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RESEARCH MEMORANDUM

PRELIMINARY EVALUATION OF THE AIR AND FUEL SPECIFIC-IMPULSE CHARACTERISTICS OF SEVERAL POTENTIAL RAM-JET FUELS

I - OCTENE-1, ALUMINUM, AND ALUMINUM - OCTENE-1 SLURRIES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A preliminary analytical evaluation of the air and fuel specific-impulse characteristics of octene-1, aluminum, and aluminum - octene-1 slurries was made.

The adiabatic combustion flame temperature, combustion equilibrium-gas composition, air specific impulse, and fuel-weight specific impulse are presented for each fuel. These data, calculated for a combustor inlet-air temperature of 560° R, are presented for a range of equivalence ratios for octene-1 and for aluminum, and over a range of aluminum - octene-1 ratios at a fixed total fuel-equivalence ratio of 1.0. At an equivalence ratio of 1.0, the adiabatic combustion-gas temperature was 4180° and 6160° R for octene-1 and for aluminum, respectively. At an equivalence ratio of 1.0, the air specific impulse for aluminum was 213.3 [(lb)(sec)/lb air] and 170.4 [(lb)(sec)/lb air] for octene-1. The maximum air specific impulse for octene-1 was 172.8 [(lb)(sec)/lb air] and occurred at an equivalence ratio of 1.2.

At a combustor inlet-air temperature of 560° R, octene-1 gave a better fuel specific impulse on a weight basis than aluminum where both fuels are capable of giving the same air specific impulse.

Aluminum - octene-1 slurries offer a means of increasing the limited air specific impulse values available with octene-1 or hydrocarbon-type fuels.

INTRODUCTION

The ram-jet engine requires no significant moving parts for its operation; a greater variety of potential fuels is therefore available

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for the ram-jet engine than for the turbojet and reciprocating engines. Specifically, the ram-jet engine is capable of utilizing fuels that may produce considerable solid materials in the products of combustion. On a research basis a number of conventional and unconventional ram-jet fuels have been suggested because a need exists for ram-jet fuels that may permit the realization of flight range and thrust beyond the limits attainable with conventional hydrocarbon fuels. The suggested fuels include: aluminum, magnesium, boron, diborane, pentaborane, hydrogen, α-methylnaphthalene, aviation gasoline, graphite carbon, and slurries of some of these metals in aviation gasoline.

The problems involved in the utilization of bulk solid metals as fuels are minimized by use of the metals in slurry form. Slurries of metals in hydrocarbons have been used effectively in incendiary materials employed in large quantities in World War II. A single plant produced 80,000,000 pounds of incendiary petroleum jelly containing magnesium in 1 year (reference 1). The use of metal slurries in hydrocarbons appears to be an attractive field of ram-jet fuels research.

A survey of the thrust and fuel-economy characteristics of a large number of proposed ram-jet fuels is reported in reference 2, which evaluates the performance characteristics at the stoichiometric point; it assumes that no dissociation occurs. Because knowledge of the thrust and fuel-economy characteristics of the ram-jet fuels previously listed herein is desirable over a range of equivalence ratios (with allowance for dissociation), an analytical investigation was made at the NACA Lewis laboratory.

The performance characteristics obtainable with octene-1, taken as representative of hydrocarbon fuels, were chosen as the reference standard with which the performance of the other fuels was to be compared. Inasmuch as a previous experimental investigation was made of the use of aluminum as a potential ram-jet fuel (reference 3), the first fuels to be reported are aluminum and slurries of aluminum in octene-1.

For each of these fuels the following data are presented:

(1) Adiabatic combustion flame temperature as a function of equivalence ratio

(2) Equilibrium combustion-gas composition

(3) Air specific impulse

(4) Fuel-weight specific impulse

SYMBOLS

The following symbols are used in this report:

f/a	fuel-air ratio
g	acceleration due to gravity, (ft/sec^2)
H_T^o	molar enthalpy, (cal/gram mole)
I_r	ideal rocket specific impulse, (lb-sec/lb mixture)
M_i	molecular weight of constituent i
n_i	number of moles of constituent i
R	gas constant, (ft-lb/(lb)(^{o}R))
S_a	air specific impulse, (lb-sec/lb air)
S_f	fuel-weight specific impulse, (lb-sec/lb fuel)
T	static temperature, (^{o}R)
V_J	jet velocity, (ft/sec)
X	weight fraction of solids in jet gases

Subscripts:

c	combustor-exit conditions
e	nozzle-exit conditions determined by ambient pressure

ANALYTICAL METHOD

The analytical method is described with specific reference to the fuel octene-1. The general procedure used with the aluminum and with the aluminum - octene-1 slurries was similar; the significant differences will be indicated.

Octene-1. - The octene-1 was assumed to be 100 percent pure; air was assumed to be composed of 3.78 moles of nitrogen to every mole of oxygen. For convenience in calculation and for comparison of theoretical and actual performance values, the combustor conditions were selected, as inlet-air temperature of 560° R and pressure of 2 atmospheres. The combustor inlet-air velocity was assumed to be negligibly small; friction effects were neglected. The combustion-product gases of fixed composition were assumed to be expanded to an ambient pressure of 1 atmosphere at the exit of a converging nozzle. The air-specific-impulse function proposed in reference 4 was used as a measure of the power output in order to make the results as general as possible. The air specific impulse is defined as the stream thrust per unit of air flow.

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At a given stoichiometric fuel fraction, the ram-jet combustion-gas temperature and composition were calculated for an adiabatic constant-pressure combustion at 2 atmospheres by the matrix method of reference 5. All gases were assumed to follow the universal gas law. Thermodynamic data of reference 6 were used. The constituents considered in the equilibria were: molecular carbon dioxide, water, oxygen, nitrogen, carbon monoxide, and atomic carbon, hydrogen, oxygen, and nitrogen. The calculations were made over an equivalence-ratio range from 0.1 to 1.3 in intervals of 0.1 unit.

The nozzle-exit gas temperature was calculated at a frozen composition for isentropic expansion to ambient pressure at the nozzle exit. From the gas composition and temperature, the jet velocity was calculated by using the following equation (reference 7):

$$\frac{V_J}{g} = I_r = 9.328\sqrt{\left(\frac{\Sigma n_i H_T^O}{\Sigma n_i M_i}\right)_c - \left(\frac{\Sigma n_i H_T^O}{\Sigma n_i M_i}\right)_e} \qquad (1)$$

The Mach numbers at the exit nozzle covered a range near unity. It is conventional to report air-specific-impulse values for an exit Mach number of exactly 1. For the calculation reported herein, the percentage error due to this deviation from Mach number 1 was 0.5 percent or less. Consequently, corrections of the air-specific-impulse function for such a small effect were omitted. The air-specific-impulse values were calculated according to the equation:

$$S_a = \left(1 + \frac{f}{a}\right)\left[\frac{V_J}{g} + \frac{RT}{V_J}(1 - X)\right] \qquad (2)$$

The fuel-weight specific impulse is defined as the stream thrust at the nozzle exit per unit fuel flow and it is a measure of the fuel economy. The fuel-weight specific impulse values were derived from the air specific impulse values from the following relation:

$$S_f = S_a(a/f) \qquad (3)$$

Aluminum. - The constituents assumed present in the equilibria where aluminum was used as the fuel were: molecular aluminum monoxide, solid, liquid, and gaseous aluminum sesquioxide, nitrogen, nitric oxide, oxygen, and atomic nitrogen, oxygen, and aluminum. The reaction of aluminum with nitrogen to form aluminum nitride was omitted inasmuch as the thermodynamic data for this reaction were inadequate. The calculations were made over an equivalence-ratio range from 0.1 to 1.0 in intervals of 0.1 unit or less. The fuel equivalence ratio is based on the chemical equation for reaction with oxygen of the air; the terms fuel equivalence ratio and stoichiometric fuel fraction are synonymous.

