°. A 1/16-in. O.D., 0.020 in. I.D. stainless steel capillary tube is fitted coaxially inside the oxygen inlet port and serves for the injection of solid fuel. Air is used as the carrier for the solid particles and at the same time serves as a diluent to lower the temperature of the burnt gases. Four combustion chambers, with lengths of 3, 6, 9 and 12 in., are available. Taps for monitoring pressures and temperature are installed near the exhaust end of the chamber.

An exhaust duct is mounted downstream of a replaceable nozzle section. This duct can be fitted with two windows or a sampling probe. Five different sizes of graphite inserts were fabricated for use in the replaceable nozzle section to yield 5, 10, 15, 25 and 40 psia burner pressure at a specific flow rate setting. Difficulty was experienced in maintaining the desired temperature level, or sometimes even sustaining combustion, when large throat inserts were used. Using a 12-in. long chamber instead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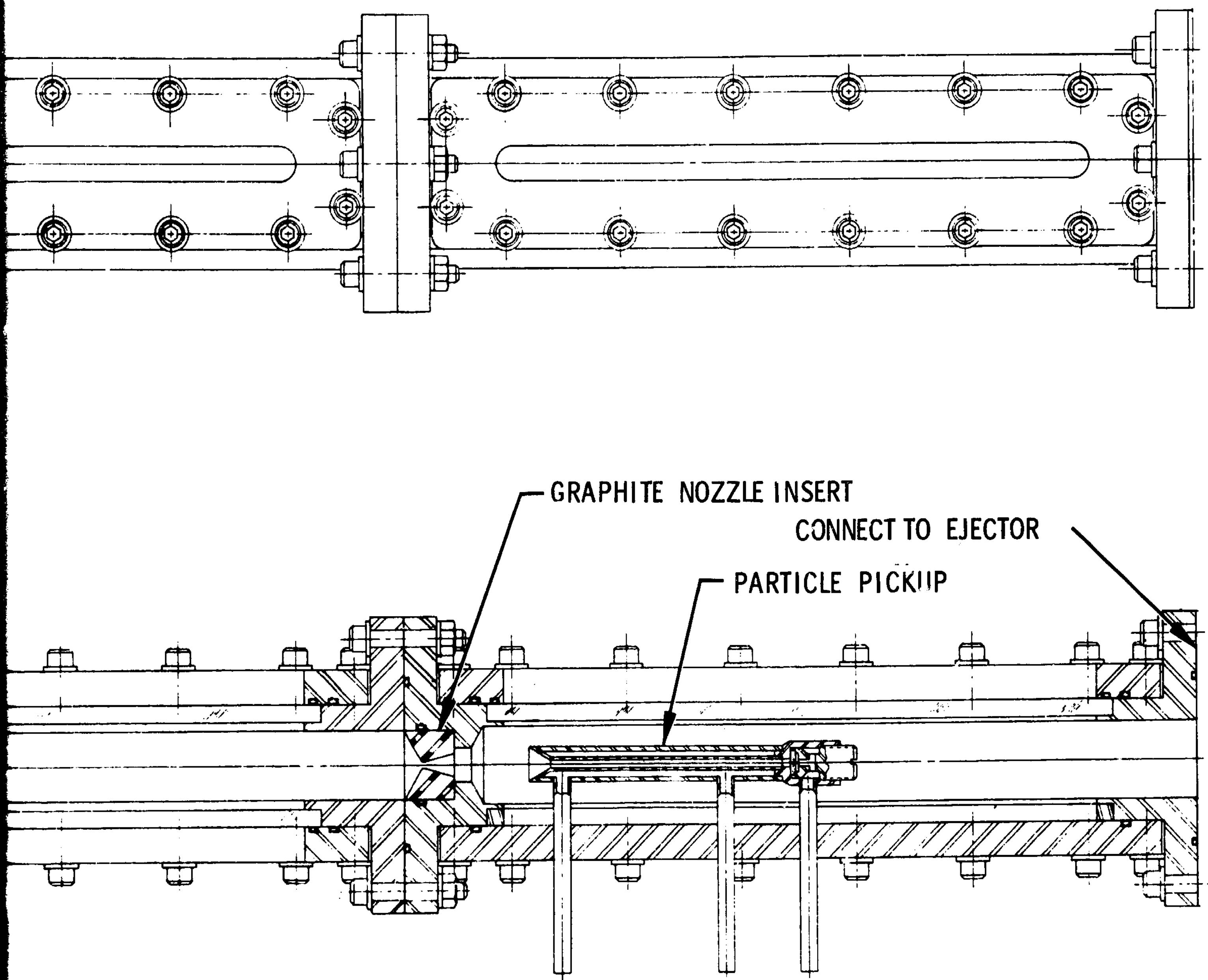

Figure 6. Optical Burner

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of the 6-in. chamber, thus increasing the L* by a factor two and facilitating combustion, did not fully resolve the problem. However, a trial-and-error adjustment of CO, O_2 and air flow rates made it possible to obtain the desired pressure and temperature level for each specific size of nozzle throat insert.

(2) Ignition System

Ignition is initiated by a pilot flame in an antechamber attached to the main burner which is itself ignited by a spark plug. Originally the pilot flame operated on small amounts of CO and O_2 regulated by needle valves. Problems were encountered in obtaining a stable pilot CO flame since ignition was very sensitive to the gas flow rates and the flame often went out when the spark was turned off. High gas flow rates or long spark durations resulted in rough starts, burnout of the spark plug, and window breakage. On the other hand, low pilot flow rates or short spark durations failed to give good combustion and caused carbon to deposit on the window in the main burner. The problem was resolved by switching to a H_2/O_2 pilot flame and by installing fixed orifices in lieu of the needle valves to insure a stoichiometric flow rate ratio in the pilot gas supply. Satisfactory ignition of the main burner gas was achieved with a pilot flame turned on for the first second only, in total run times up to 10 seconds. Any effect of the presence of water vapor on the combustion of the materials under investigation should be negligible under these circumstances.

(3) Particle Feed System

The particle feed system is shown in Figure 7. The diluent air supply to the main burner also provides the air supply to the particle injector. The latter is taken off through a tee placed downstream of the main air venturi so that no correction to the chamber condition is necessary for the air injected through the particle feeder. A check valve in the main air line downstream of the tee provides a small pressure drop which is independent of the absolute pressure of the system. This pressure drop assures a positive flow of air through the particle feeder throughout a firing.

