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RESEARCH MEMORANDUM

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A PRELIMINARY EXPERIMENTAL AND ANALYTICAL EVALUATION OF DIBORANE AS A RAM-JET FUEL

By Benson E. Gammon, Russell S. Genco, and Melvin Gerstein

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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RESEARCH MEMORANDUM

A PRELIMINARY EXPERIMENTAL AND ANALYTICAL EVALUATION OF DIBORANE AS A RAM-JET FUEL

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SUMMARY

A preliminary analytical and experimental evaluation of diborane as a ram-jet fuel has been made because there is a need for a ram-jet fuel that will permit a realization of flight range, thrust, and combustion stability beyond those attainable with petroleum fuels. Diborane, though at present expensive and not readily available, is a fuel that appears to offer some of these needed characteristics.

Air specific thrusts of 80 percent of the ideal values were attained for diborane. The experimental air specific thrusts for diborane were approximately equal to the ideal values for octene-1 for corresponding values of the stoichiometric fraction of fuel. With diborane, smooth stable operation of the combustor unit was maintained over a range of fuel-air ratios from 0.0015 to 0.10 and at combustor inlet-air velocities up to 500 feet per second in the absence of a flameholder. Stable combustion of hydrocarbon fuels was not attained in a combustor employing the identical configuration as that used for diborane. This stability and range of operation is apparently related to the wide inflammability limits and to the extremely high spatial flame speeds of diborane-air mixtures. Spatial flame speeds for diborane-air mixtures as high as 169.5 feet per second were observed under conditions where normal hexane gave a spatial flame speed of 3.22 feet per second or less.

Flight range calculations for an altitude of 20,000 feet, flight Mach number of 1.665, and ambient temperature of 362° R, indicate that liquid diborane is capable of maximum ranges as much as 30 to 50 percent greater than that obtained with aviation gasoline, depending upon the weight of equipment necessary to maintain the diborane as a liquid during flight. If diborane is carried as a gas, it is inferior to aviation gasoline from the viewpoint of the available range.

Results of theoretical calculations for maximum adiabatic combustor flame temperature, combustor-gas composition, exit-gas composition, and net internal air specific thrust are also presented.

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INTRODUCTION

For several years the NACA Lewis laboratory has been engaged in a study of special fuels for ram-jet power plants. First consideration in this study has been given to fuels that may increase flight range, thrust, and combustion stability beyond that attainable with conventional fuels derived from petroleum. Preliminary selection of fuels for investigation in experimental ram-jet facilities has been based on properties such as heating value, density, maximum adiabatic flame temperature at constant pressure, and inflammability limits.

The search for new fuels has been resolved chiefly into a study of metals and metallic compounds as potential sources of energy for ram-jet propulsion. The use of solid fuels creates an unusually difficult injection problem in any service power-plant installation. Liquid metallic compounds, such as diborane B_2H_6 and pentaborane B_5H_9, have been considered as possible ram-jet fuels. Because of its availability as compared with pentaborane, diborane was selected for first evaluation although its use involved special storage and handling problems. Both diborane and pentaborane are expensive and relatively unavailable as compared with petroleum fuels.

Some of the comparative properties of diborane and gasoline that led to this evaluation are presented in the following table:

Property	Diborane	Gasoline
Heat of combustion, Btu/lb	33,513	18,700
Heat of combustion, Btu/cu ft	935,220[a]	840,000
Flammability limits, percent by volume (lean)	<2	1.4
(rich)	78	6.5

[a]Specific gravity of liquid taken as 0.4470.

The wide combustion limits of diborane in air as compared with gasoline indicates that diborane might be capable of stable operation under more severe conditions than is possible with gasoline.

A preliminary study of the combustion properties of diborane as a possible ram-jet fuel made at the Johns Hopkins Applied Physics

Laboratory (reference 1) indicates that ignition could be satisfactorily obtained in high-velocity gas streams. Experimental values for the air specific impulse with diborane were reported to be 10 to 15 percent greater than values obtainable with the best hydrocarbon fuels under similar conditions.

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The present study includes both an analytical and an experimental evaluation of diborane performance in a ram-jet combustor. Calculations of the potential flight ranges to be realized from diborane and from gasoline are presented for a single flight condition. An experimental evaluation of the spatial flame velocity of diborane-air mixtures in a 1-inch-diameter glass tube is also presented.

APPARATUS

Burner. - A diagrammatic sketch of the burner setup is shown in figure 1. The combustion tube is a 2-inch O.D. stainless-steel tube consisting of a fuel-injection section, a combustion section, and an exhaust nozzle. No flameholder was employed. The entire unit was immersed in a coolant trough. Fuel was introduced 2 feet from the burner exit and 3 inches upstream of the spark plug. Two exhaust nozzles were used. The first exhaust nozzle, used in a greater part of the investigation, had a throat diameter of 1.25 inches with a convergent angle of 7°. The other nozzle was a straight tube (1.875-in. I.D.) with no reduction at the exit. The installation is shown in figure 2.

Fuel system. - Diborane slowly decomposes at room temperatures; it was therefore necessary to store the diborane at dry-ice temperature until it was used. The refrigeration system consisted of a pump, jacketed fuel line, and two coolant-bath chambers (fig. 3). Chamber A served as a reservoir where methyl cellosolve was cooled by dry ice to -100° F. Chamber B contained methyl cellosolve and coolant coils through which the refrigerated methyl cellosolve from chamber A was circulated. Refrigerated methyl cellosolve from chamber A was also circulated through the jacketed fuel line to maintain a reduced fuel temperature up to the point of injection.

The refrigeration system was started several hours before test time. When the temperature in chamber B fell below -80° F, a molybdenum steel tank containing 3 pounds of diborane was transferred from the dry-ice storage and placed in a rack in chamber B. The rack was designed to hold two tanks of diborane, but only one was used in any given run. The rack was suspended from the lever arm of a beam balance

modified to allow for mounting the rack and counterbalance weights. Unbalanced forces caused by the change in fuel weight during a run were transmitted to a cantilever beam equipped with a strain gage. The strain gage formed part of a recording self-balancing Wheatstone-bridge circuit. Strain-gage readings were recorded automatically on a moving-strip recorder every 4 seconds, giving a measure of the fuel flow as a function of time. Coolant-bath density changes were insignificant during any run.

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Each diborane tank was fitted with a siphon extended to the bottom of the cylinder and a gas inlet at the cylinder top. Fuel was forced from the diborane tank by helium pressure. The helium pressure was controlled by means of a single-stage regulator. Once the helium pressure was set, the fuel flow could be started and stopped by remote control. The fuel flow rate was governed by the applied helium pressure and by the size of the orifice used in the fuel nozzle.

A conventional hollow-cone, swirl-type nozzle with a rated spray angle of 60° was used. The ratio of liquid to gaseous diborane in the fuel system changed with operating conditions, which caused difficulty in obtaining any given mass fuel flow. The diborane temperature at the injection nozzle was -67° F.

Fuel lines were purged with helium before and after each run. The fuel weighing system was calibrated before each run.

Air. - Air at 100 pounds per square inch absolute was supplied to the setup and kept at a constant upstream pressure by means of a remote-control pressure regulator. Air flow was controlled by a hand-operated V-port valve and was measured by an orifice located between the pressure regulator and the V-port valve. A critical pressure ratio across the V-port valve was maintained for all tests. The inlet-air temperature was held at 100° F by an automatically controlled electric air heater.

An instrument section consisting of a static-pressure ring, a total-pressure tube, and an iron-constantan thermocouple was installed upstream of the combustion chamber. Inlet-air temperatures and pressures were indicated by a potentiometer and a manometer, respectively.

Thrust measurement. - The barrel-type target used to measure thrust is shown in figure 1. The velocity of the exhaust gases in the barrel was relatively low, inasmuch as the barrel was much larger than the burner diameter. Aided by guide vanes, the exhaust gases left the barrel target at a 90° angle. The forward force on the

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thrust target was indicated by means of a strain gage and self-balancing Wheatstone-bridge circuit. Thrust measurements were recorded automatically on a moving-strip recorder every 4 seconds with a 2-second time interval between the thrust record and the fuel-flow record made on the same tape. The thrust-measuring apparatus was calibrated by dead loading prior to each run. The calibration curve was essentially constant; the maximum change in this calibration curve was 2 percent, or less, from run to run.

The exhaust gases were cooled by water sprays to protect the barrel and strain gage. A drain was provided in such a manner that the water height in the barrel would be constant. Calibration, with and without water sprays during air-blast tests, indicated that the water sprays had no effect on the measured thrust.

FUEL

Source. - The diborane used in this investigation was obtained through the cooperation of the Department of the Navy, Bureau of Aeronautics. The material was approximately 95-percent diborane by volume according to the supplier. The major impurities present were probably ethane and ethyl ether.

Properties. - Values for several of the physical properties of diborane are as follows:

Formula	B_2H_6
Formula weight	27.7
Melting point, °F	-265
Boiling point, °F	-134.5

RESULTS AND DISCUSSION

Ideal Thrust

The ideal thrust obtainable from diborane-air mixtures in a ram-jet, operating under conditions comparable to those investigated experimentally, was calculated in order to provide a standard for evaluating the experimental results. This ideal thrust was obtained in the following manner: The diborane was assumed to be 100-percent pure; air was assumed to be composed of 1 mole of oxygen to every 3.78 moles of nitrogen. The ideal ram-jet combustor gas temperature and composition were calculated for a constant-pressure combustion

process by the matrix method of reference 2. The molecules assumed to be present in the complex equilibria were atomic hydrogen, molecular hydrogen, water vapor, hydroxyl radical, boron hydride radical BH, atomic oxygen, molecular oxygen, solid, liquid, and gaseous boron trioxide B_2O_3, boron monoxide BO, atomic boron, atomic nitrogen, molecular nitrogen, and nitric oxide NO. In the absence of reliable thermodynamic data for the reactions of boron with nitrogen, these possible reaction products were not included in the calculations.

The combustor gas-composition data are presented in figure 4 and the combustor temperature data, in figure 5. The thermodynamic data of reference 3 were used. Similarly, the exit-gas composition and temperature following isentropic-equilibrium expansion from combustion pressure (2 atmospheres) to exit pressure (1 atmosphere) were calculated. These exit-gas compositions are presented in figure 6 and the exit gas temperatures are presented in figure 5. Figure 7 presents the gross enthalpy change from combustor conditions to exit conditions as a function of the stoichiometric fraction of diborane used.

The ideal specific thrust derivable from the enthalpy change from combustor to exit conditions upon complete expansion was calculated from the equation given in reference 4.

$$I_{Rocket} = 9.328\sqrt{\left(\frac{\sum n_i H^o{}_T}{\sum n_i M_i}\right)_{c,2} - \left(\frac{\sum n_i H^o{}_T}{\sum n_i M_i}\right)_e}$$

where

I_{Rocket}	ideal rocket specific thrust, lb-sec/lb mixture
n_i	number of moles of constituent i
$H^o{}_T$	molar enthalpy, calories/gram mole
M_i	molecular weight of constituent i
$\sum$	summation
$(\ )_{c,2}$	combustor-exit conditions
$(\ )_e$	exit conditions determined by free-stream pressure

The conversion from rocket to ram-jet specific thrust is made as follows:

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$$I_{Ram\ jet} = I_{Rocket}\ (0.066916\ F + 1) - I^{o}$$

where

$I_{Ram\ jet}$ ideal ram-jet specific thrust, lb-sec/lb air

F stoichiometric fraction of diborane used

I^{o} flight velocity divided by acceleration of gravity

The ram-jet thrust given by this equation is the thrust measured by a thrust target; that is, the change in momentum due to mass times flow velocity only. (The internal thrust actually obtainable from a ram jet is derived from changes in total momentum, or mass flow times flow velocity plus pressure times area.)