When a liquid or solid phase of aluminum sesquioxide was present in the combustor, it was assumed that:

(1) The volume occupied by the condensed phase was negligible compared with the gas phase

(2) The condensed-phase particles were in thermal, velocity, and chemical equilibria with the gas phase in the combustor

(3) The condensed-phase particles were in thermal and velocity equilibria with the gas-phase particles in the exit nozzle

Aluminum and octene-1 slurries. - The constituents considered in the equilibria here include all those covered under the aluminum and octene-1 systems. This group of calculations was made at the stoichiometric point only; the metal content of the fuel was varied in regular steps over the range from 0 to 100 percent. The assumptions concerning the condensed phase were the same as for the aluminum system.

RESULTS AND DISCUSSION

Temperature. - The adiabatic combustion temperatures and the nozzle-exit gas temperatures for the octene-1, aluminum, and aluminum - octene-1 fuels are presented in figures 1(a), 1(b), and 1(c), respectively. At a combustor inlet-air temperature of 560° R, the maximum combustion temperature for octene-1 is about 4200° R and occurs at a stoichiometric fraction of about 1.05 (fig. 1(a)). At a stoichiometric fraction of 1.0, the adiabatic combustion temperature for aluminum is about 6160° R (fig. 1(b)). At a fixed total stoichiometric fuel fraction of 1.0, the adiabatic combustion temperature for the aluminum - octene-1 slurry varies nonlinearly from the value for octene-1 to the value for aluminum. The irregular nature of the aluminum and aluminum - octene-1 temperature curves is due to a phase transition of aluminum sesquioxide from liquid to gas.

Composition. - The theoretical combustion gaseous- and condensed-phase composition data in terms of the mole fraction of constituent as a function of the stoichiometric fraction of octene-1, aluminum, and of aluminum in octene-1 slurries are presented in figures 2(a), 2(b), and 2(c), respectively. These composition data were obtained simultaneously with the combustion-temperature data; they were used to arrive at the air and the fuel specific-impulse data. 2130

Air specific impulse. - The variation of air specific impulse with stoichiometric fuel fraction of octene-1 and of aluminum is presented in figure 3(a). The maximum air specific impulse for octene-1 at an inlet-air temperature of 560° R is 172.8 ((lb)(sec)/lb air) and occurs at an equivalence ratio of 1.20. At an equivalence ratio of 1.0, the air specific impulse for aluminum is 213.3 ((lb)(sec)/lb air).

The variation of air specific impulse with the stoichiometric fraction of aluminum in an aluminum - octene-1 slurry at a fixed total stoichiometric fraction of 1.0 is shown in figure 3(b). The air specific impulse for these slurries of aluminum varies nonlinearly from 170.4 to 213.3 ((lb)(sec)/lb air).

A comparison that indicates the relative importance of the factors contributing to the air-specific-impulse function follows. The ratio of the air specific impulse of aluminum to octene-1 is 1.25 at a stoichiometric fraction of 1.0. If the function air specific impulse divided by the factor 1 plus fuel-air ratio is considered, the ratio of this function for aluminum to octene-1 is 1.06 at the equivalence point. This result means that the increased value of the air specific impulse of aluminum over that for octene-1 is, to a large extent, due to the increased mass flow available with aluminum fuel.

Fuel-weight specific impulse. - Figure 4(a) presents the fuel-weight specific-impulse data for octene-1 and for aluminum as a function of the stoichiometric fraction of fuel. The fuel-weight specific impulse for aluminum slurries in octene-1 as a function of the stoichiometric fraction of aluminum in the slurry is presented in figure 4(b); the total stoichiometric fraction of fuel is fixed at 1.0 for this curve.

Relation between air and fuel specific impulse. - The variation of fuel-weight specific impulse with air specific impulse for octene-1 and for aluminum is shown in figure 5(a). These data were obtained by cross-plotting the appropriate data for the variation of fuel and air specific impulse with stoichiometric fuel fraction. The data in figure 5(a) are presented because comparisons of fuel economy for various fuels should be made at the same performance level, that is, at the same air specific impulse. Conversely, the relative air specific impulse of several fuels at a fixed fuel-economy value may be of interest. Such data are readily obtained from figure 5(a).

The variation of fuel-weight specific impulse with air specific impulse for aluminum - octene-1 slurries at a fixed total stoichiometric fraction of 1.0 is presented in figure 5(b).

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SUMMARY OF RESULTS

For the conditions of this preliminary analysis, the following results were obtained:

1. At a fixed air-specific-impulse level below a value of 172 ((lb)(sec)/lb air), octene-1 will give a fuel-weight specific impulse superior to aluminum.

2. Values of the air specific impulse greater than the octene-1 limit of 172.8 ((lb)(sec)/lb air) may be achieved with aluminum. The air specific impulse of aluminum at an equivalence ratio of 1.0 is 213.3 ((lb)(sec)/lb air).