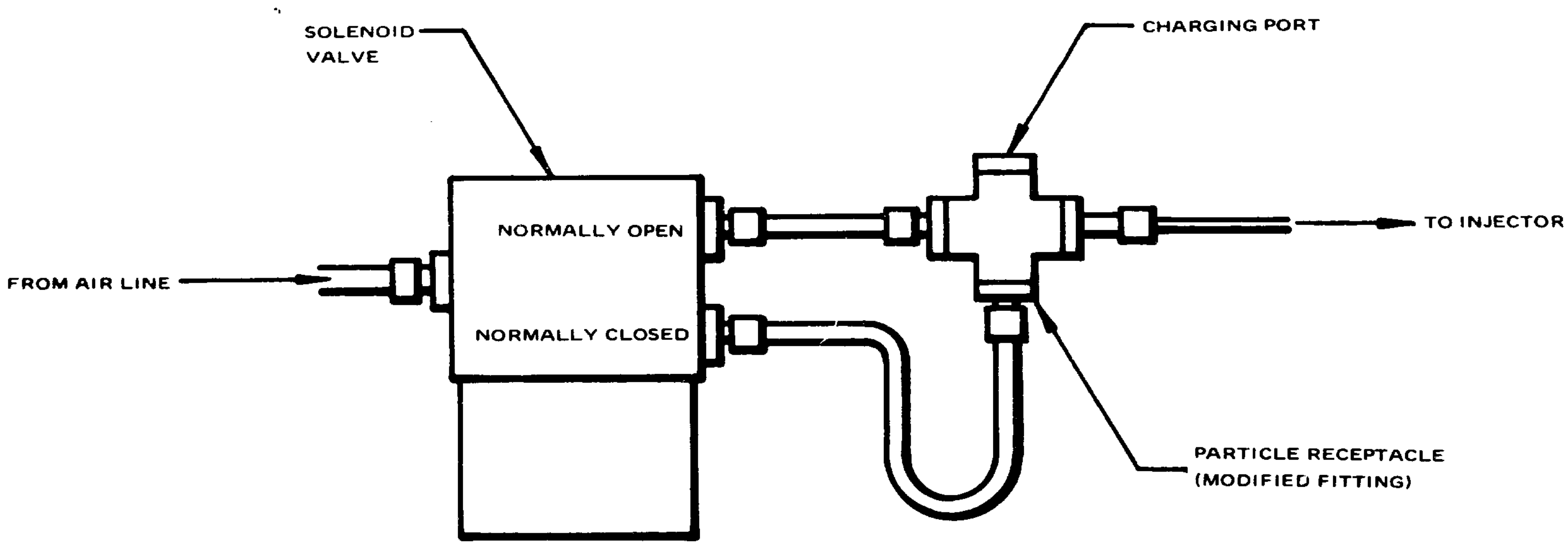

Figure 7. Particle Feed Mechanism

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In operation, air begins to flow through the particle injector as soon as the main combustion gas valves open. The solenoid valve on the injector is not activated, and the air flows through the normally open port without disturbing the particle container. After 1 second of firing, when flow rates and pressures have stabilized, the injector solenoid valve is activated; the air flow is diverted through the sintered filter which supports the particle charge and the latter is fed into the combustion chamber.

(4) Sampling Probe

The sampling probe available for use from the previous program is a miniature water-cooled condenser designed for insertion into the exhaust gases immediately downstream of the nozzle (Figure 6). The probe is mounted on a plate dimensionally identical to that retaining the windows in the exhaust section. The entire assembly replaces one of the windows when the exhaust residue is to be sampled. In operation the probe is fitted with a 10-mm diameter sintered glass filter disc through which a vacuum is drawn. The particles in the gas sample are thus drawn into the condenser section, quenched and deposited on the removable filter disc for analysis. In the previous program, some difficulties were experienced in obtaining samples. The sampling probe burned out twice, once because of inadequate cooling water and once because of the cracking of a faulty weld. In the current program, a commercial water-cooled gas sampling probe (United Sensor and Control Corporation GC-24-24-050) has been acquired as a back-up. This probe has been endurance tested up to 4,000°F.

In the previous program the sampling problem was also in part due to an insufficient quantity of particles. This should no longer be a difficulty since the running time has been successfully extended to 10 seconds without causing any damage to the test hardware.

Another sampling technique under consideration is the use of a microscope slide which would be dropped, appropriately guided, through the exhaust gas stream to collect burned and unburned particles which are quenched and deposited on the face of the glass. This technique has proven fruitful in another investigation.[20]

(5) Ejector System

An ejector system was designed, fabricated and installed to provide the exhaust vacuum required for the low pressure runs. The ejector system replaces closed vacuum tank originally installed, which presented a potential hazard due to the possibility of the formation of an explosive mixture in the tank. As shown in Figure 8, the ejector uses nitrogen supplied by a high pressure reservoir to drive the exhaust gas through the concentric channel. The back pressure reached the desired 2 psia as required to permit running the combustion chamber at 5 psia.

b. Gas Supply System

All CO, O_2 and air used are supplied by commercial bottled gases (CO and O_2 by Liquid Carbonic Corp., CO commercial grade, by Matheson Company). Three sets of regulators, valves and control venturis are provided for control of the flow of CO, O_2 and air. A fourth system, originally designed to be compatible with fluorine serves as a spare. Remotely operated regulators reduce the supply pressure to the desired working pressure. The gases are metered through variable venturis which were calibrated against standard orifices using nitrogen as a test gas.

c. Control Console and Sequencer

A schematic diagram of the control console containing the sequencer for operating the optical burner system is shown in figure 9. This sequencer provides for programmed operation of the burner control components. Six individual channels are available; one channel is hard-wired in, the other five may be programmed by utilizing a patchboard to set up the desired sequence. Five of the outputs provide 28-vdc power, the sixth supplies a contact closure for remote starting of recorders. A manual switch for purging the burner with inert gas is also provided.

To provide the most versatility, the sequencer makes use of a relay-controlled switch, switch driver, and patch panel. This allows the operator to set up a sequence where power may switch any function on and off repeatedly and to vary the time for each condition.

The stepper switch is relay-operated and consists of 10 banks of contacts; each bank contains 10 active positions and a home position. One bank of contacts is used to supply timing resistors for the driver, and one bank is used for supplying power to a series of lights which