The experimental combustor inlet-air design conditions were 2 atmospheres pressure and 560° R; these conditions would result from isentropic compression from 1 atmosphere and 459.7° R for a flight speed of 1101.1 feet per second. The ram-jet ideal internal air specific thrust presented in figure 8 represents the maximum net internal air specific thrust for the diborane-air system under the conditions of operation.

The ideal air specific thrust for a representative hydrocarbon fuel (octene-1) was calculated from the data of reference 5. The results are presented in figure 9. Figures 8 and 9 establish two comparative references for the evaluation of the experimental thrust measurements with diborane.

Experimental Results

Thrust and efficiency. - Figure 10 presents the experimentally determined net internal air specific thrust for diborane. The values were obtained by direct measurement of the total thrust with a thrust target and were corrected for the inlet-air thrust. The method of analyzing experimental data is given in table I.

Figure 11 presents a comparison of the theoretical specific thrust values for diborane and octene-1 with experimental specific thrust values for diborane. Experimental specific thrust values for diborane are approximately 80 percent of the theoretical values over the range investigated. Experimental specific thrusts for diborane are equal to, or less than, the theoretical values for octene-1 up to a stoichiometric fraction of about 1.3, and from this point on, they are greater than those for octene-1.

Stability. - Operation of the experimental ram-jet combustor with diborane was smooth and stable over a range of fuel-air ratios from 0.0015 to 0.10 and at combustor inlet-air velocities up to 500 feet per second even in the absence of a flameholder. Operation would probably have been satisfactory even at higher combustor inlet-air velocities; however, this velocity was the highest attainable in this investigation. Stable combustion of hydrocarbon fuels was not attained in a combustor employing the identical configuration as that used for diborane.

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No blow-out limits for diborane could be determined during operation at 2 atmospheres burner pressure. Available facilities did not permit operation at burner pressures less than atmospheric. Figure 12 shows the approximate range of inlet-air velocities and fuel-air ratios investigated for the two exhaust nozzles.

The stability of operation with diborane over such wide fuel-air ratios is probably related to the wide inflammability limits and to the high spatial flame speeds of diborane-air mixtures. The diborane-air inflammability limits have been stated earlier in this report. The velocity of flame propagation for a range of fuel-air ratios was determined in a series of experiments described in appendix A. The results of these experiments are indicated in figure 13. The measured value of the spatial flame speed for a 0.0634 fuel-air ratio diborane-air mixture was 169.5 feet per second. For normal hexane the maximum observed value for the spatial flame speed in the same type of apparatus was 3.22 feet per second. Premature ignition of the diborane-air mixtures by extraneous sources prevented extension of the spatial-flame-speed data to higher fuel-air ratios in this apparatus. For the range of mixture ratios covered, the data on flame speeds reported here are in reasonable agreement with the data reported in reference 6.

Deposits. - Little, or no, difficulty was caused by the formation of solid products on the nozzle and burner walls when diborane was used. The maximum duration of any run was 7 minutes. A thin deposit (approximately 1/8-in. thick) formed on the burner and nozzle walls, but this deposit did not interfere with the burner operation. The nozzle with a deposit of solid-combustion products is shown in figure 14.

Flight Range

As previously stated, the density and heat-release properties of diborane considerably differ from those of aviation gasoline. The effects of these differences in fuel properties on aircraft range were calculated. Detailed assumptions necessary for the analysis are given in appendix B.

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Figure 15 presents the aircraft ultimate range as a function of combustor-outlet total temperature for various ratios of fuel-system weight to fuel weight. The combustor-outlet temperatures investigated ranged from 1350° R to choking conditions at the combustor outlet.

All range calculations were made for an altitude of 20,000 feet, flight Mach number of 1.665, and ambient temperature of 362° R. These are not standard conditions, nor do they represent an attempt to describe the most logical flight conditions for either fuel. The conditions were chosen because, together with the assumed diffuser performance, they result in combustion inlet conditions identical to those for which the diborane thermodynamic data were available. Of course no rigid conclusions can be drawn as to the absolute aircraft range possible with either fuel by an examination of one arbitrary flight condition, but the comparison between the two fuels at the one flight condition is probably valid over a range of flight conditions. The range analysis was conducted with this limited objective in mind and is intended to afford an insight into the relative advantages of the two fuels by comparing them at a single flight condition.

Gaseous diborane. - The data in figure 15(a) are based on the assumption that the diborane is carried as a compressed gas. The specific gravity of diborane assumed for this figure is 0.170, which is approximately the specific gravity at the critical temperature. The range with a conventional aviation gasoline is shown by a dashed curve.

It is apparent from figure 15(a) that if diborane is carried as a gas, it could show little or no range advantage over the aviation gasoline. In the region of low combustor-outlet temperatures (below 2000° R), the diborane compares more favorably with the hydrocarbon fuel than in the high-temperature region because a shorter combustion chamber was assumed for the diborane owing to its high flame speed. The shorter combustor results in lower nacelle drag, which is very important in the low-temperature region because nacelle drag represents such a large percentage of the total engine thrust output. In the high-temperature region, nacelle drag is not so important. In addition, the effective heating value of diborane decreases rapidly between 2000° and 3200° R owing to the gradual disappearance of the nongaseous phase B_2O_3 in the combustor-outlet equilibrium products.

Inasmuch as it was not considered practical to make rigid estimates of the fuel-system weight that might be necessary for diborane, three weight ratios are shown in figure 15(a). The hydrocarbon curve is presented for the single weight ratio of 0.1, which is a normal value for the conventional fuel. Because the vapor pressure of diborane at

ambient temperature is in the range of 600 to 700 pounds per square inch, it is reasonable to expect diborane fuel-system weight ratios far greater than 0.1. The aircraft range predicted for diborane under these conditions would be greatly inferior to that predicted for the hydrocarbon fuel (fig. 15(a)). 2008

Liquid diborane. - A range comparison between diborane, carried as a liquid, and the conventional fuel is presented in figure 15(b). The dashed hydrocarbon curve in figure 15(a) is repeated in figure 15(b) to facilitate comparison. Diborane specific gravity was taken as 0.447, which is approximately the specific gravity at the sea-level boiling temperature. Low-temperature operation is again more favorable for diborane than operation in the high-temperature region for the reasons previously discussed in figure 15(a).

Because the sea-level boiling temperature of diborane is -134.5° F, it is logical to assume fuel-system weight ratios greater than 0.1 if refrigeration during flight were assumed necessary. Figure 15(b) indicates that even if the weight ratio reached 0.3, diborane would still exhibit a range advantage over the hydrocarbon fuel. For missile applications it might be practical to maintain the diborane as a liquid during the flight by allowing it to evaporate as it is used and utilizing the latent heat of evaporation to cool the remaining liquid. This method would involve a loss of diborane due to evaporation and possibly some additional weight and bulk required for tank insulation. Under these conditions, fuel-system weight ratios between 0.1 and 0.2 might possibly be realized with a range 30 to 50 percent greater than that provided by a conventional fuel if the evaporation loss of diborane is small.

SUMMARY OF RESULTS

From a preliminary experimental and analytical evaluation of diborane as a ram-jet fuel, the following results were obtained:

1. In a 2-inch experimental ram-jet combustor, diborane gave measured air specific thrusts 80 percent of the theoretical values.

2. Smooth stable operation was maintained over a wide range of fuel-air ratios (0.0015 to 0.10) even in the absence of a flameholder. Stable combustion of hydrocarbon fuels was not attained in a combustor employing the identical configuration as that used for diborane. No blow-out limits for diborane were located for operation at 2-atmosphere combustor pressure.

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3. Spatial flame speeds for diborane-air mixtures as great as 169.5 feet per second were observed under conditions where normal hexane gave a spatial flame speed of 3.22 feet per second, or less.

4. The maximum adiabatic combustion temperature for air and liquid diborane mixtures is 4898° R for an inlet-air temperature of 560° R and a combustor pressure of 2 atmospheres.

5. Range calculations for an altitude of 20,000 feet and flight Mach number of 1.665 indicate that liquid diborane is capable of maximum ranges as much as 30 to 50 percent greater than aviation gasoline, depending upon the weight of equipment necessary to maintain diborane as a liquid. If diborane is carried as a gas, it is inferior to aviation gasoline from the available range viewpoint.

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APPENDIX A

MEASUREMENT OF SPATIAL FLAME SPEED OF DIBORANE

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The rate of flame propagation in diborane-air mixtures was determined in a pyrex tube approximately 8 feet long and 1 inch in diameter. A diagrammatic sketch of the apparatus is shown in figure 16. Measurements were made over a 6-inch length of the tube 8 inches from the open end. One end of the tube was equipped with a ground-glass joint that could be removed to open the tube to the atmosphere just prior to ignition. Ignition was accomplished by a spark gap actuated by the secondary circuit from a transformer whose primary current was supplied by a 110-volt a.c. line.

Fuel vapor was admitted from the closed end of the tube and the fuel vapor pressure was measured on a manometer. This measurement was used, in conjunction with the total pressure, to calculate the fuel-air ratio. Air was introduced from each end of the tube to facilitate mixing. Sufficient air was added to bring the total pressure inside the tube to atmospheric pressure. A mechanical stirrer was propelled back and forth inside the tube by an externally controlled magnetic field in order to insure a homogeneous mixture along the tube length. This arrangement was employed to minimize the handling of an explosive mixture that is sensitive to extraneous ignition sources. Even with these precautions some mixtures exploded prematurely, probably induced by weak electric discharges within the tube caused by friction of the stirrer on the glass walls. These premature explosions increased in frequency with increasing fuel-air ratio and placed a limit on the maximum fuel-air ratio for which flame speeds could be determined in this apparatus.

The first photocell served as the starter for the pulse input from an audio-oscillator into a four-decade electronic counter. The second photocell acted as the cut-off for the pulse input to the electronic counter. The average rate of flame propagation over the 6-inch length was determined from the indicated pulse count on the electronic timer and the frequency setting of the audio-oscillator. The electronic timer and photocell circuit were calibrated and were capable of an accuracy of about ±3 percent for a time interval of 0.006 second, the shortest time interval measured in this flame-speed investigation.

APPENDIX B

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SUMMARY OF AIRCRAFT-RANGE ANALYSIS

An analysis was made of the potential range of a supersonic ram jet operated with diborane and with aviation gasoline. Flight conditions for the comparison were chosen as pressure altitude of 20,000 feet, flight Mach number of 1.665, and ambient temperature of 362° R. This combination of flight conditions, together with the assumption of a diffuser total-pressure ratio of 0.95 and a combustor-inlet Mach number of 0.18, results in combustor-inlet conditions of 2 atmospheres static pressure and 560° R static temperature. These are the conditions for which diborane combustion data have been calculated. A convergent exhaust nozzle was assumed in all cases because diborane isentropic-expansion data were available for only a 2:1 pressure ratio. Inasmuch as the purpose of the analysis was mainly to provide a comparison, the aviation gasoline fuel was also calculated only for a convergent nozzle. Other assumptions for each fuel were identical wherever possible.