3. An improvement in the air-specific-impulse value for hydrocarbon fuels may be attained by use of metallic slurries of aluminum in the hydrocarbon. Better fuel-weight specific-impulse values are available with aluminum - octene-1 slurries than are available with aluminum alone at the same air specific impulse.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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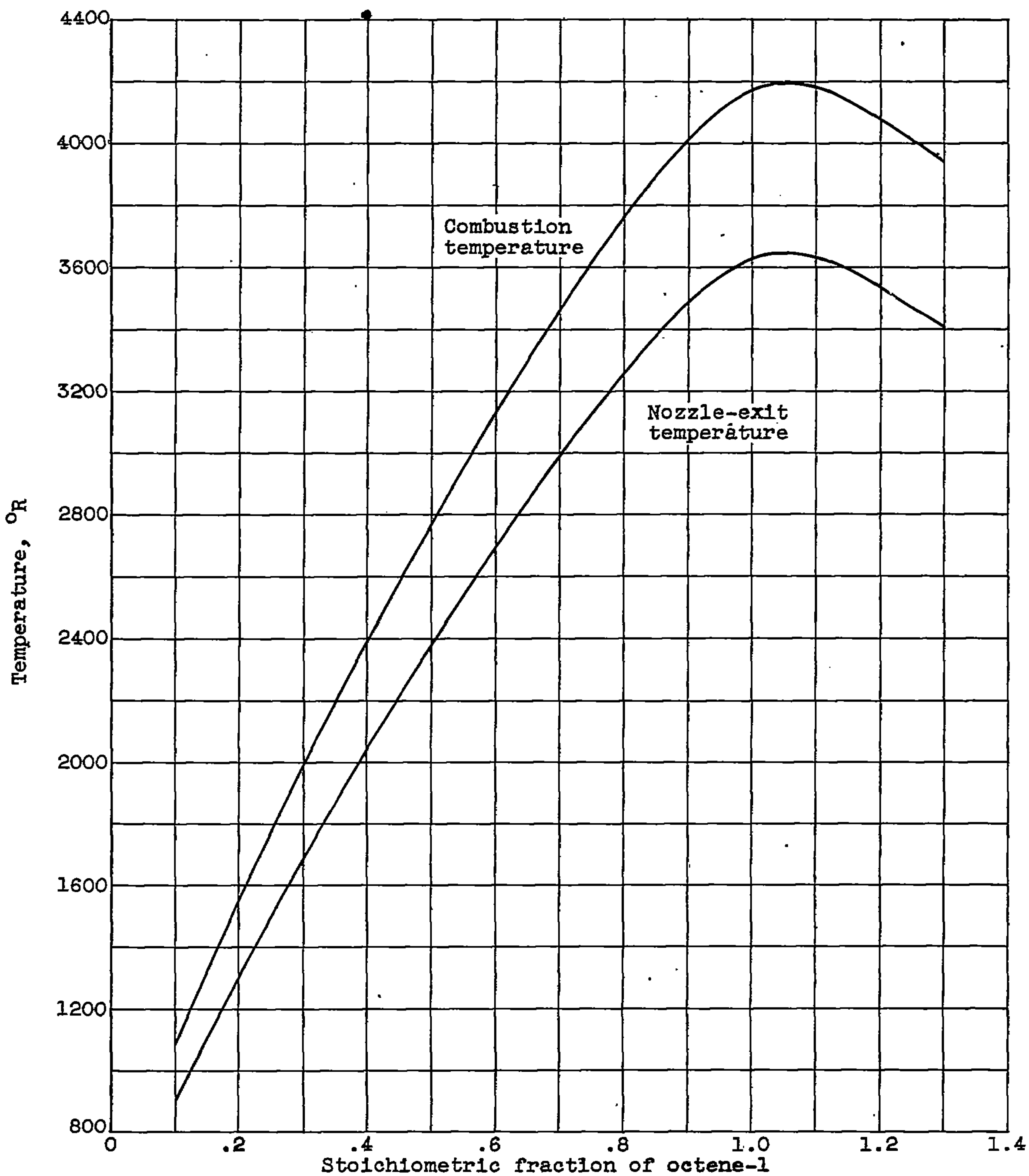
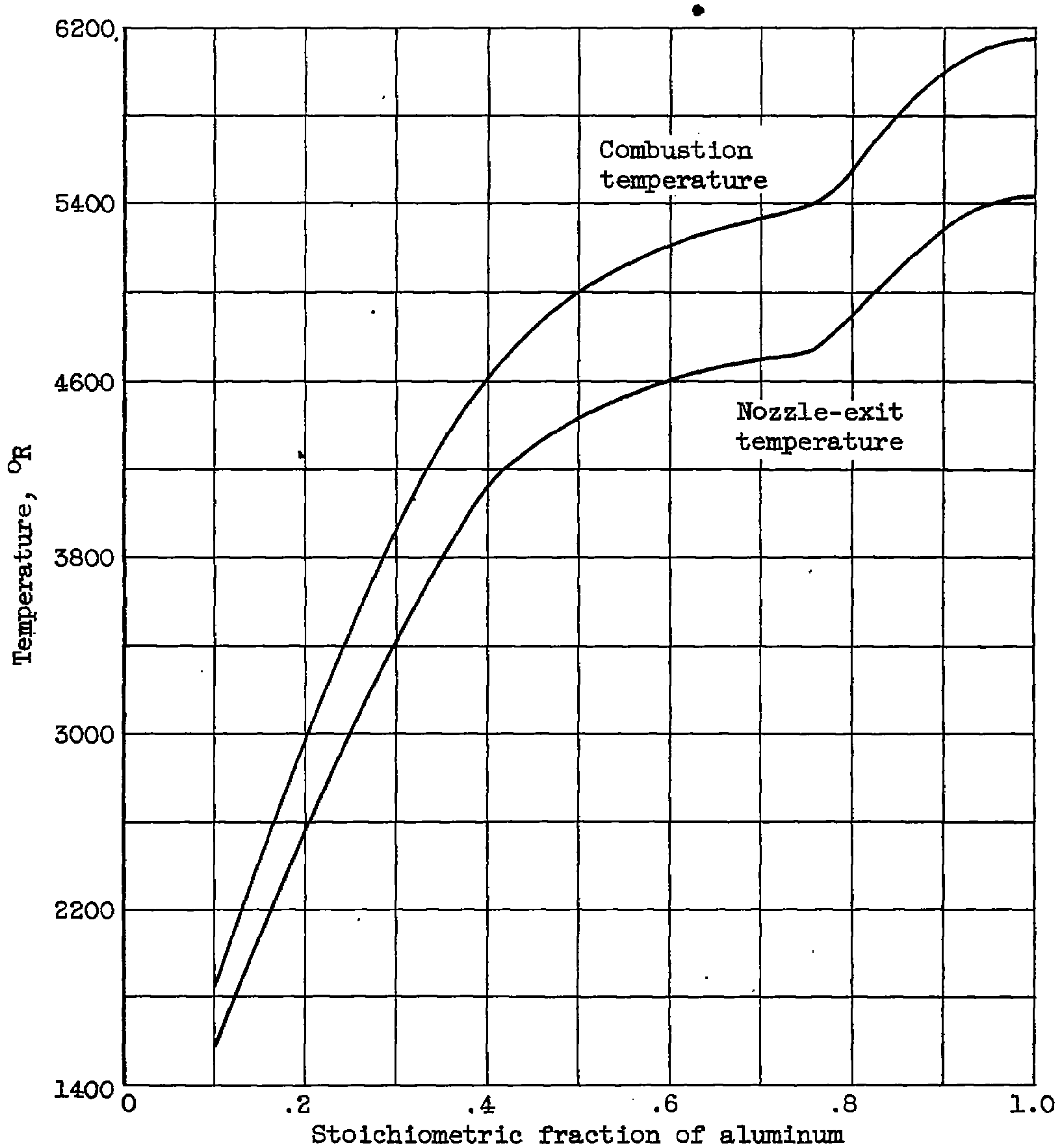


(a) Fuel, octene-1.

Figure 1. - Theoretical combustion- and nozzle-exit temperature variation with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.



(b) Fuel, aluminum.

Figure 1. - Continued. Theoretical combustion- and nozzle-exit temperature variation with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.