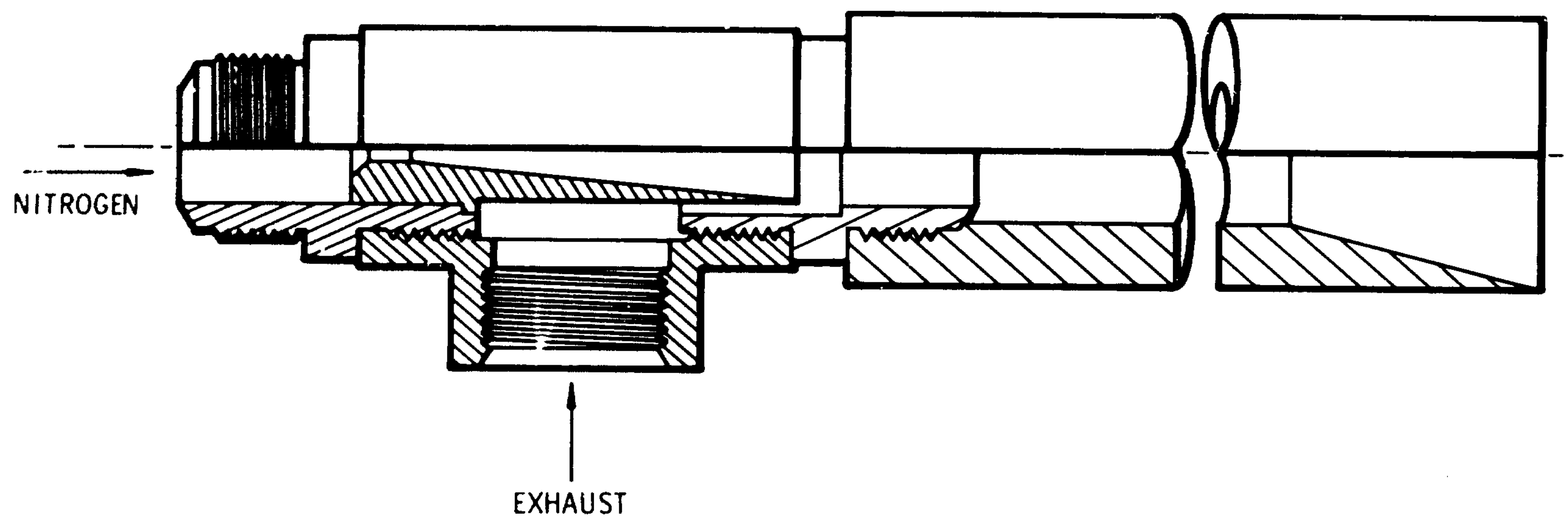

Figure 8. Ejector

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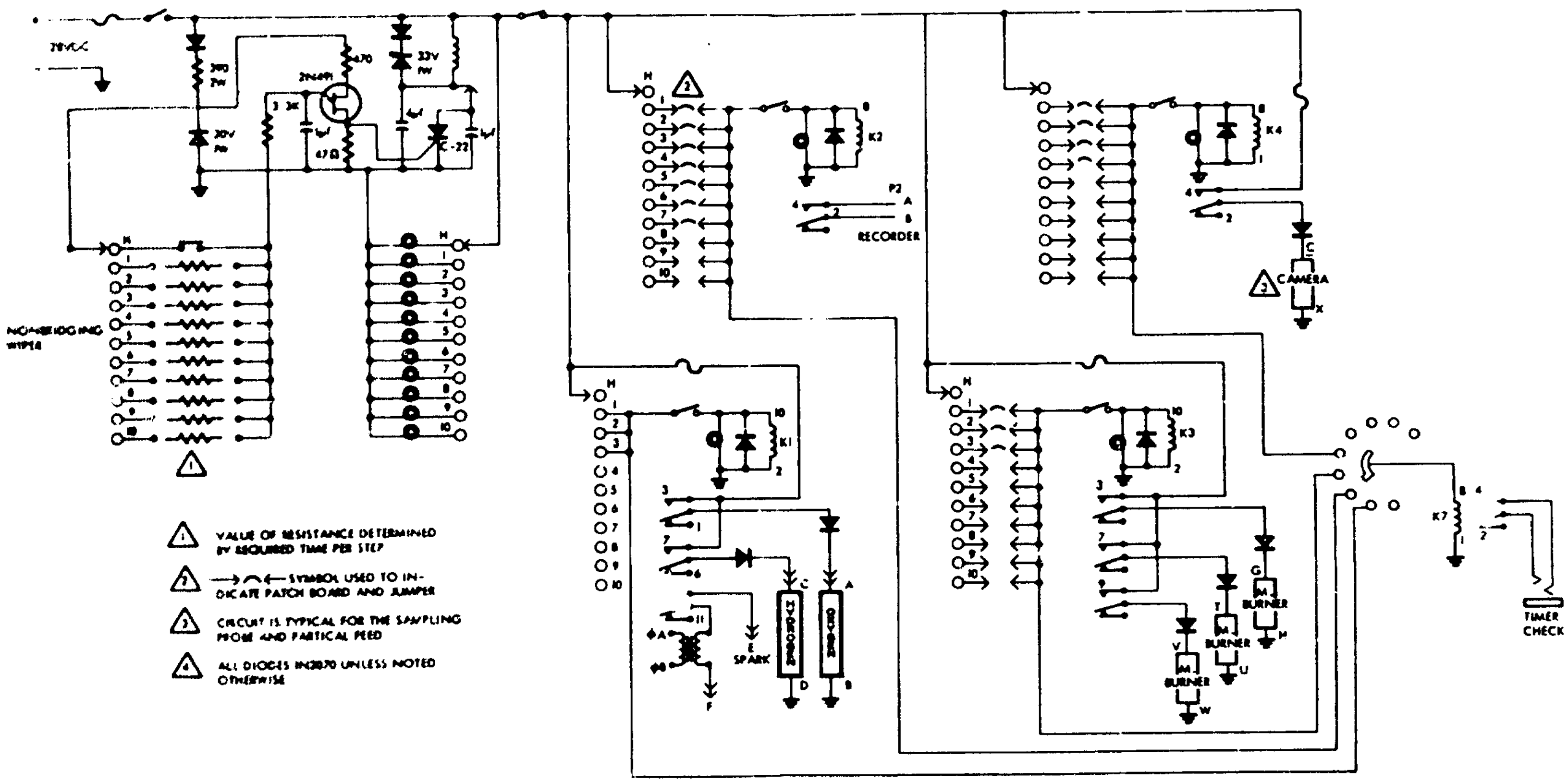

Figure 9. Schematic Diagram of Sequencer

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indicate the position of the switch. Five banks are wired to the patch panel for programming, one bank is hard-wired in for the ignition function, and the remaining two banks are spares.

The stepper switch driver is a solid-state device that is used to switch power on and off the stepper switch solenoid. The time that the switch is in any one position may be varied by connecting an external resistor across the test jacks supplied for this purpose. One pair of jacks is supplied for each step position of the switch. The time for each step may be varied from approximately 70 msec to 5 sec.

Provisions have been included in the sequence to enable the operator to check the time duration of any step of the switch or the time duration of the entire sequence. A phone jack has been provided on the side of the console; by plugging a standard timer into this jack and selecting the desired channel on the timer check rotary switch, the time for that particular event may be checked.

The patch panel consists of 10 rows of 10 contacts. Two rows of contacts are utilized for each control function. One row of contacts is wired together and is connected to the otuput function control switch. The other row is connected to the contacts of the stepper switch. The wiper of the stepper is wired to +28 vdc; as the stepper is advanced the contacts pick up the 28 v and apply it to the patch board. If a patch wire is plugged into the board, this voltage is jumped onto the common bus and is applied to the load. This is typical for each channel.

The function control switches are supplied power from the patch board. If a particular channel is patched in and the control switch is turned on, an indicator light next to the switch will light when that channel is activated, indicating that power is present and that a relay is energized. The contacts of the stepper switch have a low-power switching capacity; therefore, an additional relay was used to supply power to the load. Loads requiring up to 5 amp at 28 vdc may be powered from this sequencer. The recorder channel is an exception to the above; instead of switching 28 vdc to the output, it supplies a contact closure which is used to turn a recorder on and off remotely.

The emergency shutdown switch is the main power shut-off switch. In order to have power available to the output, this switch must be in the "on" position. If for any reason it becomes necessary to cut off power to the load during the sequence, the red switch guard is pushed down which cuts off all output power. The sequencer will continue to step through the remaining steps until it hits the home position where it will stop; however, no power will be supplied to the load during this time.

d. Optical System

Two cameras are being used in connection with this study. High-speed photographs were taken with a Hycam* K-1001 camera and particle tracks were photographed using an Automax† pulse camera. The high speed camera was used to limit the motion of the particles on the film and thereby permit a direct velocity measurement.

The first photographs were taken of boron, MgB_2 and LiB_2 in the CO-O_2-air flame with the pulse camera at 1/60 sec and f/8 lens opening, and show fairly straight particle trajectories. As can be seen from a typical photograph, figure 10, the ignition delay is evidenced by the location of which particle ignition occurs. Because of the long burning time of these particles, their combustion was not completed when they left the 6-in. chamber used. The 12-in. chamber will be used later and may provide sufficient length for complete particle combustion.

e. Data Recording

A platinum-platinum/10% rhodium thermocouple (Tempton, Inc.) was used to measure the flame temperature just upstream of the exhaust nozzle during calibration. The burner pressure is monitored by a CEC (Consolidated Engineering Corporation) pressure transducer, model 4-327-001, connected to a pressure tap located at 90° to the thermocouple connection. Both temperature and pressure measurement are recorded by a CEC recorder, Type 5-124.

4. CALIBRATION OF BURNER FOR THE TEST CONDITIONS

The test conditions are set at 5, 10, 15, 25 and 40 psia and at 2000° and 1700°K. 2000°K was chosen because it represents the threshold of boron ignition at low pressure and the upper limit of the platinum thermocouple used, and 1700°K is the limit at which the CO_2 flame is stable. As mentioned in the previous sections, the calibration was carried out by trial-and-error adjustment of CO, O_2 and air flow rates. Over three hundred test runs were conducted. The CO/O_2 ratio was held at the approximate stoichiometric ratio for CO_2 and air was added as diluent. All the settings were obtained with a 0.336-in. diameter throat nozzle,