Inasmuch as diborane might require refrigeration or pressurization or both at ambient sea-level and altitude conditions, allowance was made for the weight and bulk of the equipment necessary to accomplish this requirement. It was assumed that the density of this equipment was 40 pounds per cubic foot. It is convenient to include the weight of this equipment in the fuel-system weight by increasing the ratio of fuel-system weight to fuel weight. In this way, the weight and bulk of the pressurization and refrigeration equipment are made directly proportional to fuel load. Inasmuch as an estimate of the amount of this equipment necessary for any practical installation would be of questionable accuracy, the weight of this equipment was included in the diborane analysis as a variable, and the entire diborane calculations were repeated for three different ratios of the fuel-system weight to fuel weight. Fuel-system weight includes all equipment, such as tanks, pumps, and plumbing, that is necessary to store the fuel during flight and deliver it to the engines as required.

The calculations were made over a range of combustor-outlet total temperatures for both fuels in order to observe the effect of this variable on the results.

The calculations were performed twice: (1) diborane was assumed to be carried as a gas with the specific gravity of 0.170, (2) the diborane was assumed to be carried as a liquid with the specific gravity of 0.447. Specific gravity of the hydrocarbon fuel was taken as 0.720 in all cases.

Only the cruising part of the flight was analyzed. The manner in which the aircraft reached the cruising altitude and Mach number, whether by rocket boost or other means, was not considered. Inasmuch as all calculations were performed for only one aircraft gross weight, cruise altitude, and Mach number, similar boosting procedure could be used in all cases and, therefore, the boosting required would not influence the final comparison between the two fuels. 2008

Cruising range was calculated by means of the Breguet range equation, which assumes that aircraft lift-drag ratio, engine specific fuel consumption (lb/(hr)(lb thrust)) and flight velocity remain constant during cruise. In practice this can be very nearly realized by maintaining constant velocity and constant angle of attack and allowing the aircraft to gain altitude as its gross weight decreases owing to the consumption of fuel during the flight. If ambient temperature remains constant with this increasing altitude, Mach number will not change and, except for combustion and Reynolds number effects, the engine specific fuel consumption will remain constant.

Detailed engine and airplane assumptions are as follows:

Engine

Cycle. - Diffuser total-pressure ratio was taken as 0.95 and combustion chamber inlet Mach number was assumed to be 0.18. Aviation-gasoline combustion data were taken from reference 7, and the properties of the products of combustion were obtained from reference 8. Hydrogen-carbon ratio was taken as 0.168. Combustion and exit temperature, and enthalpy-change data for diborane were taken from figures 5 and 7, respectively. Combustor pressure losses were estimated by using reference 9. The factor KA^2 of reference 9 was taken as 0.020 for the aviation-gasoline combustor and as 0.005 for the diborane combustor. Combustion efficiency was assumed to be 100 percent for each fuel. Exhaust-nozzle polytropic efficiency was taken as 0.95.

Nacelle drag. - Nacelle drag was calculated by assuming a definite engine configuration for each fuel as follows:

Length-diameter ratios based on combustor diameter:

Aviation-gasoline engine 11

Diffuser 4
Combustor 4
Nozzle 3

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Diborane engine . . . . . $9\frac{2}{3}$

Diffuser 4
Combustor . . . . . $2\frac{2}{3}$
Nozzle 3

It was assumed that each engine consisted of a conical cowl section, a cylindrical combustor, and a conical boat-tail (converging) nozzle section. It was assumed that the boat-tail pressure drag was equal to the pressure drag that would be experienced by a cowl of identical shape. Cowl pressure drags were obtained from reference 10. The skin-friction drag coefficient, based on wetted area, was taken as 0.0025. It was assumed that the engine inlet, operating at its design point, just swallowed the free stream; that is, no additive drag was incurred.

Weight. - Engine weights were calculated in a manner similar to that described in reference 11. The pressure difference across the combustor shell is 22.6 pounds per square inch, which results in a thickness diameter of 0.00189 for an allowable hoop stress of 6000 pounds per square inch. Minimum stiffness requirements were assumed to demand a thickness-diameter ratio of 0.002. The engine weight was therefore calculated on this basis. The weight estimates assumed an engine combustor area of 5 square feet. Weight was calculated by assuming uniform skin thickness over the entire engine. The diffuser section was assumed to be aluminum and the remaining part of the engine steel.

Airplane

Airplane gross weight was taken as 50,000 pounds. The gross weight was assumed to be composed of aircraft structural weight, engine weight, and fuel and fuel-system weights; zero payload was assumed. The structural weight was taken as 30 percent of the gross weight, as in reference 12.

Wing. - Wing data were taken from reference 12. These data assumed a rectangular wing with an aspect ratio of 5, and a double-wedge section of 5-percent thickness ratio. The wing was assumed to fly at the angle of attack for maximum lift-drag ratio. At an altitude of 20,000 feet and flight Mach number of 1.665, the wing maximum lift-drag ratio is 6.6; wing loading is 401 pounds per square foot, and optimum lift coefficient for maximum lift-drag ratio is 0.213. The wing skin-friction drag coefficient based on wetted area was 0.0025. Tail drag was 30 percent of the wing zero-lift drag.

Fuselage. - Fuselage-wave drag coefficient was calculated using data in reference 12, which is based on a Class I body of reference 13. Skin-friction drag coefficient based on wetted area was taken as 0.0020 together with a fuselage-fineness ratio of 12. It was assumed that the fuselage was entirely filled with fuel, fuel system, and controls. Required control volume was taken from reference 11, which assumed 2 cubic feet per ton of aircraft gross weight.

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TABLE I - SUMMARY OF COMBUSTION DATA FOR LIQUID DIBORANE IN A 2-INCH RAM JET OPERATING AT INLET-AIR TOTAL TEMPERATURE OF 100° F

Run	Burner nozzle (in.)	Fuel nozzle (gal/hr)	Helium pressure (lb/sq in. gage)	Fuel flow (lb/sec)	Air flow (lb/sec)	Fuel-air ratio	Jet thrust F_j (lb)	Inlet-static pressure (lb/sq ft abs.)	Barometric pressure p_0 (lb/sq ft abs.)	Flight Mach number, M_0[a] (calculated)	Inlet thrust[b] F_i (lb)	Air specific thrust[c] (net thrust/lb air/sec)	Inlet total pressure P_2 (lb/sq ft abs.)
1	1.25	10.5	120	0.0029	0.4078	0.00714	23.03	4685	2072	1.142	15.20	19.21	4666
			120	.0029	.3143	.00926	18.76	4242		1.088	11.03	18.23	4242
			160	.0054	.3406	.01597	23.85	4242		1.079	12.07	34.58	4313
			180	.0054	.3406	.01597	23.85	4385		1.093	12.20	34.20	4383
			185	.0069	.3251	.0212	22.41	4242		1.088	11.41	33.84	4242
			210	.0122	.2912	.04172	25.60	4383		1.093	10.08	53.29	4383
2	1.25	12.0	215	0.0212	0.2490	0.0848	25.2	4280	2061	1.09	8.82	65.8	4380
			245	.0221	.2200	.100	24.5	4240		1.07	7.84	76.8	4240
			300	.0248	.2180	.1138	24.6	4240		1.07	7.50	79.2	4240
3	1.25	12.0	180	0.0143	0.2810	0.0511	25.4	4350	2065	1.098	10.12	54.4	4380
			215	.0172	.2420	.0710	23.5	4310		1.081	8.80	57.3	4310
			215	.0176	.2420	.0728	23.8	4240		1.089	8.50	63.2	4240
4	1.875	12.0	210	0.0111	0.7245	0.0153	45.12	4383	2065	1.122	26.18	23.37	4525
				.0176	.8570	.02104	66.7	5737		1.321	34.29	38.72	5881
5	1.875	10.5	110	0.0021	1.3230	0.00158	47.79	4134	2048	1.153	48.85	-0.800	4710
			120	.0021	1.313	.00160	46.78	4206		1.155	48.89	-1.82	4782
			150	.0031	1.318	.0024	51.87	4422		1.205	50.35	1.15	5034
			170	.0063	1.325	.00475	55.98	4710		1.242	51.75	3.20	5286
			210	.0073	.952	.0076	41.65	4171		1.122	34.41	7.82	4525
			210	.0065	1.265	.00515	55.19	4878		1.284	50.09	4.04	5444
			210	.0068	1.294	.0052	60.05	5450		1.300	52.40	5.91	5718
			210	.0084	1.294	.0065	65.75	5286		1.309	53.13	9.75	5790
6	1.25	10.5	70	0.0019	0.6310	0.0030	24.30	4207	2067	1.085	22.2	3.330	4327
			85	.0020	.6210	.0032	25.26	4287		1.098	22.04	5.19	4398
			125	.0046	.4138	.0112	25.37	4288		1.083	14.53	26.21	4313
			145	.0095	.3066	.0310	23.03	4313		1.090	10.83	39.79	4383
			165	.0143	.2516	.0569	22.92	4242		1.089	8.74	56.36	4242

[a]Calculated from equation $1 + \frac{(\gamma-1)M_0^2}{2} = \left(\frac{P_2}{p_0}\right)^{\frac{\gamma-1}{\gamma}}$

where

γ specific heat ratio, 1.4
M_0 flight Mach number
P_2 inlet total pressure, lb/sq ft abs.
p_0 barometric pressure, lb/sq ft abs.

[b]Calculated from equation $F_i = \frac{V_0 W_a}{g}$

where

V_0 flight velocity, ft/sec
W_a measured air flow, lb/sec
g standard acceleration of gravity, ft/sec^2

$$V_0 = c\,M_0 \qquad c = \sqrt{\gamma g R t_0}$$

$$t_0 = \frac{T_2}{1 + \frac{(\gamma-1)}{2} M_0^2}$$

where

c velocity of sound, ft/sec
R universal gas constant, ft-lb/(lb)(°R)
t_0 ambient temperature, °R
T_2 burner inlet total temperature, °R

[c]Air specific thrust $I_a = \frac{F_j - F_i}{W_a}$

where

F_j measured jet thrust, lb
F_i inlet thrust $V_0 W_a/g$, lb
$F_j - F_i$ net thrust, lb

