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RESEARCH MEMORANDUM

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

IV - HYDROGEN, α-METHYLNAPHTHALENE, AND CARBON

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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RESEARCH MEMORANDUM

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

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SUMMARY

An analytical evaluation of the air and fuel specific-impulse characteristics of hydrogen, α-methylnaphthalene, and graphite carbon has been made.

Adiabatic constant-pressure combustion temperature, air specific impulse, and fuel specific impulse are given for each fuel. The specific impulse data for octene-1, taken as representative of aviation gasoline performance, are presented for comparison.

At an initial air temperature of 560° R and a pressure of 2 atmospheres, the adiabatic constant-pressure combustion temperatures for hydrogen, α-methylnaphthalene, and graphite carbon were 4256°, 4188°, and 4173° R, respectively, for a fuel equivalence ratio of 1.0.

At a given air specific impulse, the decreasing order of fuel-weight specific impulse is hydrogen, octene-1, α-methylnaphthalene, and graphite carbon.

At a given air specific impulse, the decreasing order of fuel-volume specific impulse is graphite carbon, α-methylnaphthalene, octene-1, and hydrogen.

INTRODUCTION

An investigation to evaluate the performance characteristics of several proposed ram-jet fuels is being conducted at the NACA Lewis laboratory. As a part of this program an analytical evaluation of the air and fuel specific-impulse characteristics of aluminum, magnesium, boron, diborane, pentaborane, hydrogen, aviation gasoline, graphite carbon, α-methylnaphthalene, and slurries of the above metals in aviation gasoline is being made. The performance characteristics obtainable with octene-1, taken as representative of aviation gasoline, were

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chosen as the reference standard with which the performance of the other fuels was to be compared. Data on the theoretical air and fuel specific-impulse characteristics of octene-1, aluminum, magnesium, aluminum - octene-1, and magnesium - octene-1 slurries, diborane, pentaborane, boron, and boron - octene-1 slurries are presented in references 1, 2, and 3. Experimental ram-jet combustion performance data for diborane, aluminum, and magnesium-hydrocarbon slurries are presented in references 4, 5, and 6, respectively.

This report presents data for hydrogen, α-methylnaphthalene, and graphite carbon in the following order:

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

(b) Air specific impulse as a function of equivalence ratio

(c) Fuel-weight specific impulse as a function of equivalence ratio

(d) Fuel-weight specific impulse as a function of air specific impulse

(e) Fuel-volume specific impulse as a function of air specific impulse

The terms fuel equivalence ratio and stoichiometric fuel fraction are based on the oxygen available in the atmosphere and are used interchangeably.

SYMBOLS

The following symbols are used in this report:

A	area, (sq ft)
F	stream thrust, (lb)
f/a	fuel-air ratio
g	acceleration due to gravity, (ft/sec^2)
H_T°	molar enthalpy, (cal/gram mole)
I_{γ}	ideal rocket specific impulse, (lb-sec/lb mixture)
M	Mach number

M_i	molecular weight of constituent i
m	mass, (slugs/sec)
n_i	number of moles of constituent i
p	pressure, (lb/sq ft)
R	gas constant, (ft-lb/(lb)($^{\circ}$R))
S_a	air specific impulse, ((lb)(sec)/lb air)
S_f	fuel-weight specific impulse, ((lb)(sec)/lb fuel)
S'_f	fuel-volume specific impulse, ((lb)(sec)/cu ft fuel)
T	static temperature, ($^{\circ}$R)
V	velocity, (ft/sec)
w	weight flow, (lb/sec)
X	weight fraction of solids in jet gases
ρ	density, (lb/cu ft)

Subscripts:

a	air
c	combustor-exit conditions
e	nozzle-exit conditions determined by ambient pressure
f	fuel
J	jet
3	nozzle throat station

ANALYTICAL METHOD

The analytical method is described with specific reference to the hydrogen fuel. The general procedure used with α-methylnaphthalene and graphite carbon was similar; the significant differences will be indicated.

Hydrogen. - The hydrogen 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 1 atmosphere at the exit of a converging nozzle. The air specific-impulse function proposed in reference 7 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 weight of air flow per second for a flow state of Mach number 1.0.

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 8. All gases were assumed to follow the universal gas law. Thermodynamic data of reference 9 were used. The gaseous constituents considered in the equilibria were: H_2, H_2O, N_2, NO, O_2, OH, H, N, and O. Calculations were made over an equivalence-ratio range from 0.1 to 1.0 in intervals of 0.1.