* Red Lake Laboratories, Santa Clara, California

† Traid Corp., Los Angeles, California

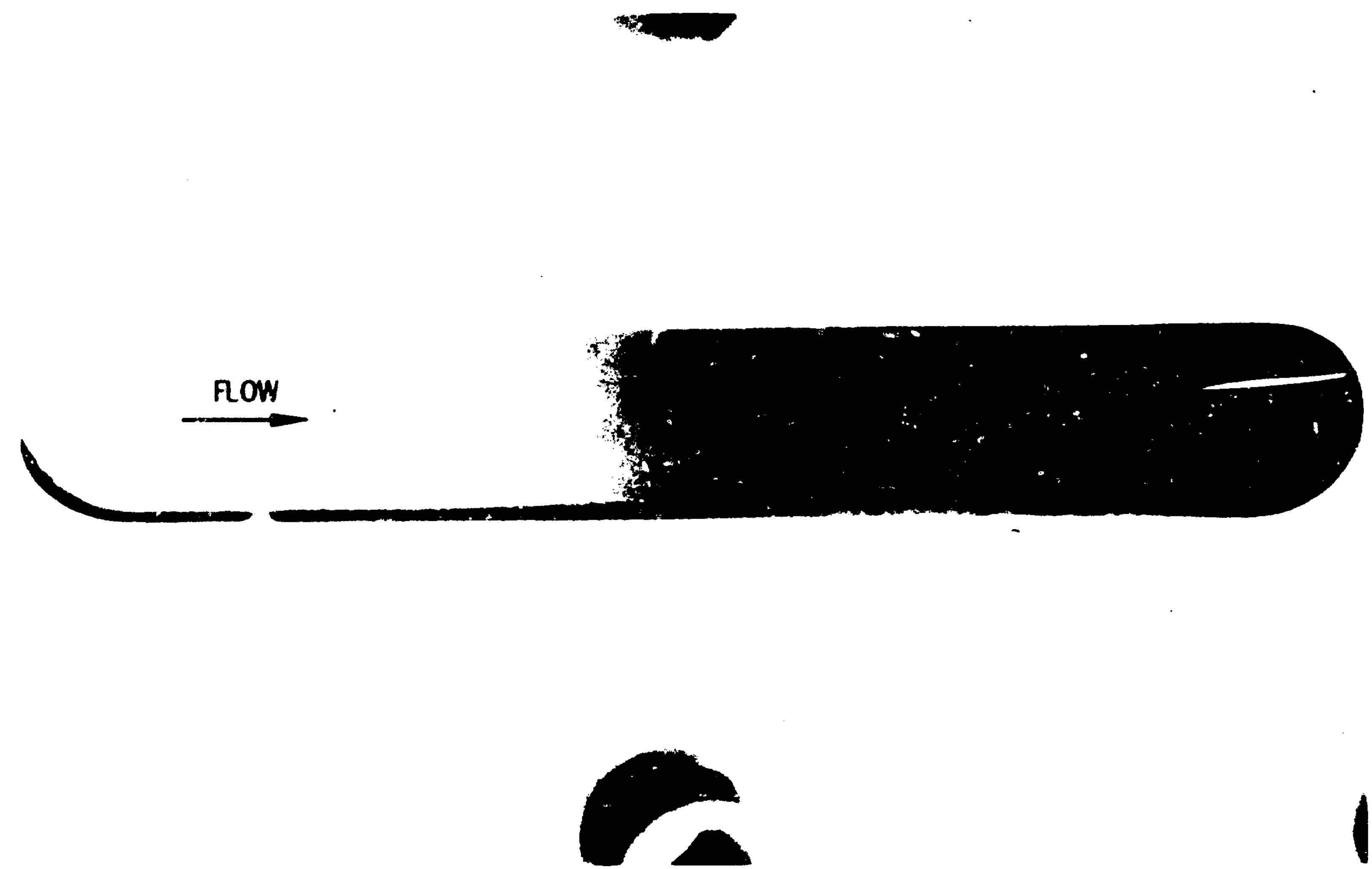

Figure 10. Typical Particle Tracks - MgB_2 in CO_2 Flame

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except the 5 psia - 2000°K condition. Stable flame could not be sustained at a pressure lower than 6 psia and a temperature higher than 1900°K. A slight modification of the burner nozzle throat size to 0.375 in. still failed to obtain precisely this desired pressure and temperature. Instead, two conditions at a pressure slightly higher than 5 psia and a temperature lower than 2000°K were obtained. The measured pressures and temperatures are listed in the following table VI, along with the flow rates of CO, O_2 and air.

Calculations, using an available UTC computer program, were carried out to evaluate the theoretical equilibrium conditions for the CO-O_2-air system, assuming complete mixing and combustion, at pressures corresponding to a given set of mass flow rates and throat areas. The results are also listed in table VI.

The characteristic velocity c* was computed from the relationship between pressure, flow rate and throat area. Comparing the experimental values with the theoretical ideal characteristic velocity, c* efficiencies were derived which are also listed in table VI.

The thermal properties of the gas system and the composition of the combustion products were also printed out in this computer program study. These data are attached as Appendix I.

TABLE VI

COMBUSTION EFFICIENCY FOR VARIOUS TEST CONDITIONS

	Flow Rates, lb/sec					Theoretical			Measured		
Calc. No.	O_2	CO	Air	D_t, in.	A_t, in.	T, °K	C*, fps	P_c, psia	T_c, °K	P_c, psia	C*Eff
UTC 1515-08	.00479	.00846	.0265	.336	.08866	2096	3661	51.02	1700	39.7	.778
-09	.00334	.00588	.01398	.336	.08866	2152	3877	31.53	1700	25	.793
-10	.0022	.00393	.00652	.336	.08866	2547	4071	18.05	1700	15	.830
-11	.00161	.00287	.0034	.336	.08866	2641	4155	11.48	1700	10	.871
-12	.001257	.002205	.000859	.336	.08866	2782	4252	6.44	1700	5	.777
-13	.00715	.0125	.01493	.336	.08866	2742	4201	50.93	2000	39.5	.776
-14	.00534	.00938	.00709	.336	.08866	2834	4269	32.64	2000	26	.796
-15	.00428	.00753	.00255	.336	.08866	2913	4319	21.74	2000	16	.735
-16	.00251	.0048	.001307	.336	.08866	2934	4336	13.10	2000	10	.764
-19	.00181	.00327	.00671	.375	.11045	2837	4285	6.93	1900	6	.865
-20	.001925	.00345	.000747	.375	.11045	2840	4286	7.38	1960	6.6	.893

SECTION III

FUTURE WORK

The modification and calibration of the burner apparatus for the current program requirements have been completed. The boron and boron-metal compounds obtained will be separated by sifting into lots of different particle sizes; these will then be ready for combustion testing under the already calibrated pressure and temperature conditions. The ignition delay times, burn times or rates and combustion efficiencies will be determined from these tests. At least two samples of the test materials will be coated with LiF as dopant. These will be burned for determination of dopant effectiveness in reducing ignition temperature, increasing burn rate and improving combustion efficiency. X-ray diffraction analysis will be carried out on the combustion residue for quantitative interpretation of the completeness of combustion. Wet chemical analysis will be performed on two selected samples of residue and compared with the result obtained by the X-ray diffraction technique. The effects of particle size and chamber pressure will be analyzed and discussed.

Sources of supply and preparation methods for the borides will be further investigated and discussed. The discussion will deal with the best preparation methods found in the literature and with the availability from commercial suppliers, including cost.

An extension of the current program to a parametric study of secondary combustion using the most promising borides selected under the current contract and employing the UTC connected pipe test facility[21] will be formulated and discussed, and potential applications of the results of the program to the design of future air-augmented propulsion systems will be investigated.