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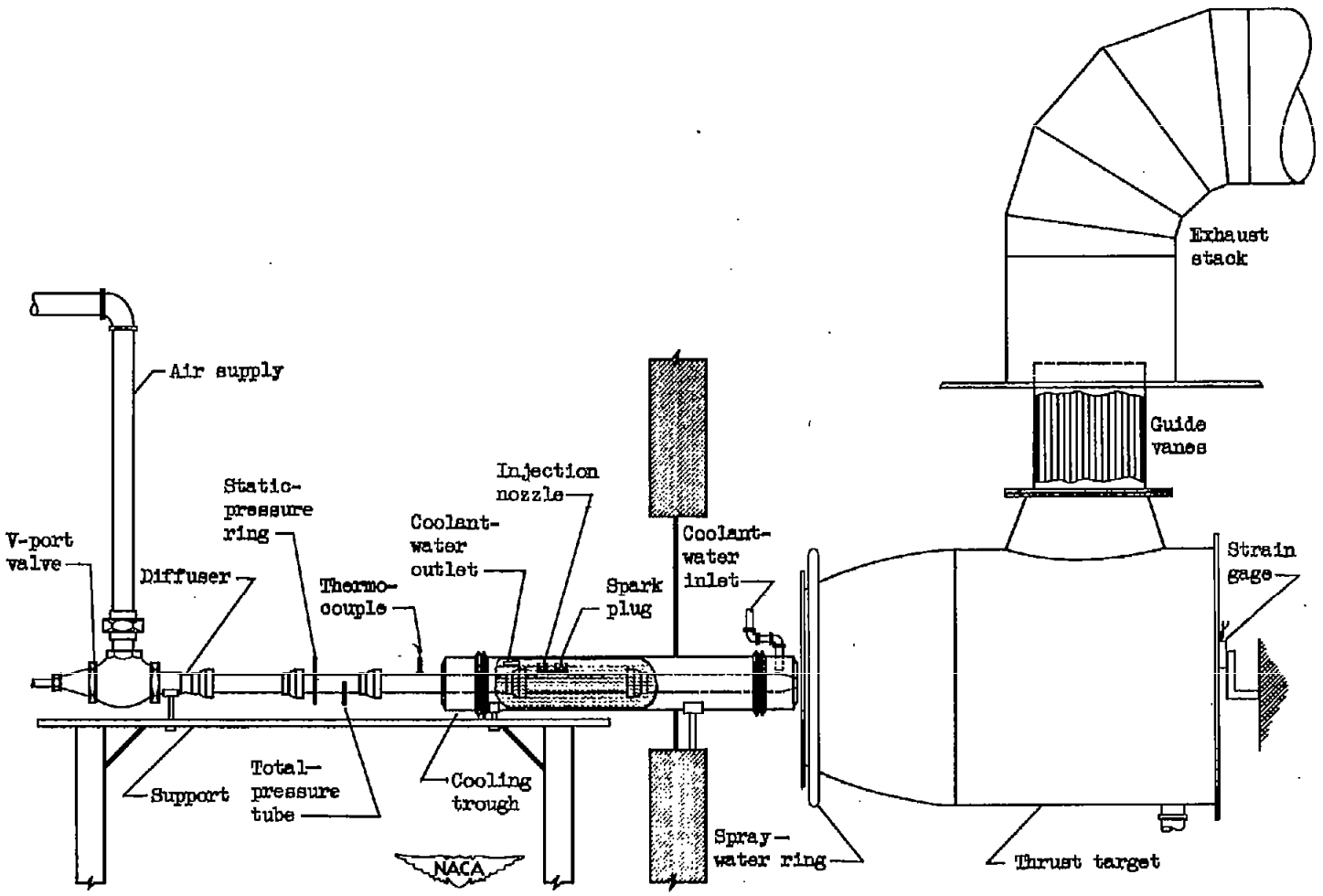

Figure 1. - Diagrammatic sketch of diborane-burner setup.

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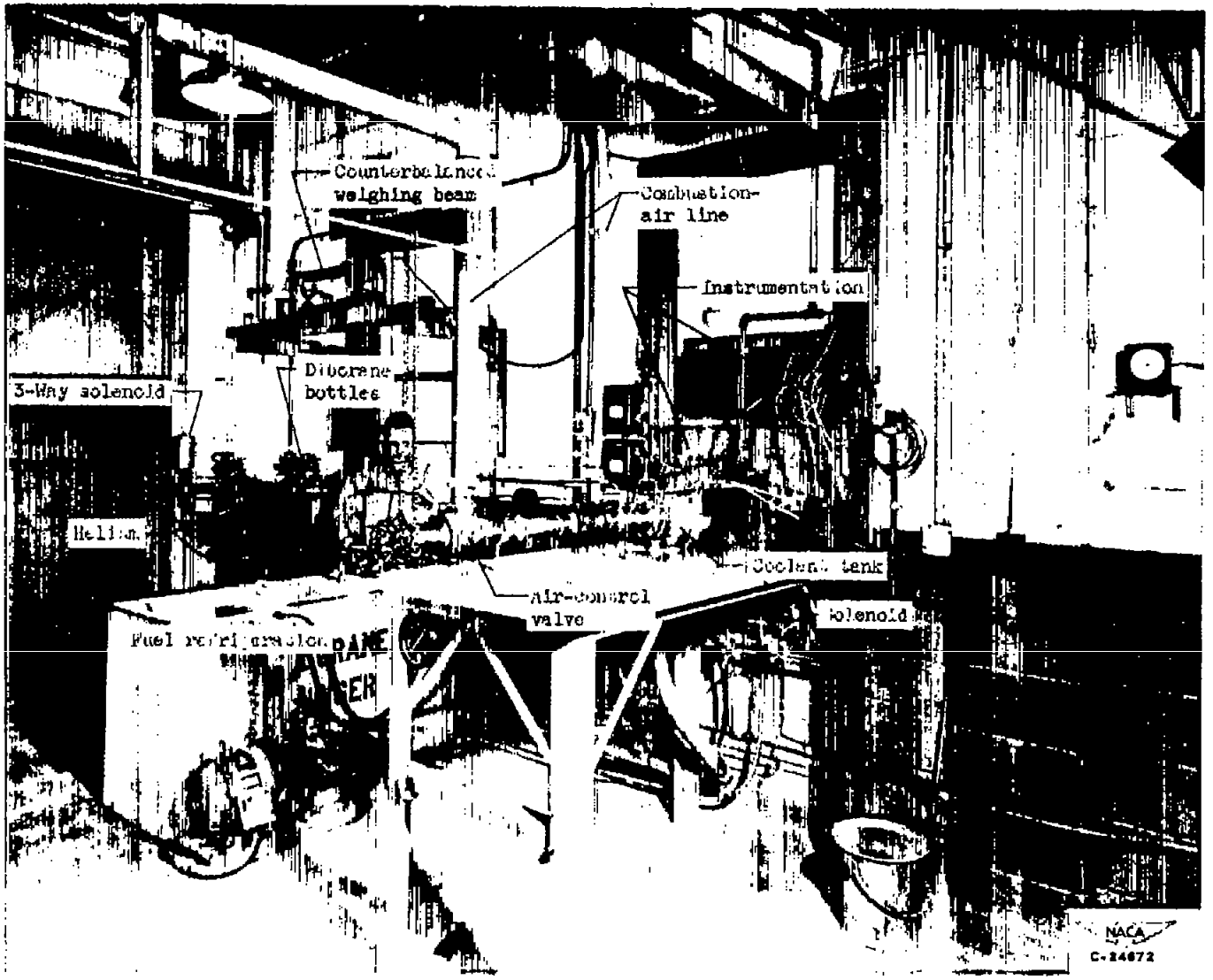

Figure 2. - Ram jet for diborane investigation.

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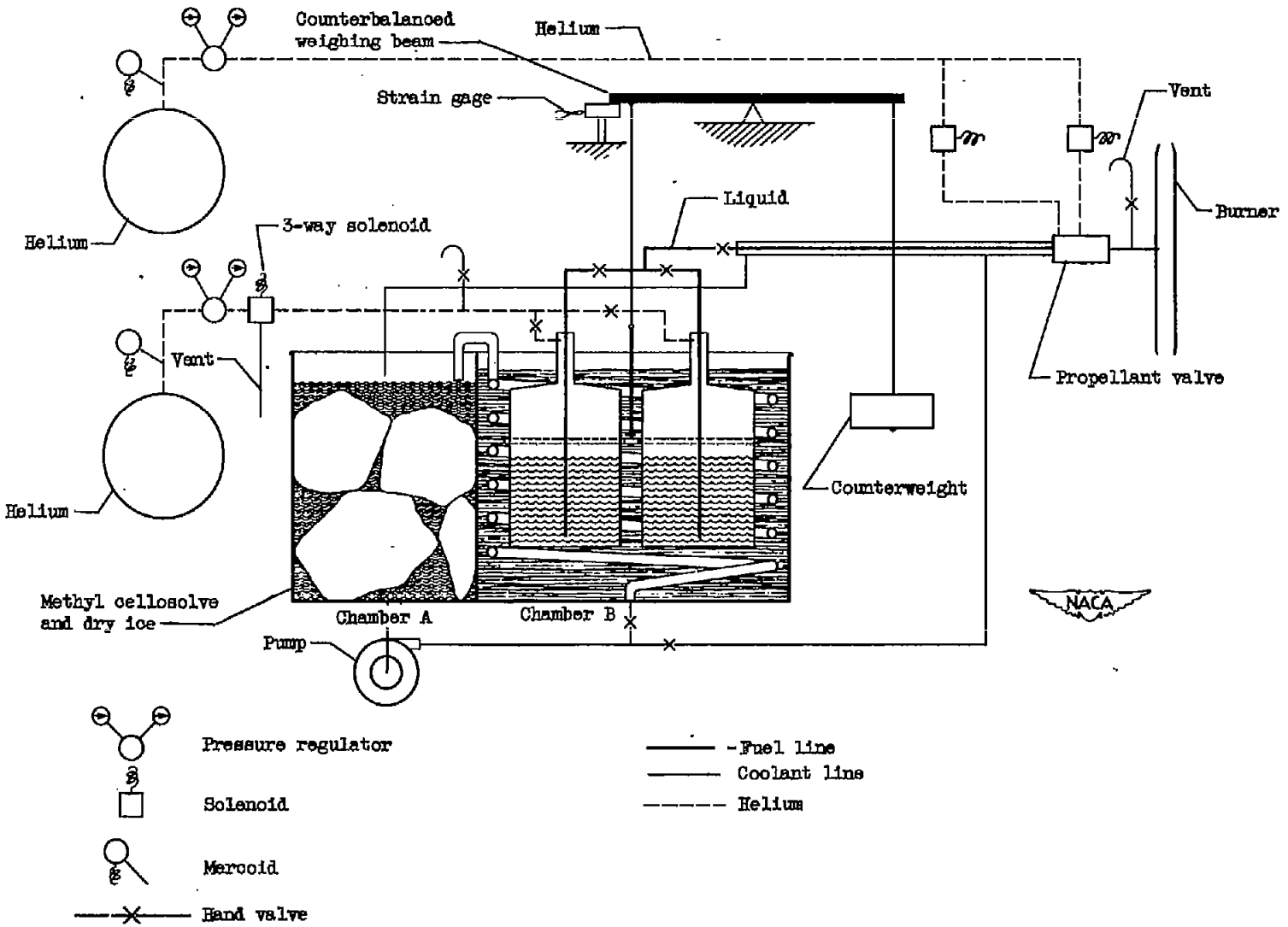

Figure 3. - Diagrammatic sketch of fuel system for liquid diborane.