The nozzle-exit gas temperature was calculated at a constant 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 10):

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

The air specific-impulse values were then calculated according to the equation given in reference 1

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

For the fuels considered herein, the weight fraction of solids in the exhaust x was zero.

Equation (2) may be derived from the defining equation for air specific impulse

$$S_a \equiv \frac{F_3}{w_a} \equiv \frac{m\ V_J + p_3\ A_3}{w_a} \tag{3}$$

The fuel-weight specific impulse is defined as the stream thrust at the nozzle exit per unit fuel flow. The fuel-weight specific-impulse values were derived from the air specific-impulse values from the relation

$$S_f = S_a\ (a/f) \tag{4}$$

Fuel-volume specific impulse is defined as

$$S'_f \equiv S_f\ \rho_f \tag{5}$$

The air specific impulse is a measure of the potential thrust; the fuel-weight specific impulse is a measure of the time 1 pound of fuel will maintain the given air specific impulse.

α-Methylnaphthalene. - The gaseous constituents assumed present in the equilibria when α-methylnaphthalene was used as the fuel were: CO_2, CO, H_2O, O_2, N_2, NO, H_2, H, O, OH, and C. The assigned enthalpy of α-methylnaphthalene was taken as 1357.3 (kcal/mole) for these calculations.

Graphite carbon. - The gaseous constituents assumed present in the equilibria when graphite carbon was used as the fuel were: CO_2, CO, O_2, N_2, NO, O, N, and C.

RESULTS AND DISCUSSION

Temperature. - The adiabatic constant-pressure combustion temperature and the nozzle-exit gas temperature for hydrogen, α-methylnaphthalene, and graphite carbon are shown in figures 1(a), 1(b), and 1(c), respectively. The nozzle-exit gas temperatures are those used in deriving the air and fuel specific-impulse values from equations (2) and (4); they are the static temperatures at the nozzle throat for a flow state Mach number of 1.0.

At a stoichiometric fuel fraction of 1.0, an initial air temperature of 560° R, and 2 atmospheres pressure, the combustion temperatures for hydrogen, α-methylnaphthalene, and graphite carbon are: 4256°, 4188°, and 4173° R, respectively.

Air specific impulse. - The variation of air specific impulse with stoichiometric fuel fraction for hydrogen, α-methylnaphthalene, and graphite carbon is presented in figures 2(a), 2(b), and 2(c), respectively. At a stoichiometric fuel fraction of 1.0, the air specific-impulse values are 179.3, 168.7, and 166.1 ((lb)(sec)/lb air) for hydrogen, α-methylnaphthalene, and graphite carbon, respectively.

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with stoichiometric fraction of hydrogen, α-methylnaphthalene, and graphite carbon is presented in figures 3(a), 3(b), and 3(c), respectively.

Relation between air and fuel specific impulse. - Comparison of fuel specific impulse for a series of fuels can best be made at the same air specific impulse, that is, at equivalent thrust levels. The variation of fuel-weight specific impulse with air specific impulse for hydrogen, α-methylnaphthalene, and graphite carbon is presented in figures 4(a), 4(b), and 4(c), respectively. These data were obtained by cross-plotting the data for air and fuel-weight specific impulse presented in figures 2 and 3.

The data presented in figure 4 are shown again in figure 5 for comparison with the octene-1 reference curve. Reference lines of constant fuel-air ratio are shown in figure 5 to facilitate comparisons. It is evident from figure 5 that hydrogen gives a better fuel-weight specific impulse at a given air specific impulse than octene-1, α-methylnaphthalene, or graphite carbon. Octene-1 is better than α-methylnaphthalene and α-methylnaphthalene is better than graphite carbon on a fuel-weight specific impulse basis.

The limiting value of air specific impulse for octene-1 is 172.8 ((lb)(sec)/lb air). Limiting values of air specific impulse were not calculated for hydrogen, α-methylnaphthalene, and graphite carbon. Calculations for these fuels were made up to an equivalence ratio of 1.0.

A comparison of the air and fuel-volume specific-impulse characteristics of hydrogen, α-methylnaphthalene, and graphite carbon with octene-1 is shown in figure 6. On a fuel-volume specific-impulse basis at a fixed air specific impulse, carbon and α-methylnaphthalene offer potential advantages over octene-1. Hydrogen is inferior to octene-1 on this basis. The densities used for liquid hydrogen, α-methylnaphthalene, graphite carbon, and octene-1 were: 4.426, 63.99, 141.1, 44.44 pounds per cubic foot, respectively. The density of octene-1, carbon, and α-methylnaphthalene are taken at room temperature. The density of hydrogen is taken at approximately its normal boiling point -422.86° F. All densities are quoted for 1-atmosphere pressure.