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APPENDIX I

THEORETICAL EQUILIBRIUM CALCULATION FOR $CO-O_2$-AIR COMBUSTION

INGREDIENTS		WT.PCT.	ELEMENTS	GM ATOMS
0098	CARBON MONOXIDE GAS	21.28	O	2.47795680E+00
0189	OXYGEN, GAS	12.05	C	7.59701546E-01
9999	AIR	66.67	N	3.59793187E+00
			AR	2.07307214E-02

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST(1)
AREA RATIO	1.00000000E+00	6.47224745E+00
OPTIMUM ISP, SEC	7.83971355E+01	1.74473150E+02
VACUUM ISP, SEC	1.41825159E+02	1.88788680E+02
C*, FT/SEC	3.66065124E+03	
VELOCITY, FT/SEC	2.52234944E+03	5.61349912E+03
DENSITY, GM/CC	4.13452415E-04	2.87039730E-05

	CHAMBER	THROAT	EXHAUST(1)
PRESSURE, PSIA	5.14400000E+01	2.86766781E+01	1.00000000E+00
PRESSURE, ATM	3.50027218E+00	1.95132540E+00	6.80457267E-02
TEMPERATURE, DEG K	2.09629182E+03	1.88018308E+03	9.44521556E+02
HEAT CAP., CAL/DEG K/G	3.09208377E-01	3.05457186E-01	2.81754268E-01
ENTHALPY, KCAL/G	-2.00690357E-01	-2.71291081E-01	-5.50366470E-01
ENTROPY, CAL/DEG K/G	1.96424799E+00	1.96424800E+00	1.96424799E+00
MOLS OF GAS / 100 G	3.06052959E+00	3.05907661E+00	3.05867475E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CO	G	2.90225244E-03	6.20254630E-04	1.00000000E-10
CO2	G	7.56799586E-01	7.59081637E-01	7.59702408E-01
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	4.18773626E-09	2.22871133E-10	1.00000000E-10
NO	G	2.34879577E-02	1.30138751E-02	4.24122017E-05
NO2	G	5.16551816E-05	3.13654606E-05	7.63043466E-07
NO3	G	1.20303379E-10	1.00000000E-10	1.00000000E-10
N2	G	1.78719423E+00	1.79244253E+00	1.79894439E+00
N2O	G	1.90767974E-06	8.01592846E-07	6.89979271E-10
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	8.60320181E-04	2.14959354E-04	1.00932280E-10

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST[1] MOLS/100 G
O2	G	4.68500952@-01	4.72940466@-01	4.79254059@-01
AR	G	2.07307214@-02	2.07307214@-02	2.07307214@-02
C	S	0.00000000@+00	0.00000000@+00	0.00000000@+00

THE TEMPERATURE HAS BECOME LESS THAN 1000 DEG K. THE CURVE FIT MINIMUM

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
C098 CARBON MONOXIDE GAS	25.34	O	2.67698222E+00
0189 OXYGEN, GAS	14.40	C	9.04644604E-01
9999 AIR	60.26	N	3.25200802E+00
		AR	1.87375622E-02

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST(1)
AREA RATIO	1.00000000E+00	4.74702562E+00
OPTIMUM ISP, SEC	8.15635713E+01	1.77346973E+02
VACUUM ISP, SEC	1.49497512E+02	1.95437114E+02
C*, FT/SEC	3.87692411E+03	
VELOCITY, FT/SEC	2.62422634E+03	5.70596150E+03
DENSITY, GM/CC	2.30654247E-04	2.23466452E-05

	CHAMBER	THROAT	EXHAUST(1)
PRESSURE, PSIA	3.16200000E+01	1.78265143E+01	1.00000000E+00
PRESSURE, ATM	2.15160588E+00	1.21301812E+00	6.80457267E-02
TEMPERATURE, DEG K	2.34246470E+03	2.14455945E+03	1.24390667E+03
HEAT CAP., CAL/DEG K/G	3.14440401E-01	3.11725784E-01	2.92390314E-01
ENTHALPY, KCAL/G	-2.38979965E-01	-3.15398944E-01	-6.00270282E-01
ENTROPY, CAL/DEG K/G	2.01101901E+00	2.01101901E+00	2.01101900E+00
MOLS OF GAS / 100 G	2.99750779E+00	2.98850558E+00	2.98323219E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	1.00000000E-10	1.0[illegible]000E-10	1.00000000E-10
CO	G	2.37620621E-02	8.6[illegible]31[illegible]12E-03	4.24519049E-07
CO2	G	8.80882379E-01	8.95[illegible]069E-01	9.04644783E-01
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	9.09914764E-08	1.24262973E-08	1.00000000E-10
NO	G	3.65919081E-02	2.38998383E-02	6.13601325E-04
NO2	G	4.29891051E-05	2.77029583E-05	1.77901950E-06
NO3	G	9.64828707E-11	1.00000000E-10	1.00000000E-10
N2	G	1.60768430E+00	1.61403915E+00	1.62569634E+00
N2O	G	2.22122802E-06	1.09698905E-06	7.89140687E-09
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	4.83282598E-03	1.91371659E-03	2.65547896E-07

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
O2	G	4.24971045E-01	4.25241622E-01	4.33537428E-01
AR	G	1.87375622E-02	1.87375622E-02	1.87375622E-02
C	S	0.00000000E+00	0.00000000E+00	0.00000000E+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
0098 CARBON MONOXIDE GAS	31.07	O	2.94218699E+00
0189 OXYGEN, GAS	17.39	C	1.10920710E+00
9999 AIR	51.54	N	2.78142206E+00
		AR	1.60261194E-02

PROPELLANT DENSITY, G/CC 1.00000000E-03

	CHAMBER	THROAT	EXHAUST(1)
AREA RATIO		1.00000000E+00	3.42757678E+00
OPTIMUM ISP, SEC		8.31944930E+01	1.76351762E+02
VACUUM ISP, SEC		1.56098775E+02	2.00461982E+02
C*, FT/SEC		4.07146024E+03	
VELOCITY, FT/SEC		2.67669962E+03	5.67394160E+03
DENSITY, GM/CC		1.22509427E-04	1.68615344E-05
PRESSURE, PSIA	1.79900000E+01	1.03642781E+01	1.00000000E+00
PRESSURE, ATM	1.22414262E+00	7.05244837E-01	6.80457267E-02
TEMPERATURE, DEG K	2.54654922E+03	2.40269293E+03	1.70861016E+03
HEAT CAP., CAL/DEG K/G	3.18540421E-01	3.17284398E-01	3.06313127E-01
ENTHALPY, KCAL/G	-2.93019239E-01	-3.72524876E-01	-6.50266058E-01
ENTROPY, CAL/DEG K/G	2.06085019E+00	2.06085019E+00	2.06085019E+00
MOLS OF GAS / 100 G	2.94390009E+00	2.91983605E+00	2.87837325E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CO	G	1.14789175E-01	7.31510411E-02	8.99114261E-04
CO2	G	9.94419121E-01	1.03605628E+00	1.10830836E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-20	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	7.98805019E-07	2.69238906E-07	1.00000000E-10
NO	G	4.67024786E-02	3.56866814E-02	5.58162954E-03
NO2	G	3.15105851E-05	2.12295510E-05	3.26877511E-06
NO3	G	5.05214204E-11	1.00000000E-10	1.00000000E-10
N2	G	1.36734165E+00	1.37285579E+00	1.38791854E+00
N2O	G	1.99260735E-06	1.16115691E-06	5.94188448E-08
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	1.73823798E-02	1.08818377E-02	1.89340201E-04

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
O2	G	3.87205861P-01	3.75155641P-01	3.59446813P-01
AR	G	1.60261194P-02	1.60261194P-02	1.60261194P-02
C	S	0.00000000P+00	0.00000000P+00	0.00000000P+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
0498 CARBON MONOXIDE GAS	36.42	O	3.20172781E+00
0189 OXYGEN, GAS	20.43	C	1.30020349E+00
9099 AIR	43.15	N	2.32864497E+00
		AR	1.34172886E-02

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST[1]
AREA RATIO	1.00000000E+00	2.66574008E+00
OPTIMUM ISP, SEC	8.38481989E+01	1.69063834E+02
VACUUM ISP, SEC	1.58902270E+02	1.99207800E+02
C*, FT/SEC	4.15483464E+03	
VELOCITY, FT/SEC	2.69773195E+03	5.43945981E+03
DENSITY, GM/CC	7.56139185E-05	1.40678253E-05