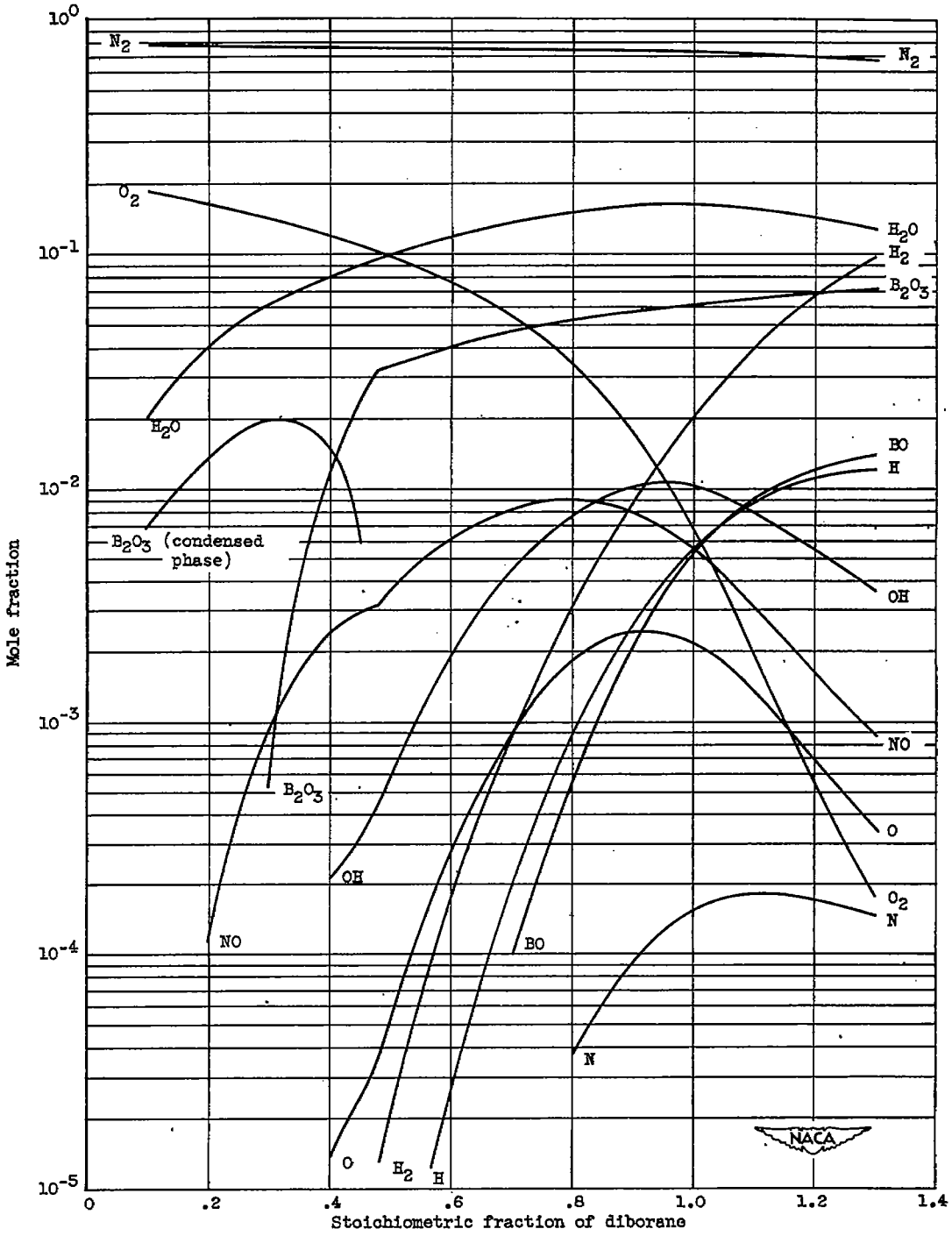

Figure 4. - Equilibrium composition of combustion-chamber products of reaction of diborane with three formula weights of dry air at inlet-air pressure of 2 atmospheres and combustor inlet-air temperature of 560° R.

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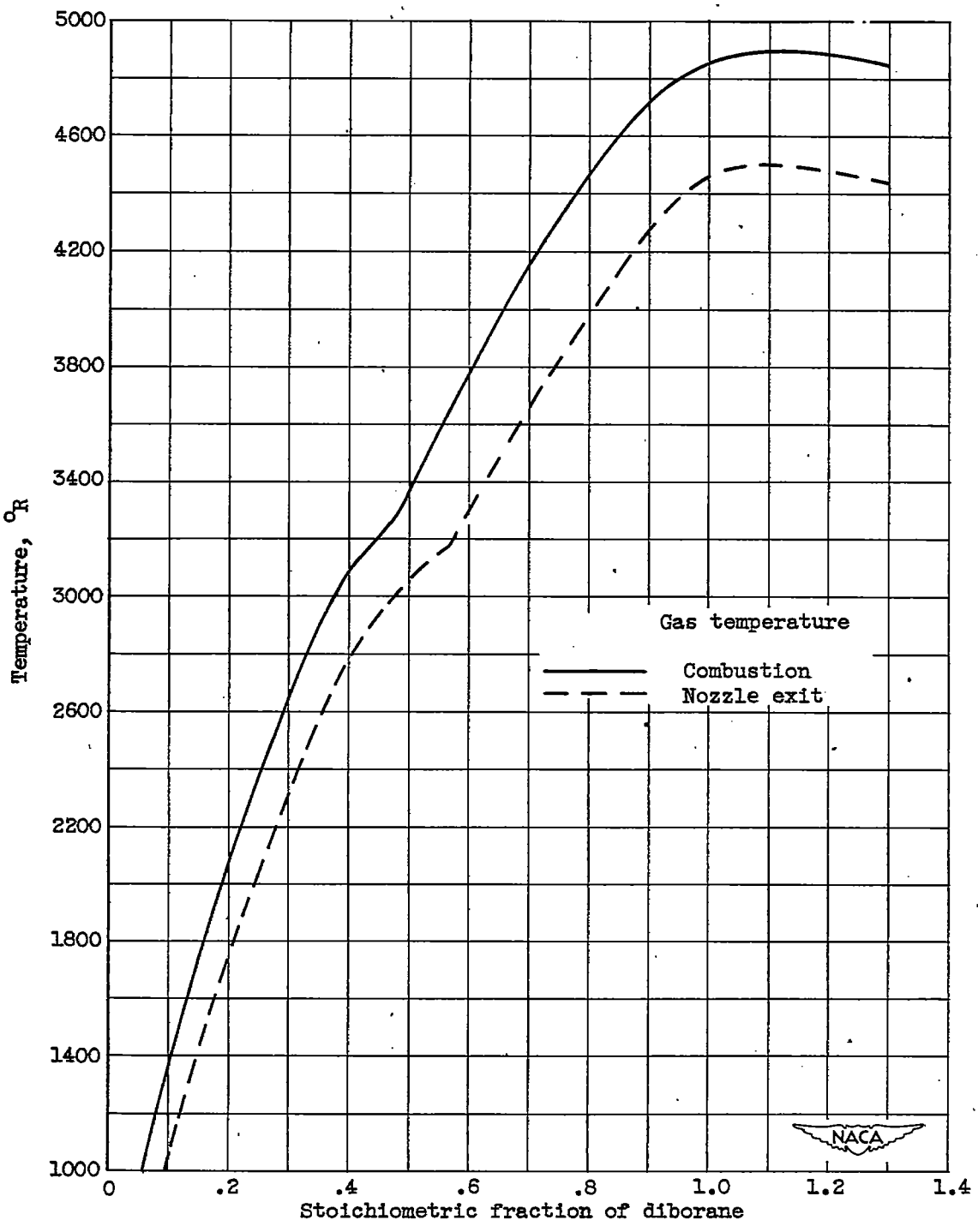

Figure 5. - Theoretical combustion-gas and nozzle-exit temperatures for diborane-air system. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; exit gas pressure, 1 atmosphere.

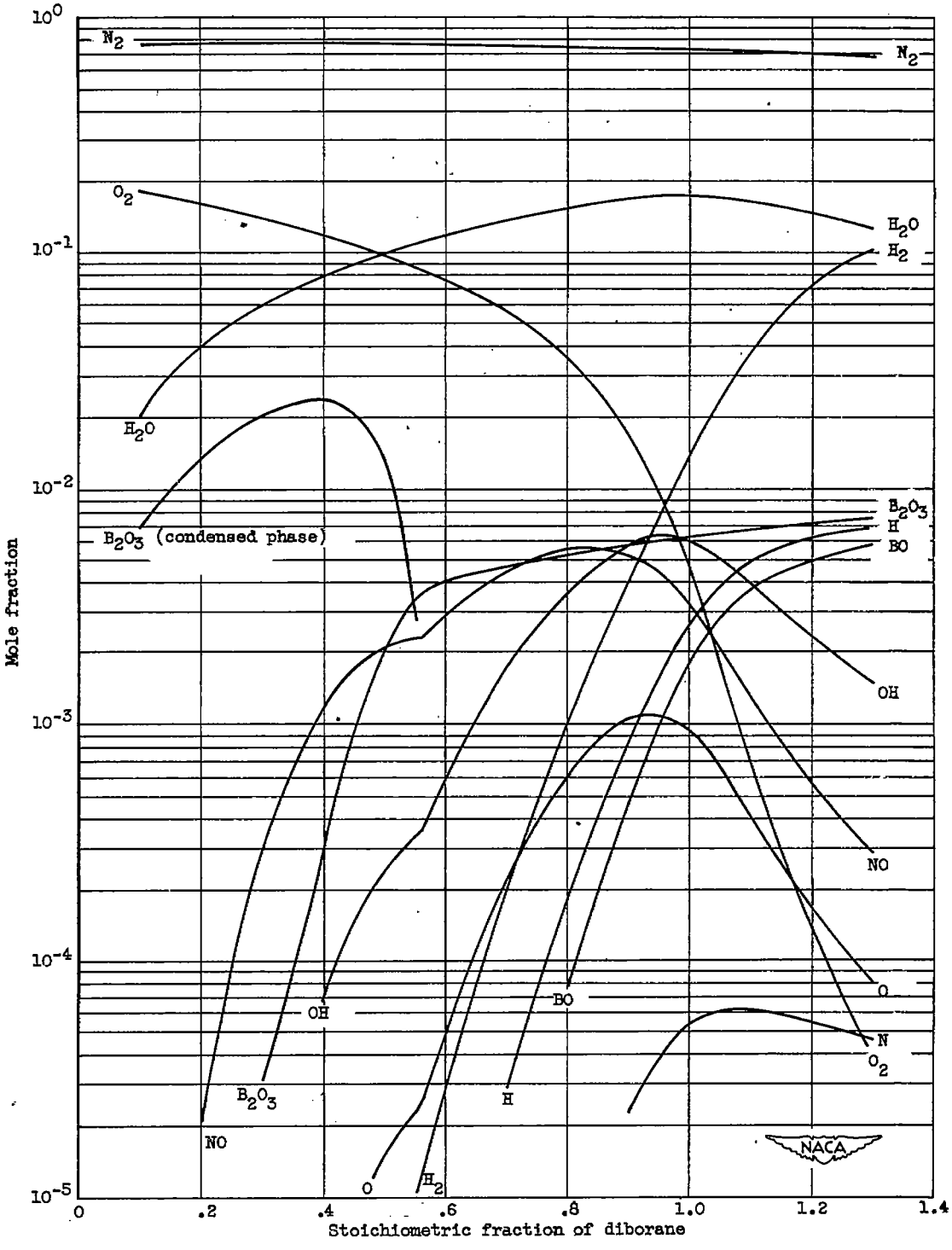

Figure 6. - Equilibrium composition of exit gas products of reaction of diborane with three formula weights of dry air following isentropic expansion from 2-atmosphere pressure in combustor to 1-atmosphere exit pressure. Combustor inlet-air temperature, 560° R.