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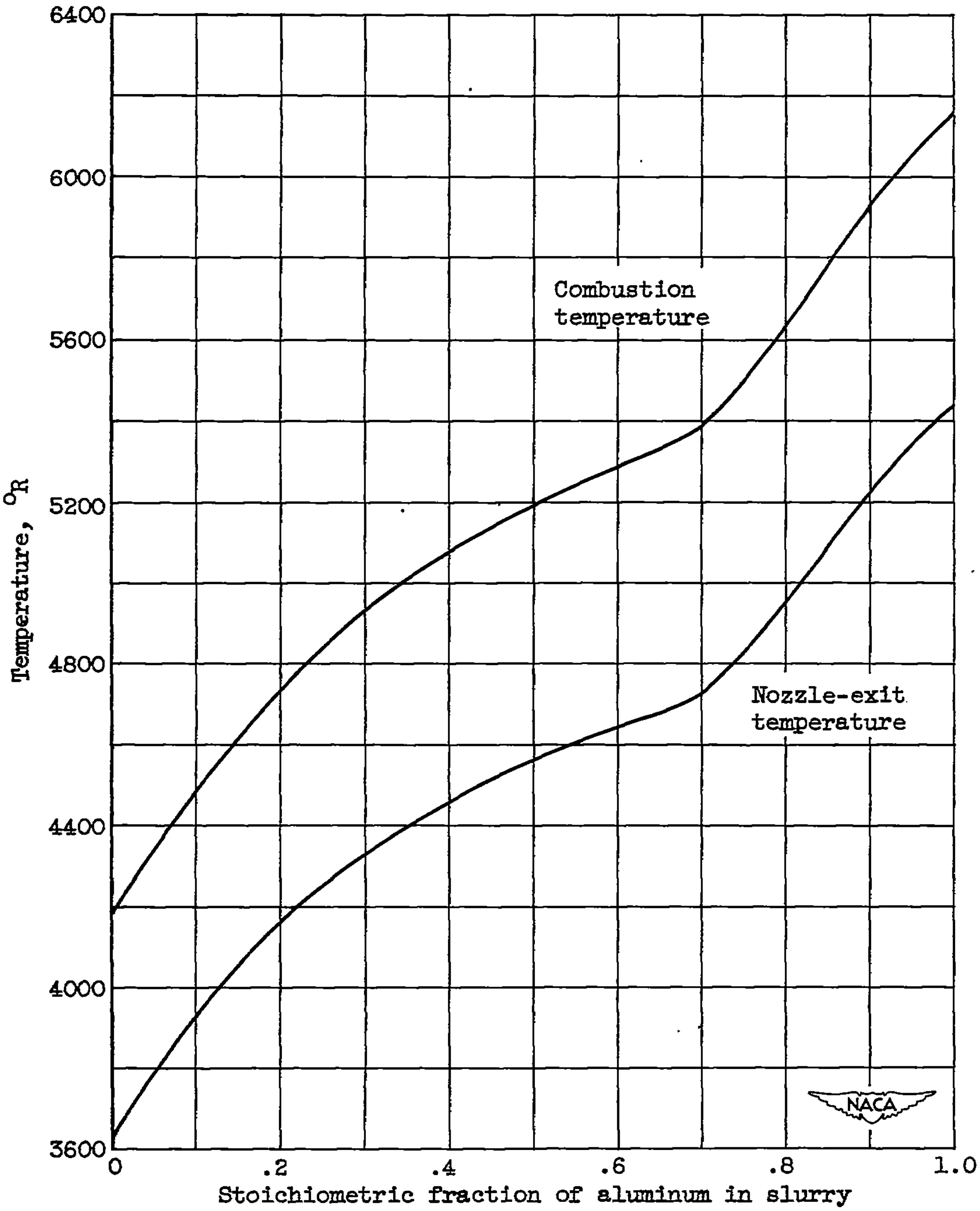

(c) Fuel, aluminum - octene-1 slurry; stoichiometric fraction of aluminum plus octene-1 fixed at 1.0.

Figure 1. - Concluded. Theoretical combustion- and nozzle-exit temperature variation with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.

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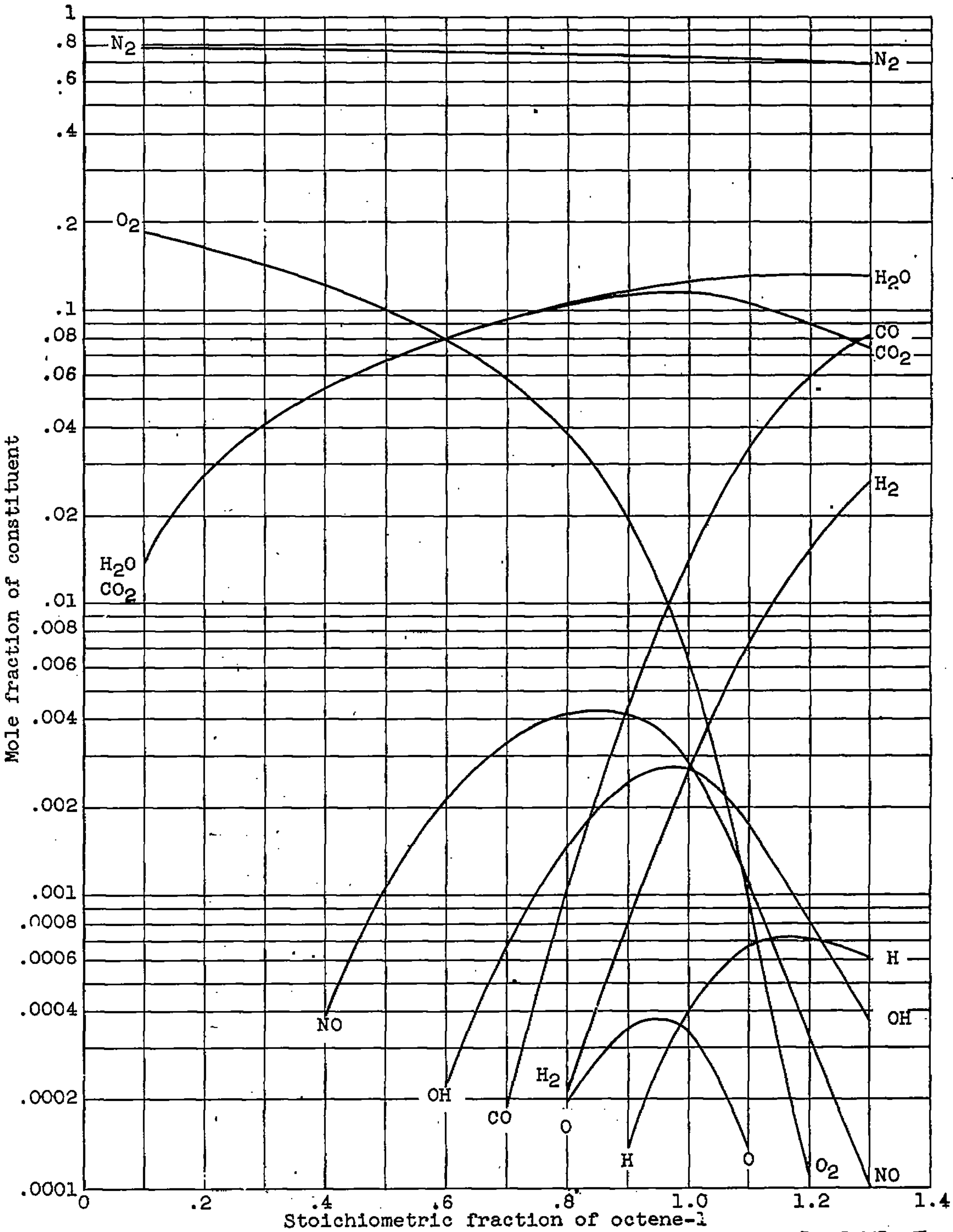

(a) Fuel, octene-1.

Figure 2. - Variation of theoretical mole fraction of constituents with stoichiometric fraction of fuel.