	CHAMBER	THROAT	EXHAUST[1]
PRESSURE, PSIA	1.14200000E+01	6.63730344E+00	1.00000000E+00
PRESSURE, ATM	7.77082199E-01	4.51640136E-01	6.80457267E-02
TEMPERATURE, DEG K	2.64088072E+03	2.52228413E+03	2.10334226E+03
HEAT CAP., CAL/DEG K/G	3.20460318E-01	3.19781745E-01	3.15667128E-01
ENTHALPY, KCAL/G	-3.43474756E-01	-4.24234743E-01	-6.71804473E-01
ENTROPY, CAL/DEG K/G	2.09777849E+00	2.09777849E+00	2.09777849E+00
MOLS OF GAS / 100 G	2.91721042E+00	2.88591214E+00	2.80253000E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST[1] MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CO	G	2.44025479E-01	1.90191777E-01	4.27981482E-02
CO2	G	1.05617820E+00	1.11001191E+00	1.25740561E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	2.05344322E-06	9.57162105E-07	2.53647192E-08
NO	G	4.92702048E-02	3.97433818E-02	1.56814065E-02
NO2	G	2.39833123E-05	1.63612311E-05	4.05358311E-06
NO3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2	G	1.13967283E+00	1.14444119E+00	1.15647961E+00
N2O	G	1.53902159E-06	9.51355888E-07	1.49236820E-07
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	3.32114264E-02	2.44414550E-02	5.05860167E-03

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
O2	G	3.81407415P-01	3.63646864P-01	3.11685108P-01
AR	G	1.34172886P-02	1.34172886P-02	1.34172886P-02
C	S	0.00000000P+00	0.00000000P+00	0.00000000P+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
0498 CARBON MONOXIDE GAS	51.03	O	3.92769675E+00
0189 OXYGEN, GAS	29.09	C	1.82178430E+00
9999 AIR	19.88	N	1.07284964E+00
		AR	6.18159204E-03

PROPELLANT DENSITY, G/CC 1.00000000E-03

		THROAT	EXHAUST[1]
AREA RATIO		1.00000000E+00	1.84694332E+00
OPTIMUM ISP, SEC		8.50925783E+01	1.53814147E+02
VACUUM ISP, SEC		1.62355849E+02	1.91777122E+02
C*, FT/SEC		4.25228830E+03	
VELOCITY, FT/SEC		2.73776861E+03	4.94881638E+03
DENSITY, GM/CC		4.09901692E-05	1.22778280E-05

	CHAMBER	THROAT	EXHAUST[1]
PRESSURE, PSIA	6.43000000E+00	3.75894885E+00	1.00000000E+00
PRESSURE, ATM	4.37534023E-01	2.55780406E-01	6.80457267E-02
TEMPERATURE, DEG K	2.78197708E+03	2.68188447E+03	2.45747597E+03
HEAT CAP., CAL/DEG K/G	3.23565120E-01	3.23321199E-01	3.22532287E-01
ENTHALPY, KCAL/G	-4.81260758E-01	-5.64435628E-01	-7.53030641E-01
ENTROPY, CAL/DEG K/G	2.14419891E+00	2.14419891E+00	2.14419891E+00
MOLS OF GAS / 100 G	2.87364968E+00	2.83552725E+00	2.74837735E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST[1] MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	1.89920070E-10	5.57360940E-11	1.00000000E-10
CO	G	6.52430554E-01	5.89622364E-01	4.41421878E-01
CO2	G	1.16935391E+00	1.23216211E+00	1.38036267E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	5.55974418E-06	3.32936019E-06	8.89708051E-07
NO	G	4.21030047E-02	3.55484807E-02	2.28949936E-02
NO2	G	1.40172325E-05	9.72078454E-06	3.83776774E-06
NO3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2	G	5.15362866E-01	5.18643628E-01	5.24974824E-01
N2O	G	6.71344721E-07	4.36361440E-07	1.47530169E-07
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	8.19683146E-02	6.85293353E-02	4.24263295E-02

		CHAMBER MULS/100 G	THRUAT MULS/100 G	EXHAUST(1) MULS/100 G
O2	G	4.06229192D-01	3.84826253D-01	3.30110235D-01
A2	G	6.18159204D-03	6.18159204D-03	6.18159204D-03
C	S	0.00000000D+00	0.00000000D+00	0.00000000D+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
0498 CARBON MONOXIDE GAS	36.15	O	3.20800327P+00
0189 OXYGEN, GAS	20.68	C	1.29056442P+00
9999 AIR	43.17	N	2.32972430P+00
		AR	1.34235075P-02

PROPELLANT DENSITY, G/CC 1.00000000P-03

	THROAT	EXHAUST(1)
AREA RATIO	1.00000000P+00	7.59945694P+00
OPTIMUM ISP, SEC	8.52263782P+01	2.06777903P+02
VACUUM ISP, SEC	1.60830493P+02	2.26190639P+02
C*, FT/SEC	4.20063670P+03	
VELOCITY, FT/SEC	2.74207349P+03	6.65287276P+03
DENSITY, GM/CC	3.29306156P-04	1.78602361P-05

	CHAMBER	THROAT	EXHAUST(1)
PRESSURE, PSIA	5.11100000P+01	2.95965609P+01	1.00000000P+00
PRESSURE, ATM	3.47781709P+00	2.01391950P+00	6.80457267P-02
TEMPERATURE, DEG K	2.74153321P+03	2.60435195P+03	1.66853629P+03
HEAT CAP., CAL/DEG K/G	3.21922290P-01	3.21105472P-01	3.07565554P-01
ENTHALPY, KCAL/G	-3.40928403P-01	-4.24365047P-01	-8.32081646P-01
ENTROPY, CAL/DEG K/G	2.01067685P+00	2.01067685P+00	2.01067681P+00
MOLS OF GAS / 100 G	2.89005292P+00	2.86173169P+00	2.78268684P+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
CN	G	3.57243377P-11	1.00000000P-10	1.00000000P-10
CO	G	1.91976260P-01	1.42219517P-01	6.88835067P-04
CO2	G	1.09858833P+00	1.14834509P+00	1.28987598P+00
C2	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
C2N2	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
C3	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
C3O2	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
C4	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
C5	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
N	G	2.15965638P-06	9.29844645P-07	1.00000000P-10
NO	G	5.62998453P-02	4.48476145P-02	4.08227307P-03
NO2	G	5.21113326P-05	3.54399192P-05	2.49616607P-06
NO3	G	2.38784470P-10	9.18074581P-11	1.00000000P-10
N2	G	1.13668135P+00	1.14241789P+00	1.16281974P+00
N2O	G	3.74326163P-06	2.27782598P-06	4.07065912P-08
N2O3	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
N2O4	G	1.00000000P-10	1.00000000P-10	1.00000000P-10
O	G	2.36086673P-02	1.67060288P-02	1.12708945P-04

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
[illegible]	G	1.69415940D-01	3.53733392D-01	3.11681253D-01
[illegible]	[illegible]	1.34235075D-02	1.34235075D-02	1.34235075D-02
[illegible]	[illegible]	[illegible]	0.00000000D+00	0.00000000D+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
C498 CARBON MONOXIDE GAS	43.01	O	3.53609044E+00
O149 OXYGEN, GAS	24.48	C	1.53546821E+00
9999 AIR	32.51	N	1.75444375E+00
		AR	1.01088308E-02

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST[1]
AREA RATIO	1.00000000E+00	5.94430827E+00
OPTIMUM ISP, SEC	8.59449680E+01	2.03052608E+02
VACUUM ISP, SEC	1.63199621E+02	2.27179663E+02
C*, FT/SEC	4.26896869E+03	
VELOCITY, FT/SEC	2.76519340E+03	6.53301460E+03
DENSITY, GM/CC	2.05520250E-04	1.46340717E-05