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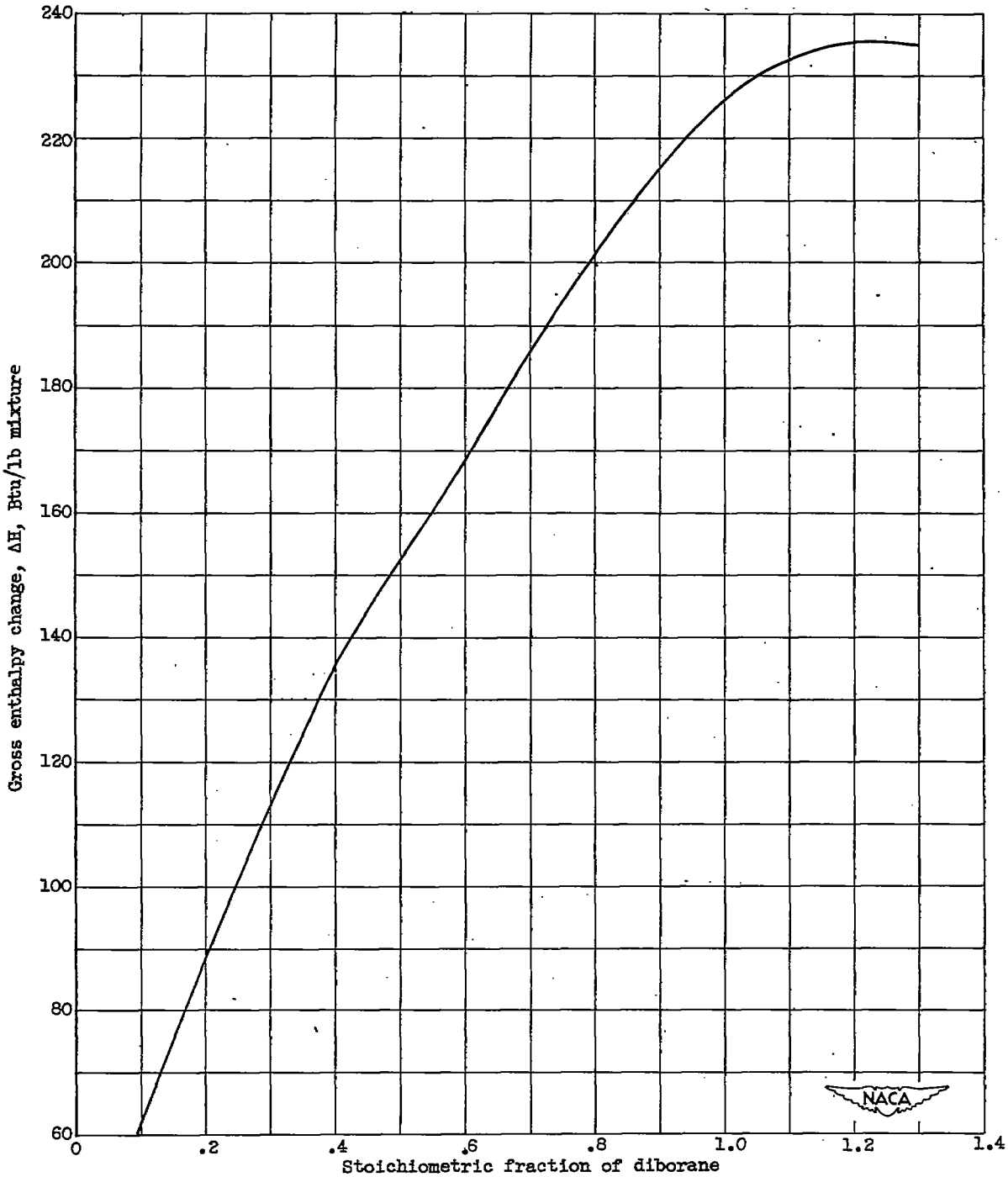

Figure 7. - Variation of gross enthalpy change per pound of mixture from combustor to exit condition with fraction of stoichiometric diborane.

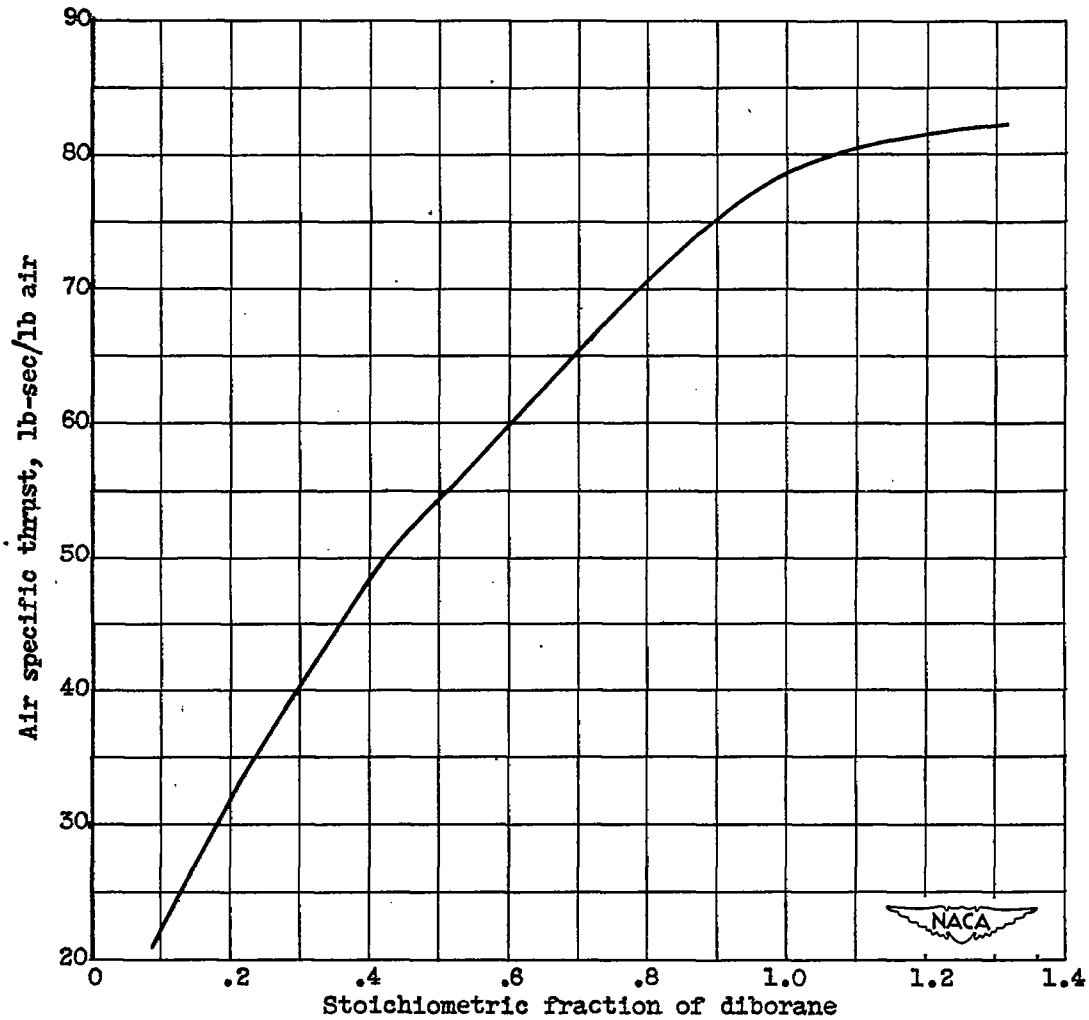

Figure 8. - Theoretical air specific thrust for ram jet using diborane. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; exit gas pressure, 1 atmosphere.

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Figure 9. - Theoretical air specific thrust for ram jet using octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; exit gas pressure, 1 atmosphere.

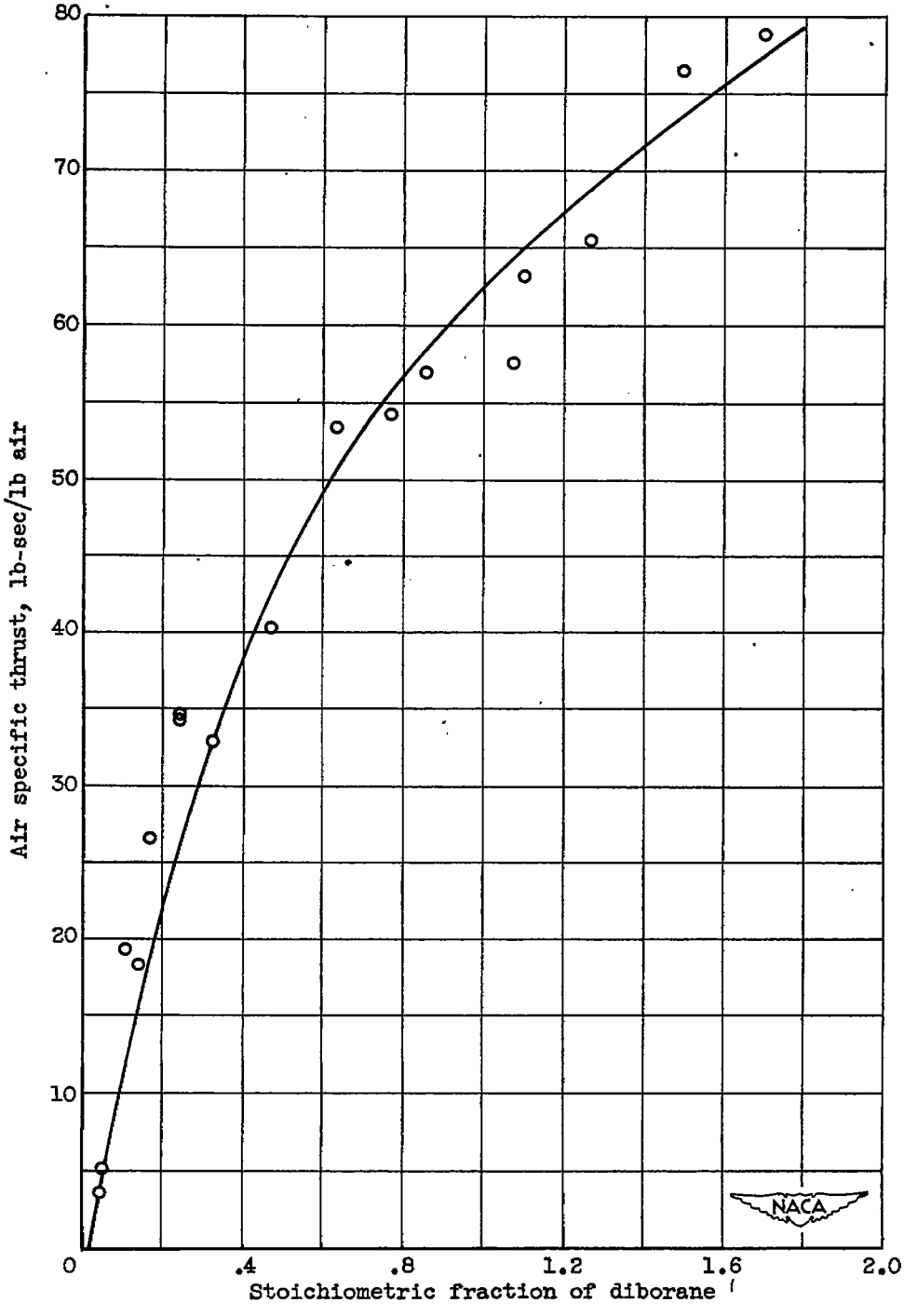

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Figure 10. - Experimental air specific thrust for 2-inch ram jet using diborane. Exhaust nozzle, 1.25 inches. Inlet-air pressure, 2 atmospheres; combustor inlet-air temperature, 560° R; exit gas pressure, 1 atmosphere.