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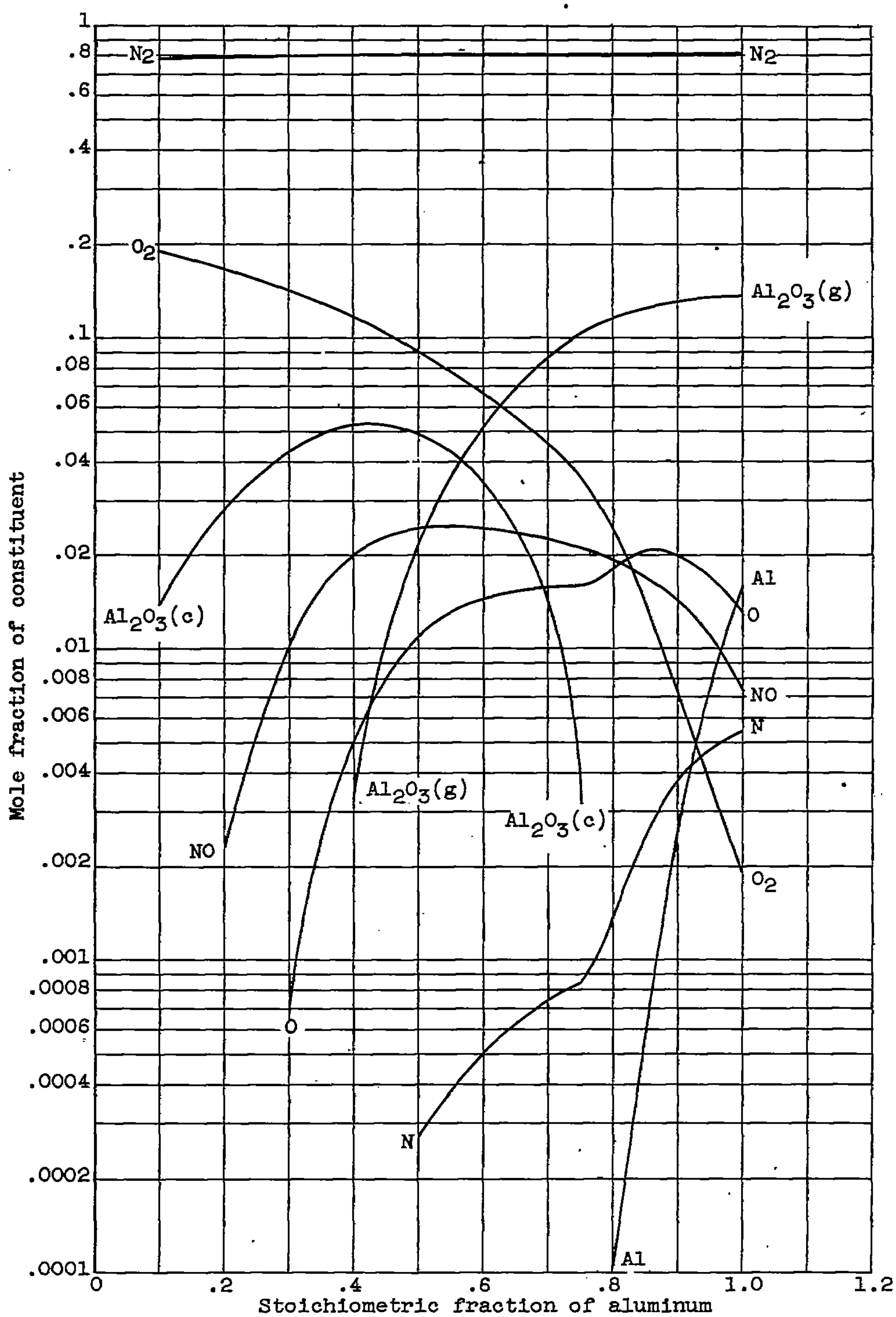

(b) Fuel, aluminum.

Figure 2.- Continued. Variation of theoretical mole fraction of constituents with stoichiometric fraction of fuel.

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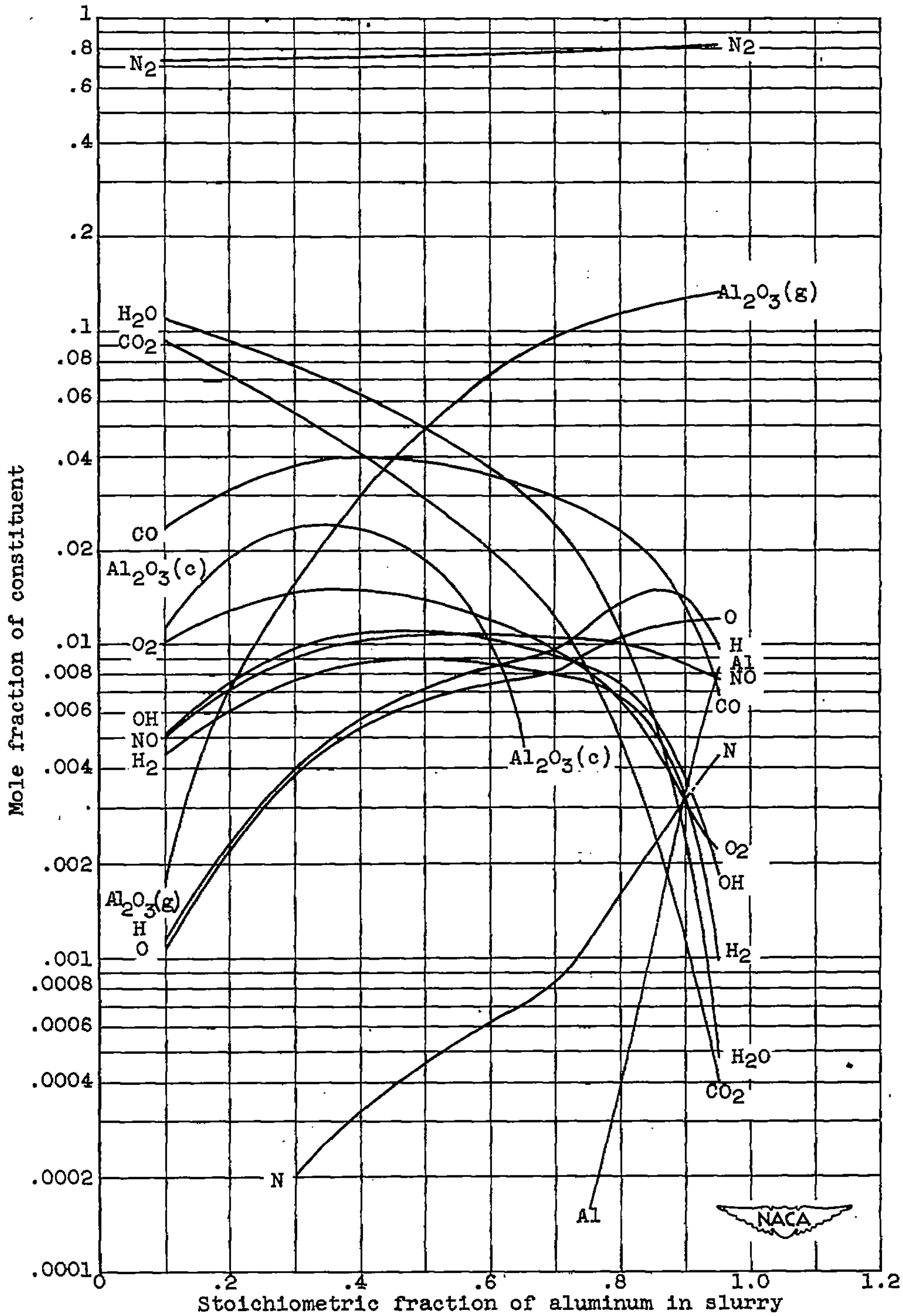

(c) Fuel, aluminum - octene-1 slurry; stoichiometric fraction of aluminum plus octene-1 fixed at 1.0.

Figure 2. - Concluded. Variation of theoretical mole fraction of constituents with stoichiometric fraction of fuel.