	CHAMBER	THROAT	EXHAUST[1]
PRESSURE, PSIA	3.26900000E+01	1.90336314E+01	1.00000000E+00
PRESSURE, ATM	2.22441481E+00	1.29515728E+00	6.80457267E-02
TEMPERATURE, DEG K	2.83394632E+03	2.71431487E+03	2.10941528E+03
HEAT CAP., CAL/DEG K/G	3.23732117E-01	3.23305528E-01	3.18492688E-01
ENTHALPY, KCAL/G	-4.05624637E-01	-4.90474212E-01	-8.79240134E-01
ENTROPY, CAL/DEG K/G	2.04619238E+00	2.04619238E+00	2.04619238E+00
MOLS OF GAS / 100 G	2.86332434E+00	2.82939769E+00	2.66633344E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST[1] MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	2.30954256E-10	5.31781729E-11	1.00000000E-10
CO	G	3.73471671E-01	3.14763570E-01	5.72672734E-02
CO2	G	1.16199670E+00	1.22070481E+00	1.47820120E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	4.63134253E-06	2.45577642E-06	2.33250313E-08
NO	G	5.54284445E-02	4.56923231E-02	1.24365962E-02
NO2	G	3.80405917E-05	2.60507515E-05	2.92865177E-06
NO3	G	1.41451382E-10	4.29293718E-11	1.00000000E-10
N2	G	8.49483758E-01	8.54359846E-01	8.71001962E-01
N2O	G	2.56776543E-06	1.62310500E-06	1.04888337E-07
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	4.24610792E-02	3.33051302E-02	4.65068625E-03