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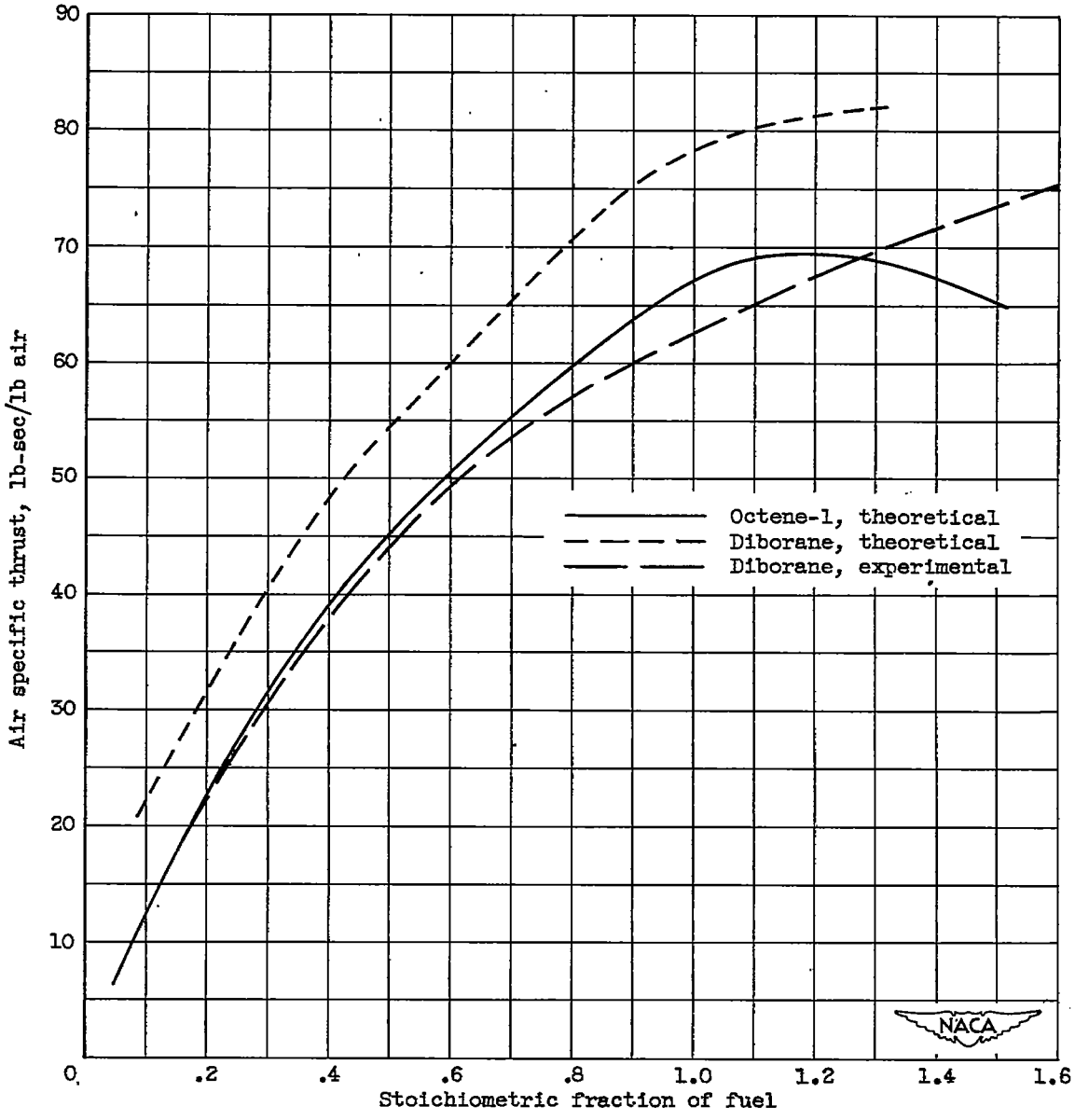

Figure 11. - Comparison of theoretical air specific thrusts for diborane and octene-1 with experimental air specific thrust for diborane. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; exit gas pressure, 1 atmosphere.

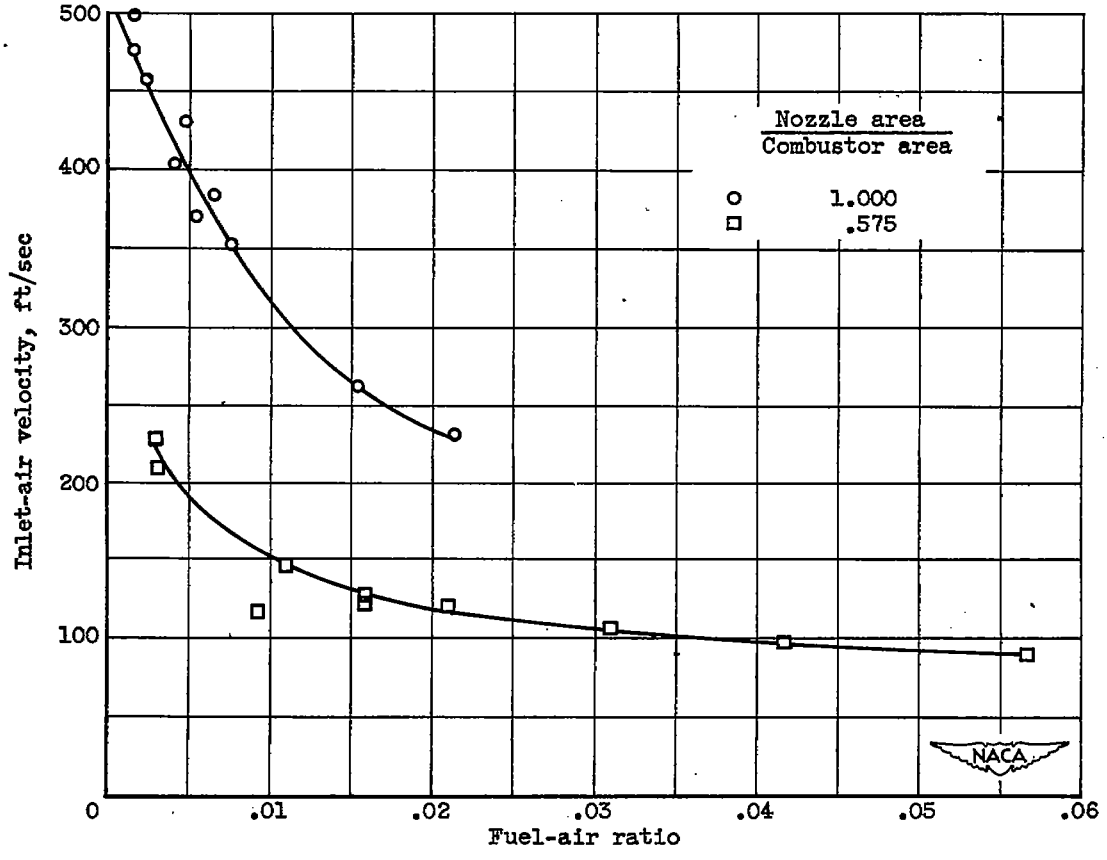

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Figure 12. - Range of combustor inlet-air velocities investigated in stability study at combustor inlet-air pressure of approximately 2 atmospheres. No blow-out limits were located.

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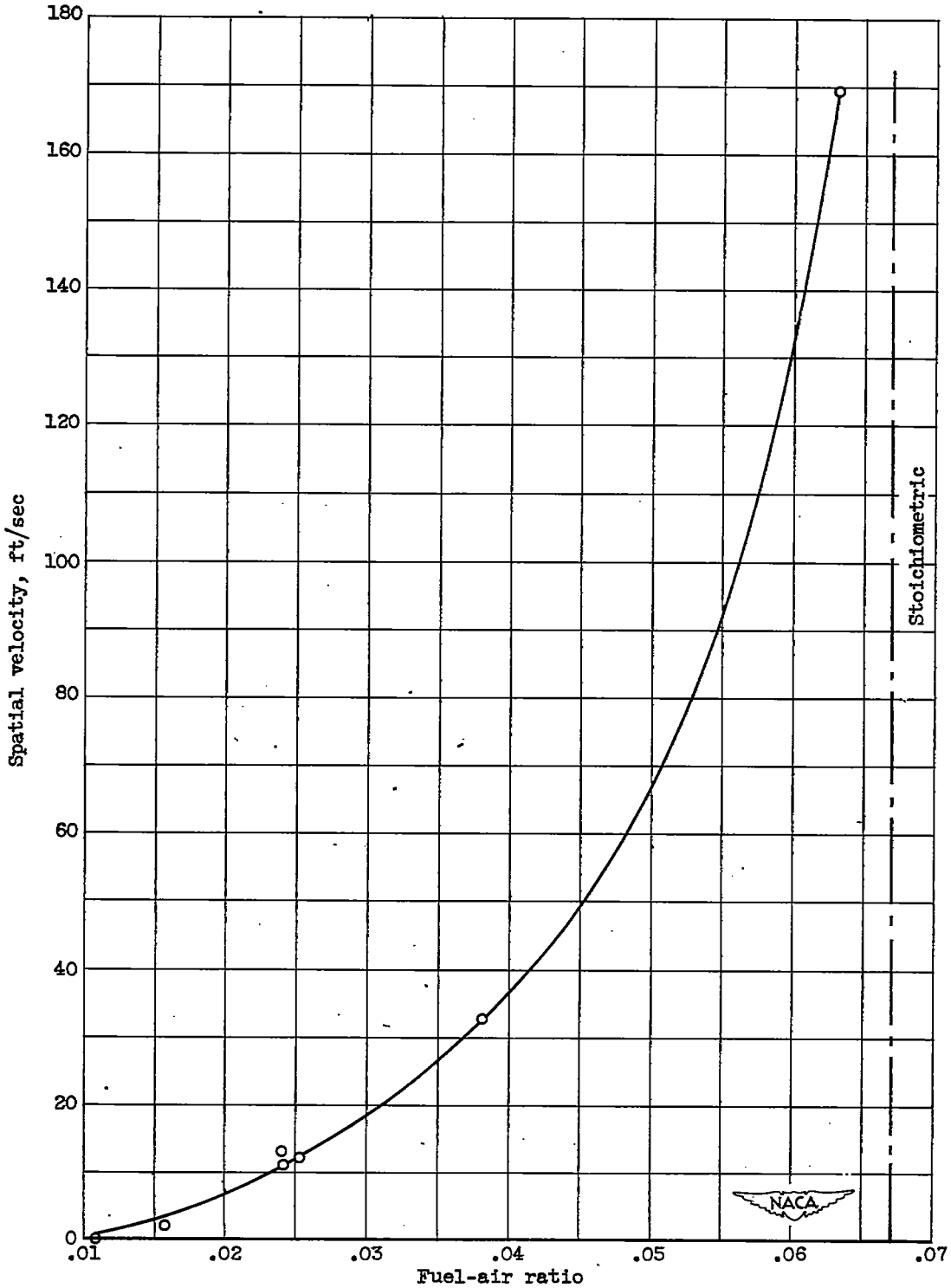

Figure 13. - Spatial flame speed of diborane in 1-inch-diameter glass tube.