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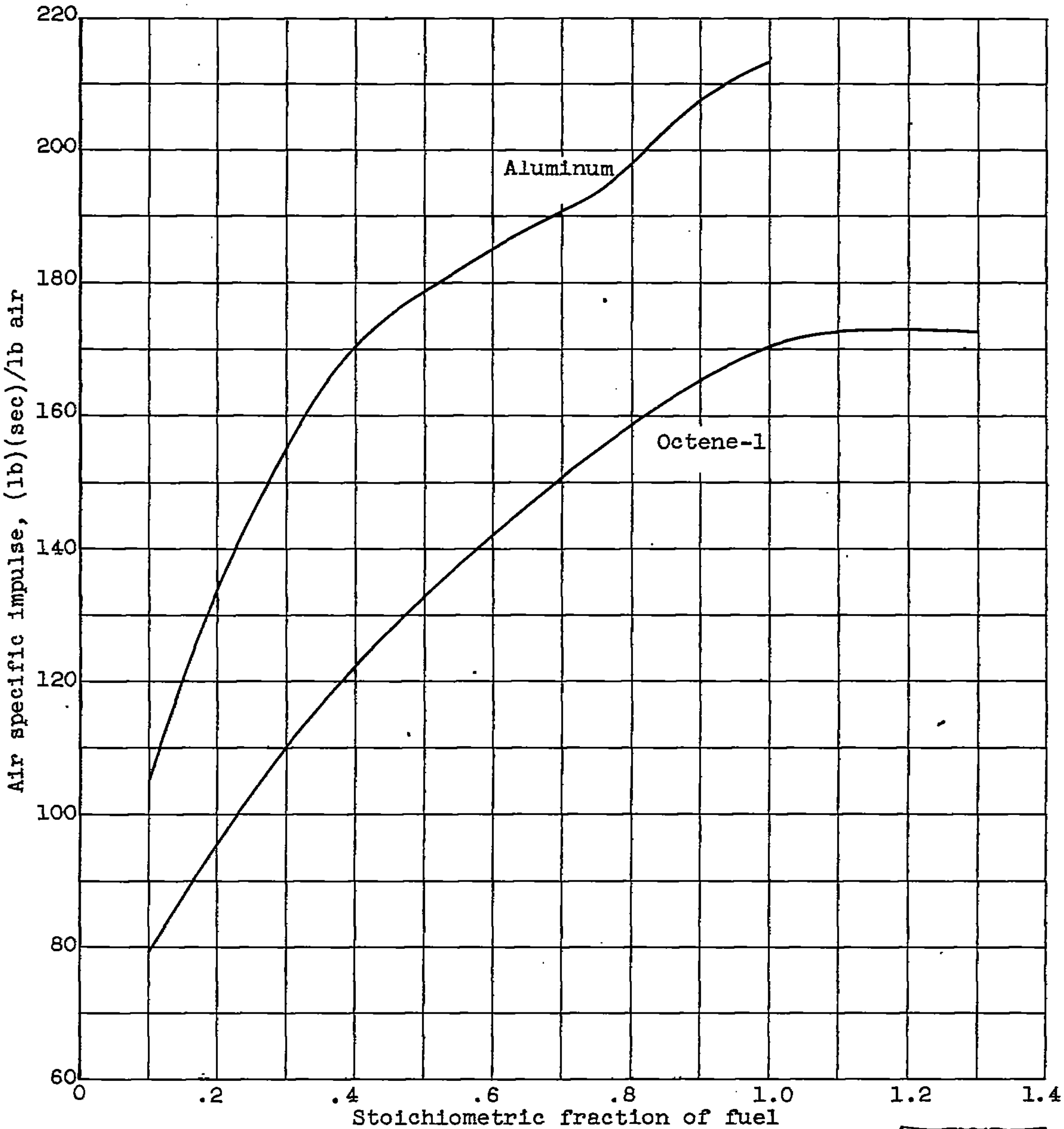

(a) Fuels, octene-1 and aluminum.

Figure 3. - Variation of air specific impulse with stoichiometric fraction of various fuels. Combustor inlet-air temperature, 560° R.

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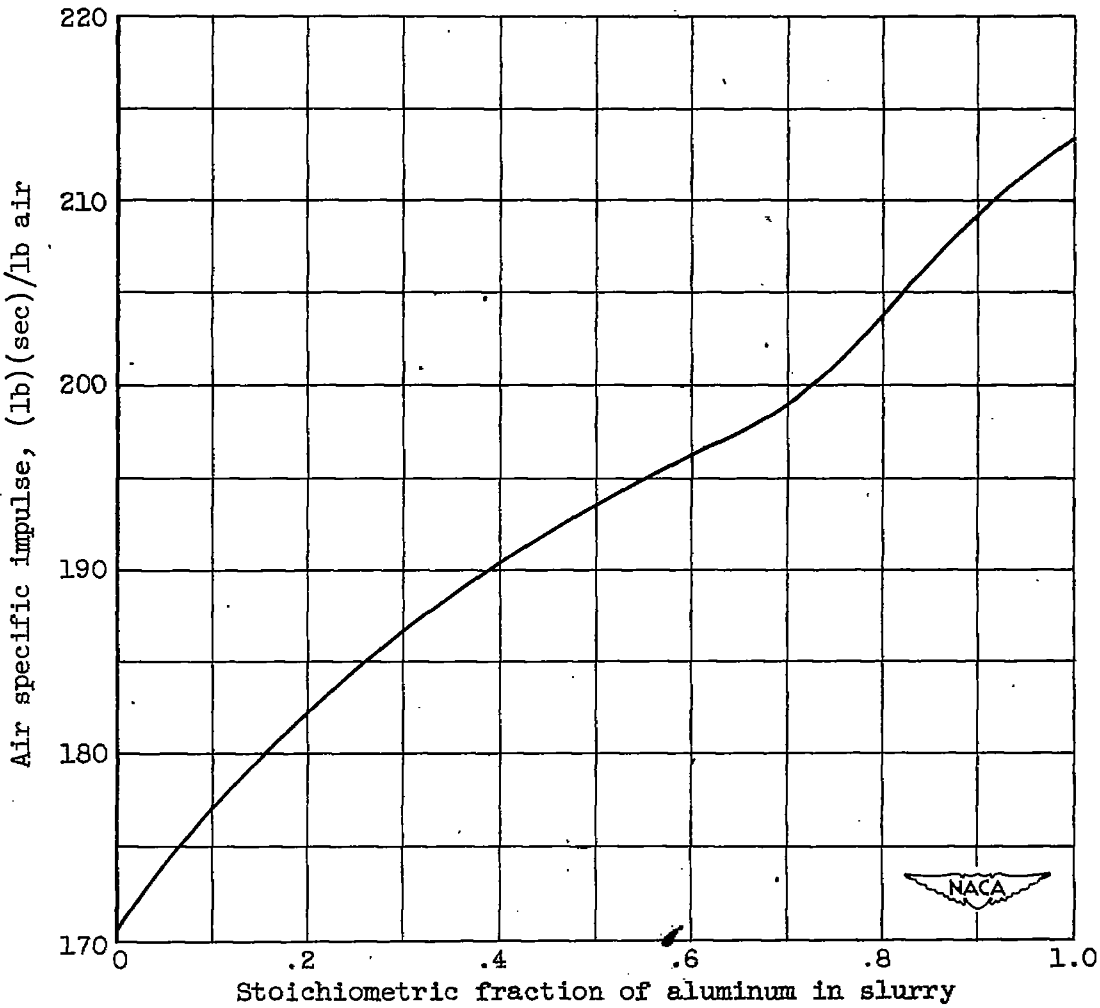
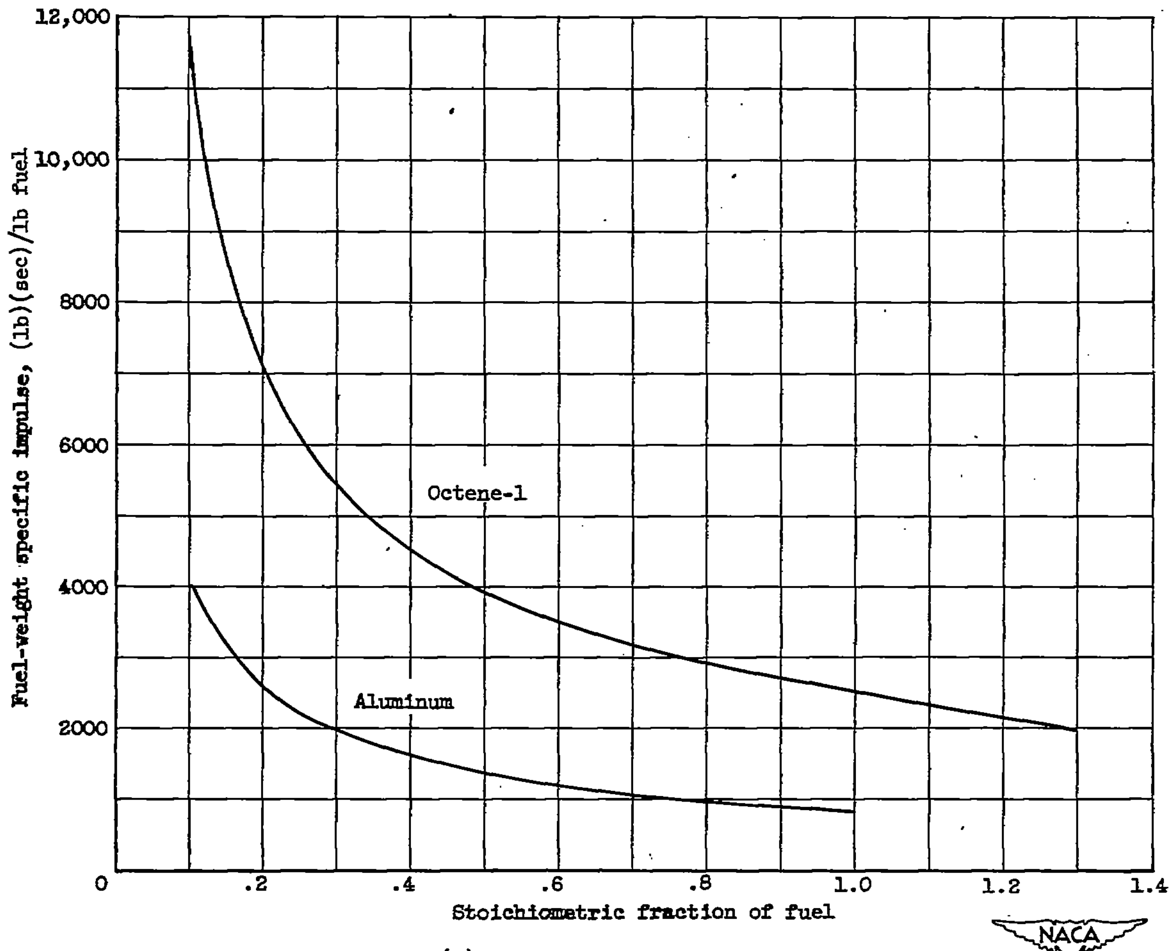