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
O2	G	3.70328612P-01	3.50433049P-01	2.52663735P-01
AR	G	1.01088308P-02	1.01088308P-02	1.01088308P-02
C	S	0.00000000P+00	0.00000000P+00	0.00000000P+00

```
                                                                     0      0.00000000E+00
ERROR =   8     SUM OF WT.PCTS. = 100.00             I =   4        0      0.00000000E+00
REGION =  3       T = 2109       P =      0.068
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0112 11 OXYGEN GAS				0.001	32.000	0.000 O	2.000		0.000
0498 11 CARBON MONOXIDE GAS				0.001	28.011	-26.417 C	1.0000		1.000
9999 12 AIR				0.001	28.944	0.000 N	1.5620		0.419
9999 22 AR	0.009	0.000	0.000	0.000	0.000	0.000	0.000		0.000

C	S	5.2596	-0.1946	0.1076	-0.0103	-1.506	43.923	12.011	170.890	0.000
CN	G	6.8845	1.0442	0.0600	-0.0203	-2.207	56.202	26.018	104.000	0.000
CO	G	5.9591	1.3414	-0.2976	0.0228	-2.348	54.831	28.011	-26.417	0.000
CO2	G	11.0933	2.6353	-0.5821	0.0466	-4.230	61.995	44.010	-94.054	0.000
C2	G	7.6536	1.0438	-0.1422	0.0108	-1.922	57.561	24.022	200.224	0.000
C2N2	G	15.0000	3.2922	-0.7576	0.0578	-5.782	74.081	52.038	73.870	0.000
C3	G	8.7504	2.5534	-0.4940	0.0350	-3.060	65.865	36.033	196.000	0.000
C3O2	G	20.2371	4.4140	-1.0222	0.0783	-7.691	86.012	68.032	-22.380	0.000
C4	G	16.1854	3.1721	-0.7399	0.0570	-6.251	70.403	48.045	232.000	0.000
C5	G	20.5144	4.2770	-0.9975	0.0768	-8.061	77.544	60.056	234.000	0.000
N	G	5.1296	-0.1713	0.0333	0.0038	-1.567	42.780	14.008	113.000	0.000
NO	G	7.3014	1.1467	-0.2544	0.0194	-2.476	58.353	30.008	21.580	0.000
NO2	G	11.1841	1.6748	-0.4410	0.0341	-4.242	68.555	46.008	7.910	0.000
NO3	G	16.8670	2.1070	-0.5015	0.0391	-6.554	76.943	62.008	17.000	0.000
N2	G	5.7004	1.4678	-0.3268	0.0251	-2.238	53.197	28.013	0.000	0.000
N2O	G	11.5132	2.2790	-0.5288	0.0405	-4.327	64.112	44.016	19.610	0.000
N2O3	G	20.1817	3.1249	-0.7505	0.0581	-7.585	94.306	76.016	19.800	0.000
N2O4	G	25.5541	4.3006	-1.0130	0.0785	-9.920	97.772	92.016	2.170	0.000
O	G	5.1307	-0.1759	0.0551	-0.0033	-1.508	44.768	16.000	59.559	0.000
O2	G	7.5538	0.8949	-0.0788	0.0008	-2.546	57.338	31.999	0.000	0.000
AR	G	4.9680	0.0000	0.0000	0.0000	-1.481	43.007	39.944	0.000	0.000
C	S	4.3545	1.1983	-0.2773	0.0236	-2.035	4.781	12.011	0.000	9.999

INGREDIENTS		WT.PCT.	ELEMENTS	GM ATOMS
0498	CARBON MONOXIDE GAS	52.44	O	3.99171951E+00
0189	OXYGEN, GAS	29.80	C	1.87212167E+00
9999	AIR	17.76	N	9.58441128E-01
			AR	5.52238806E-03

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST[1]
AREA RATIO	1.00000000E+00	4.45171071E+00
OPTIMUM ISP, SEC	8.66315700E+01	1.95573284E+02
VACUUM ISP, SEC	1.64999709E+02	2.23127289E+02
C*, FT/SEC	4.31938988E+03	
VELOCITY, FT/SEC	2.78728413E+03	6.29237485E+03
DENSITY, GM/CC	1.33703903E-04	1.33040481E-05

	CHAMBER	THROAT	EXHAUST[1]
PRESSURE, PSIA	2.16900000E+01	1.26614003E+01	1.00000000E+00
PRESSURE, ATM	1.47591181E+00	8.61554182E-01	6.80457267E-02
TEMPERATURE, DEG K	2.91336191E+03	2.80290251E+03	2.35582412E+03
HEAT CAP., CAL/DEG K/G	3.25446656E-01	3.25223730E-01	3.23429230E-01
ENTHALPY, KCAL/G	-4.94558381E-01	-5.80769073E-01	-9.33925770E-01
ENTROPY, CAL/DEG K/G	2.07555641E+00	2.07555641E+00	2.07555649E+00
MOLS OF GAS / 100 G	2.83929678E+00	2.80166915E+00	2.64582135E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST[1] MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	5.66228713E-10	2.03130461E-10	1.00000000E-10
CO	G	6.45923971E-01	5.02682648E-01	3.08944491E-01
CO2	G	1.22619784E+00	1.28943918E+00	1.56317739E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	7.24863546E-06	4.31728942E-06	2.99395564E-07
NO	G	4.61260496E-02	3.88550687E-02	1.58943262E-02
NO2	G	2.48101501E-05	1.71295997E-05	2.71647055E-06
NO3	G	6.81881836E-11	1.00000000E-10	1.00000000E-10
N2	G	4.56140232E-01	4.59781482E-01	4.71271807E-01
N2O	G	1.28473749E-06	8.32245644E-07	9.88742047E-08
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	7.14829744E-02	5.94638315E-02	2.14952384E-02

		CHAMBER	THROAT	EXHAUST(1)
		MOLS/100 G	MOLS/100 G	MOLS/100 G
O2	G	3.87860971E-01	3.65902271E-01	2.59512594E-01
AR	G	5.52238806E-03	5.52238806E-03	5.52238806E-03
C	S	0.00000000E+00	0.00000000E+00	0.00000000E+00

INGREDIENTS		WT.PCT.	ELEMENTS	GM ATOMS
C998	CARBON MONOXIDE GAS	55.70	O	3.02873392E+00
C159	OXYGEN, GAS	29.13	C	1.98850452E+00
9999	AIR	15.17	N	8.18668463E-01
			AR	4.71703980E-03

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST(1)
AREA RATIO	1.00000000E+00	4.45966637E+00
OPTIMUM ISP, SEC	8.69461818E+01	1.96380941E+02
VACUUM ISP, SEC	1.65629995E+02	2.24090516E+02
C*, FT/SEC	4.33602829E+03	
VELOCITY, FT/SEC	2.79740645E+03	6.31836036E+03
DENSITY, GM/CC	1.32708901E-04	1.31749465E-05

	CHAMBER	THROAT	EXHAUST(1)
PRESSURE, PSIA	2.16900000E+01	1.26636208E+01	1.00000000E+00
PRESSURE, ATM	1.47591181E+00	8.61705284E-01	6.80457267E-02
TEMPERATURE, DEG K	2.93442414E+03	2.82426848E+03	2.38205810E+03
HEAT CAP., CAL/DEG K/G	3.26134858E-01	3.25956603E-01	3.24442767E-01
ENTHALPY, KCAL/G	-5.25301238E-01	-6.12141234E-01	-9.68307019E-01
ENTROPY, CAL/DEG K/G	2.07816107E+00	2.07816107E+00	2.07816106E+00
MOLS OF GAS / 100 G	2.84006439E+00	2.80181239E+00	2.64232342E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	7.63355265E-10	2.90741271E-10	1.00000000E-10
CO	G	7.50634460E-01	6.86234632E-01	4.05472891E-01
CO2	G	1.23787020E+00	1.30227004E+00	1.58303183E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	7.72092303E-06	4.66162063E-06	3.62337511E-07
NO	G	4.11967414E-02	3.46205137E-02	1.39152699E-02
NO2	G	2.05225784E-05	1.40425608E-05	2.07537303E-06
NO3	G	4.37896933E-11	1.00000000E-10	1.00000000E-10
N2	G	3.88720686E-01	3.92013945E-01	4.02375310E-01
N2O	G	1.06002254E-06	6.85275715E-07	8.00357892E-08
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	7.26716804E-02	6.05637082E-02	2.23392126E-02

		CHAMBER	THROAT	EXHAUST(1)
		MOLS/100 G	MOLS/100 G	MOLS/100 G
O2	G	3.44224275E-01	3.21373125E-01	2.10469348E-01
AR	G	4.71703980E-03	4.71703960E-03	4.71703980E-03
C	S	0.00000000E+00	0.00000000E+00	0.00000000E+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
0098 CARBON MONOXIDE GAS	56.86	O	4.16572942E+00
0189 OXYGEN, GAS	31.47	C	2.02991682E+00
9099 AIR	11.67	N	6.29786484E-01
		AR	3.62873134E-03

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST(1)
AREA RATIO	1.00000000E+00	1.94459106E+00
OPTIMUM ISP, SEC	8.57061013E+01	1.57848575E+02
VACUUM ISP, SEC	1.63591247E+02	1.95221816E+02
C*, FT/SEC	4.28519671E+03	
VELOCITY, FT/SEC	2.75750810E+03	5.07862006E+03
DENSITY, GM/CC	4.35245065E-05	1.21528082E-05

	CHAMBER	THROAT	EXHAUST(1)
PRESSURE, PSIA	6.93000000E+00	4.05249199E+00	1.00000000E+00
PRESSURE, ATM	4.71556886E-01	2.75754762E-01	6.80457267E-02
TEMPERATURE, DEG K	2.83656360E+03	2.73667763E+03	2.50329204E+03
HEAT CAP., CAL/DEG K/G	3.24603550E-01	3.24621892E-01	3.23963050E-01
ENTHALPY, KCAL/G	-5.36243126E-01	-6.20621712E-01	-8.22456613E-01
ENTROPY, CAL/DEG K/G	2.14066586E+00	2.14066586E+00	2.14066592E+00
MOLS OF GAS / 100 G	2.86046703E+00	2.82112092E+00	2.72583161E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CN	G	3.02431343E-10	1.06446343E-10	1.00000000E-10
CO	G	8.21599061E-01	7.57470454E-01	5.96863864E-01
CO2	G	1.20831791E+00	1.27244653E+00	1.43303314E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2N2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	6.06625063E-06	3.75748718E-06	1.04050359E-06
NO	G	3.41587983E-02	2.90090409E-02	1.85339671E-02
NO2	G	1.11757089E-05	7.75521401E-06	2.90048187E-06
NO3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2	G	2.97804799E-01	3.00382692E-01	3.05624209E-01
N2O	G	4.31647044E-07	2.82541588E-07	9.15437666E-08
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	9.65671220E-02	8.20022489E-02	5.20078760E-02

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
O2	G	3.98372931@-01	3.76169428@-01	3.16115785@-01
AR	G	3.62873134@-03	3.62873134@-03	3.62873134@-03
C	S	0.00000000@+00	0.00000000@+00	0.00000000@+00

INGREDIENTS	WT.PCT.	ELEMENTS	GM ATOMS
C498 CARBON MONOXIDE GAS	56.36	O	4.15367669E+00
0189 OXYGEN, GAS	31.44	C	2.01206669E+00
9999 AIR	12.20	N	6.58388612E-01
		AR	3.79353234E-03

PROPELLANT DENSITY, G/CC 1.00000000E-03

	THROAT	EXHAUST(1)
AREA RATIO	1.00000000E+00	2.02931374E+00
OPTIMUM ISP, SEC	8.57377417E+01	1.60211040E+02
VACUUM ISP, SEC	1.63632329E+02	1.96840731E+02
C*, FT/SEC	4.28593397E+03	
VELOCITY, FT/SEC	2.75852610E+03	5.15463000E+03
DENSITY, GM/CC	4.63256977E-05	1.22166568E-05

	CHAMBER	THROAT	EXHAUST(1)
PRESSURE, PSIA	7.38000000E+00	4.31542152E+00	1.00000000E+00
PRESSURE, ATM	5.02177463E-01	2.93645993E-01	6.80457267E-02
TEMPERATURE, DEG K	2.83970036E+03	2.73945537E+03	2.49475642E+03
HEAT CAP., CAL/DEG K/G	3.24790934E-01	3.24604950E-01	3.23915249E-01
ENTHALPY, KCAL/G	-5.31527657E-01	-6.15968555E-01	-[illegible].26372571E-01
ENTROPY, CAL/DEG K/G	2.13694855E+00	2.13694856E+00	2.13694856E+00
MOLS OF GAS / 100 G	2.85906057E+00	2.81783834E+00	2.72086292E+00

COMBUSTION PRODUCTS

		CHAMBER MOLS/100 G	THROAT MOLS/100 G	EXHAUST(1) MOLS/100 G
C	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
CH	G	3.09764022E-10	1.08912810E-10	1.00000000E-10
CO	G	8.03437224E-01	7.39408518E-01	5.72219034E-01
CO2	G	1.20862962E+00	1.27265833E+00	1.43984795E+00
C2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C2H2	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C3O2		1.00000000E-10	1.00000000E-10	1.00000000E-10
C4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
C5	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N	G	6.14861112E-06	3.79864830E-06	9.82548763E-07
NO	G	3.52180758E-02	2.99016012E-02	1.86954261E-02
NO2	G	1.19059463E-05	8.26460729E-06	2.95831205E-06
NO3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2	G	3.11575780E-01	3.14237176E-01	3.19844540E-01
N2O	G	4.69926275E-07	3.07481150E-07	9.45414833E-08
N2O3	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
N2O4	G	1.00000000E-10	1.00000000E-10	1.00000000E-10
O	G	9.50377276E-02	8.06205113E-02	4.98564334E-02

		CHAMBER	THROAT	EXHAUST 1 1
		MOLS/100 G	MOLS/100 G	MOLS/100 G
O2	G	4.01350086E-01	3.79206293E-01	3.16602065E-01
AR	G	3.79353234E-03	3.79353234E-03	3.79353234E-03
C	S	0.00000000E+00	0.00000000E+00	0.00000000E+00

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13. ABSTRACT

Under Contract No. AF04(611)-70-C-0065, United Technology Center has completed the first 6 months of a 12-month program to investigate the ignition delay times, burn times or rates and combustion efficiencies of doped and undoped boron and compound of boron with aluminum, magnesium, and lithium.

A literature survey has been conducted for information on the properties and combustion of aluminum, magnesium and lithium borides.

An optical burner apparatus built under a previous Air Force contract, AF04(611)-11544, has been modified and calibrated for the present investigation. Eight borides have been obtained or prepared for this program, were analyzed for purity on the basis of chemical, spectrographic, or X-ray data, and are ready for test.

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