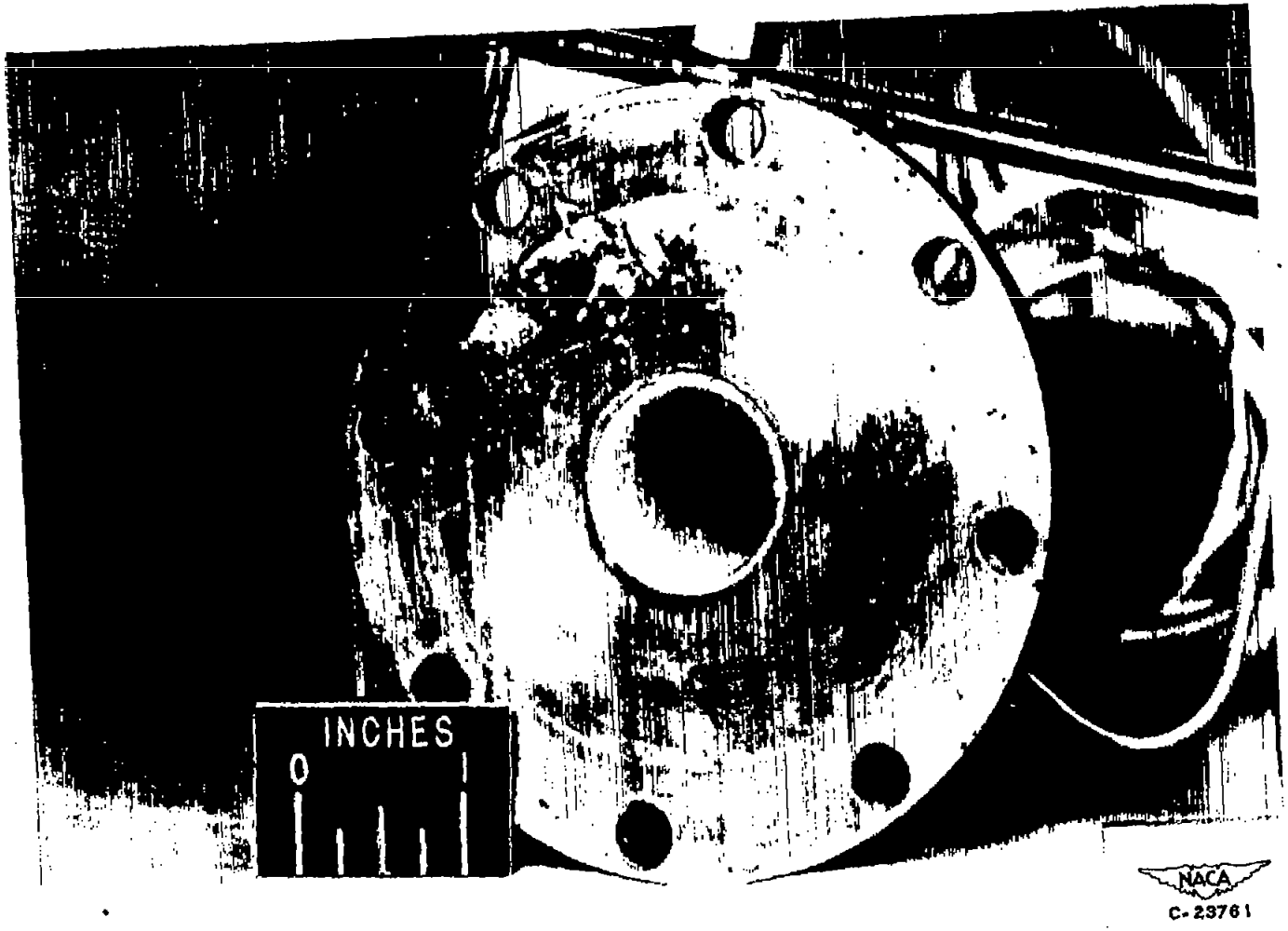

Figure 14. - Boron-oxide deposits in 1.25-inch exit nozzle after burning diborane for 7 minutes.

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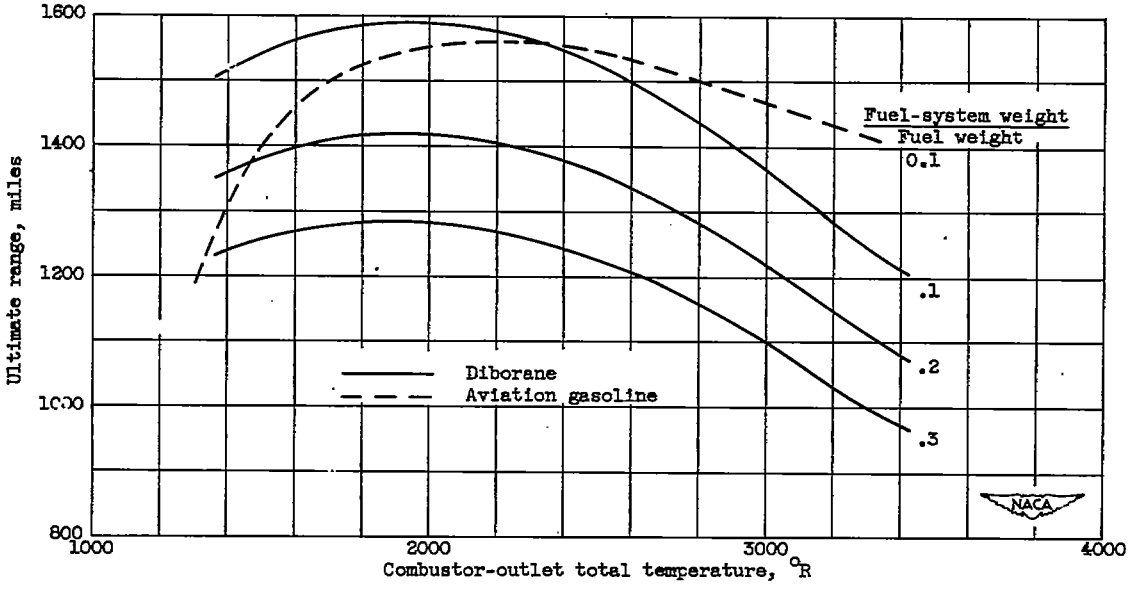
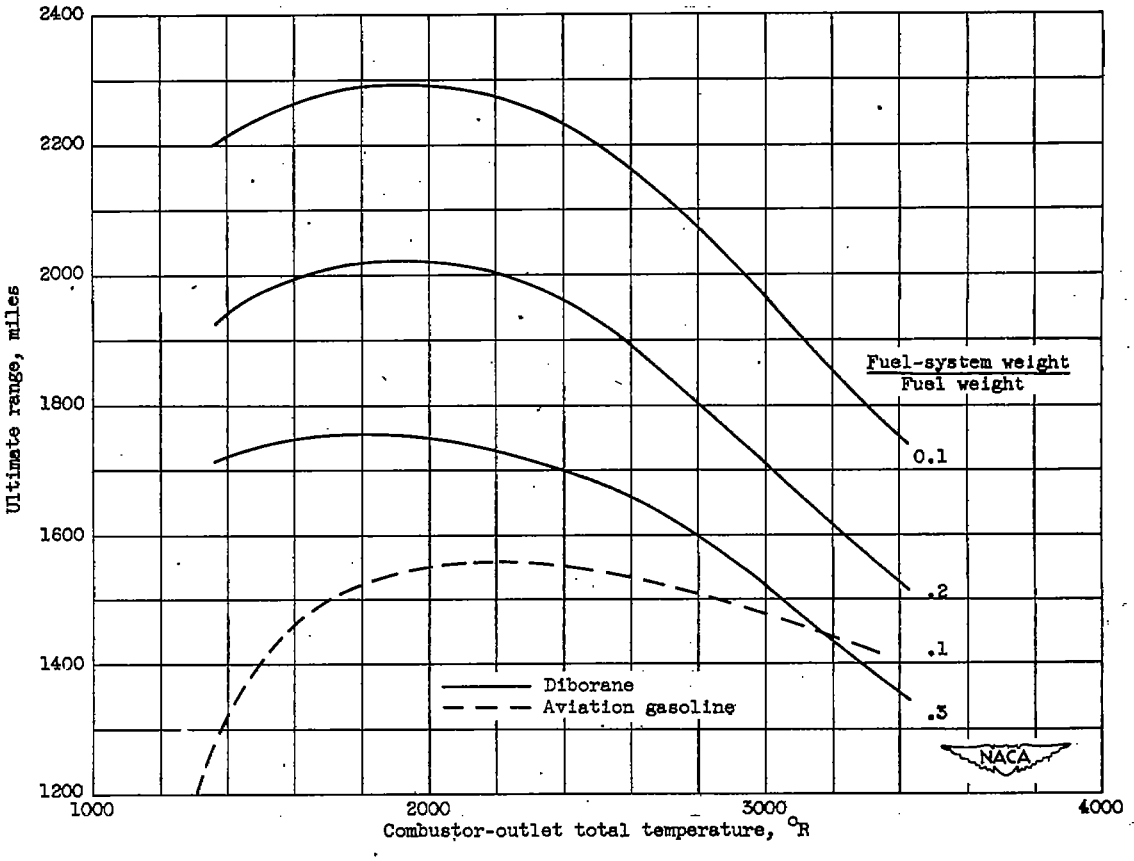


(a) Diborane specific gravity, 0.170.

Figure 15. - Comparison of aircraft ultimate range obtained with diborane and aviation gasoline. Pressure altitude, 20,000 feet; ambient temperature, 362° R; flight Mach number, 1.665.



(b) Diborane specific gravity, 0.447.

Figure 15. - Concluded. Comparison of aircraft ultimate range obtained with diborane and aviation gasoline. Pressure altitude, 20,000 feet; ambient temperature, 362° R; flight Mach number, 1.665.

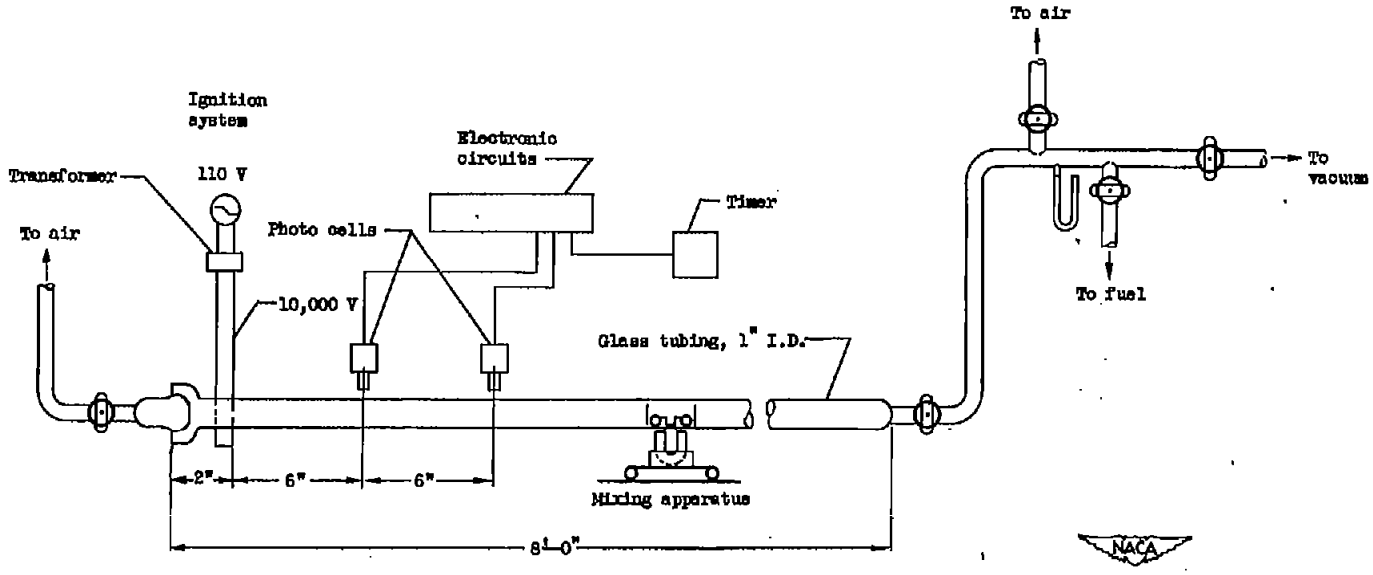


Figure 18. - Flame-speed measuring apparatus for diborane.

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