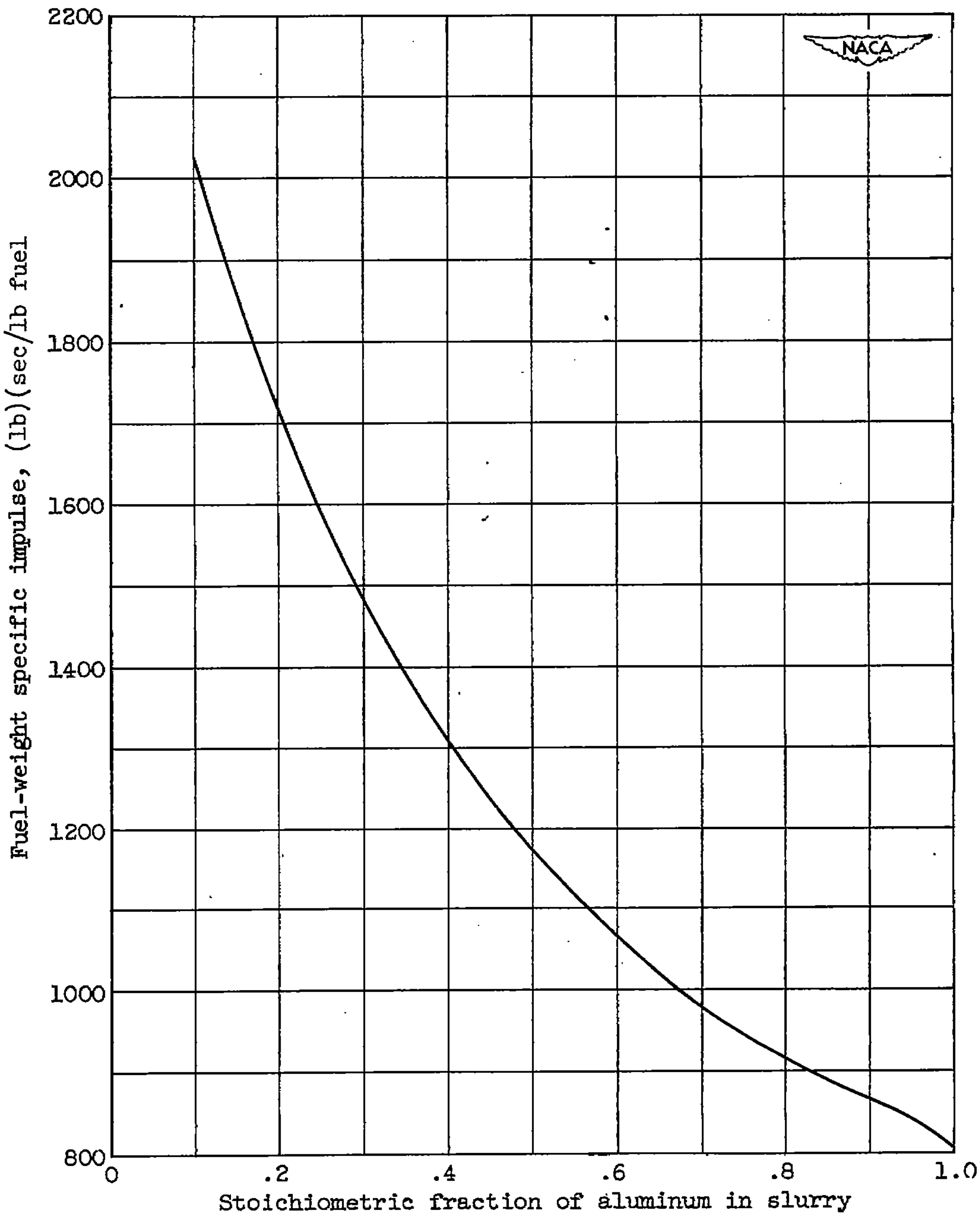
(b) Fuel, aluminum - octene-1 slurry; stoichiometric fraction of aluminum plus octene-1 fixed at 1.0.

Figure 3. - Concluded. Variation of air specific impulse with stoichiometric fraction of various fuels. Combustor inlet-air temperature, 560° R.



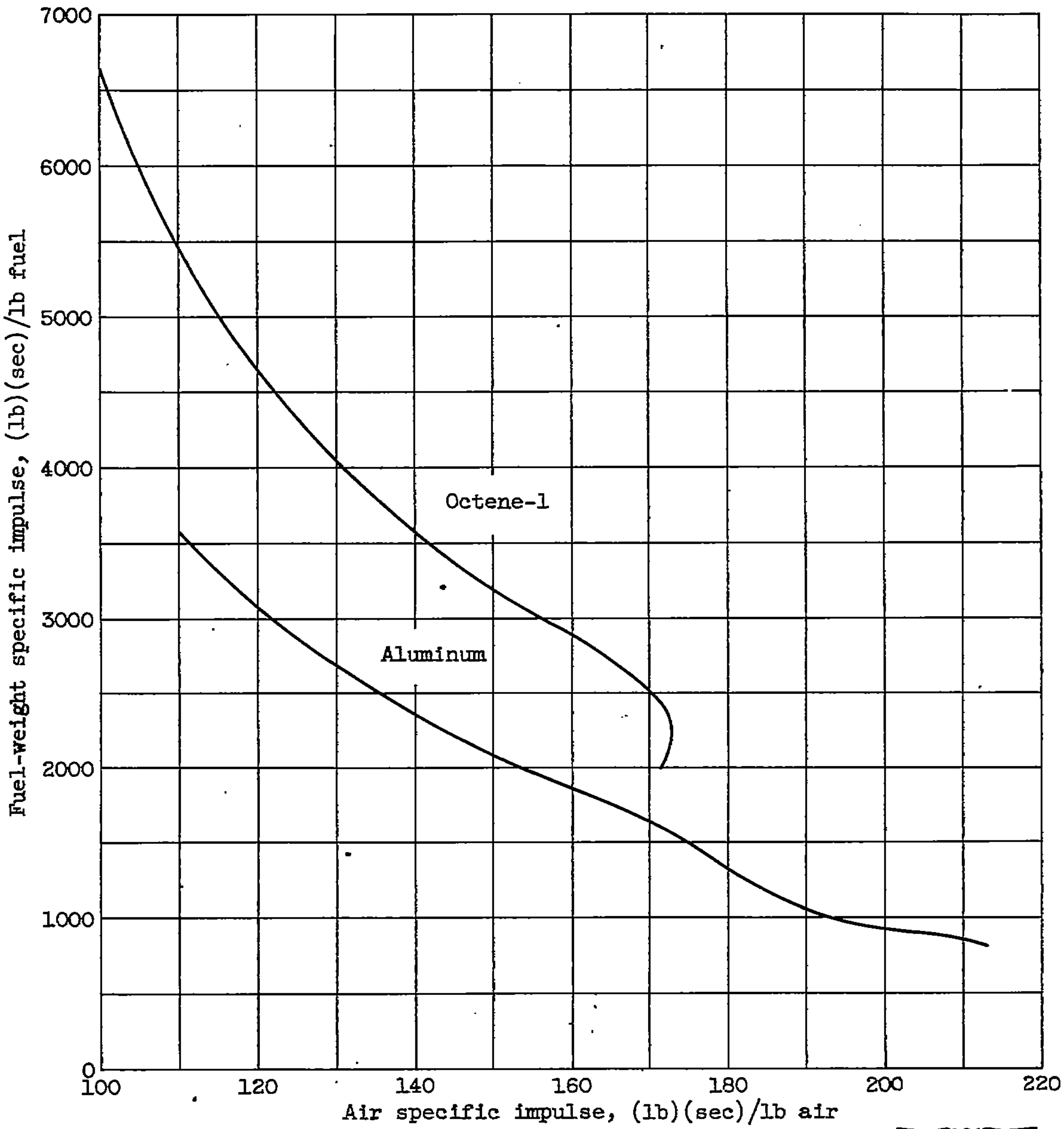
(a) Fuels, octene-1 and aluminum.

Figure 4. - Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R.



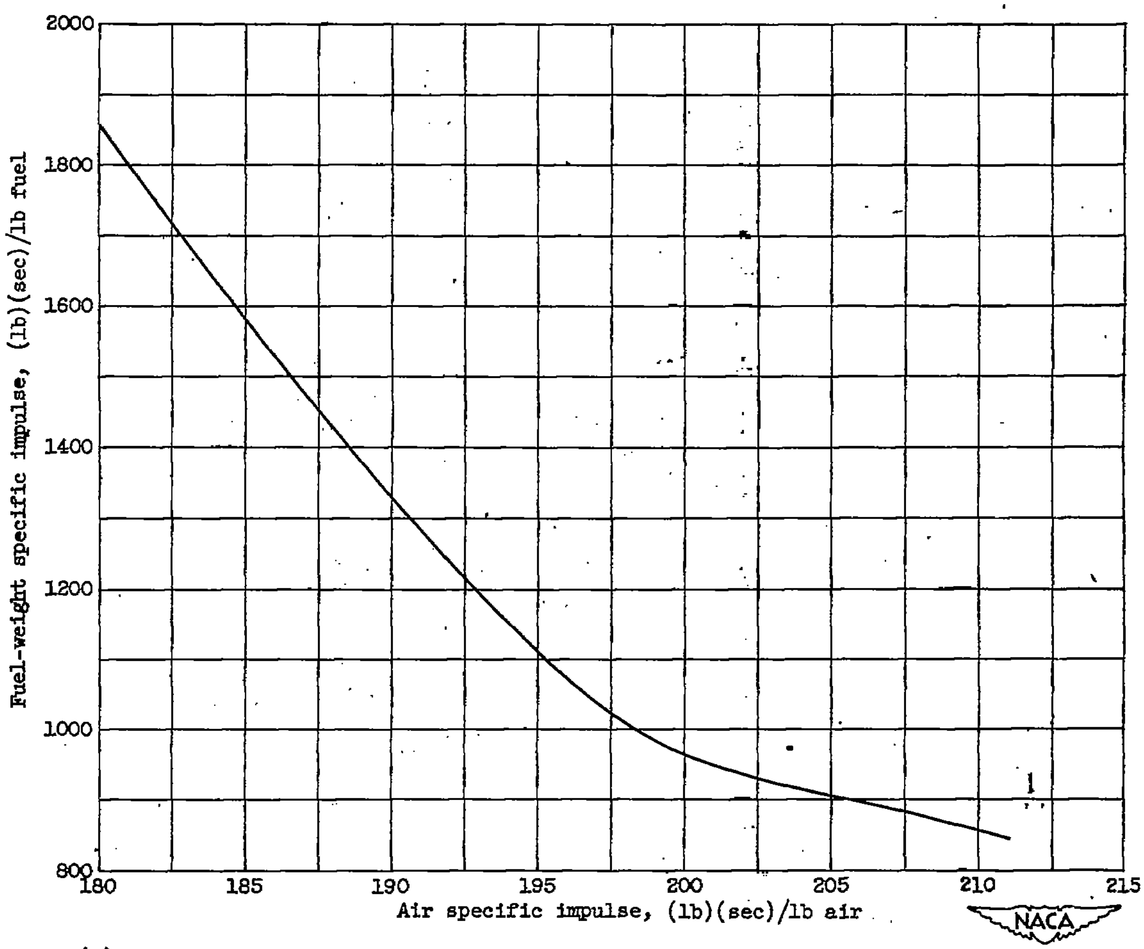
(b) Fuel, aluminum - octene-1 slurry; stoichiometric fraction of aluminum plus octene-1 fixed at 1.0.

Figure 4. - Concluded. Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R.



(a) Fuels, octene-1 and aluminum.

Figure 5. - Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R.



(b) Fuel, aluminum - octene-1 slurry; stoichiometric fraction of aluminum plus octene-1 fixed at 1.0.

Figure 5. - Concluded. Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R.