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SUMMARY OF RESULTS

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

(1) At an initial air temperature of 560° R and 2-atmosphere pressure, the adiabatic constant-pressure combustion temperatures for hydrogen, α-methylnaphthalene, and graphite carbon were 4256°, 4188°, and 4173° R, respectively, at the stoichiometric point.

(2) At a given air specific impulse, the decreasing order of fuel-weight specific impulse is hydrogen, octene-1, α-methylnaphthalene, and graphite carbon.

(3) At a given air specific impulse, the decreasing order of fuel-volume specific impulse is graphite carbon, α-methylnaphthalene, octene-1, and hydrogen.

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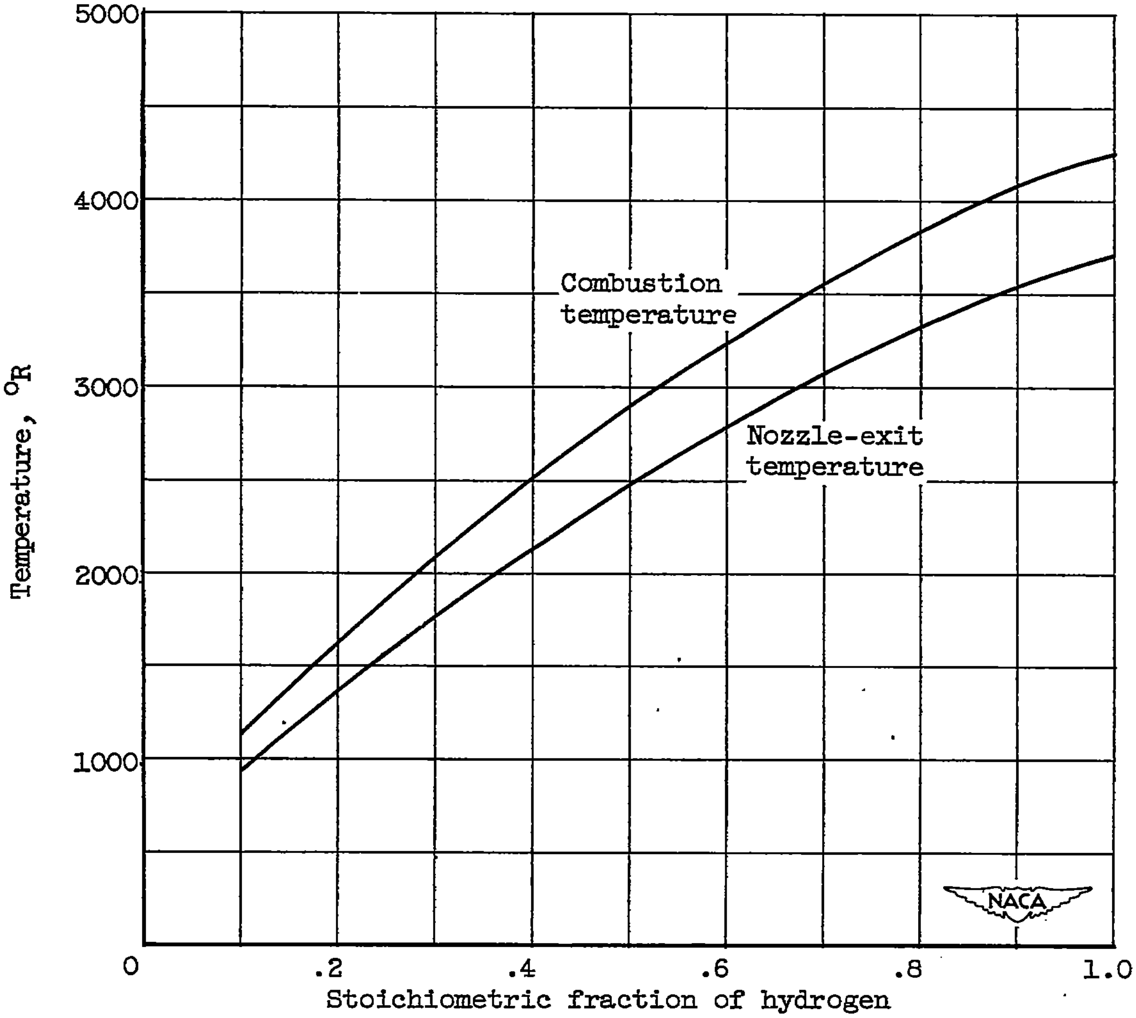

(a) Hydrogen.

Figure 1. - Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.

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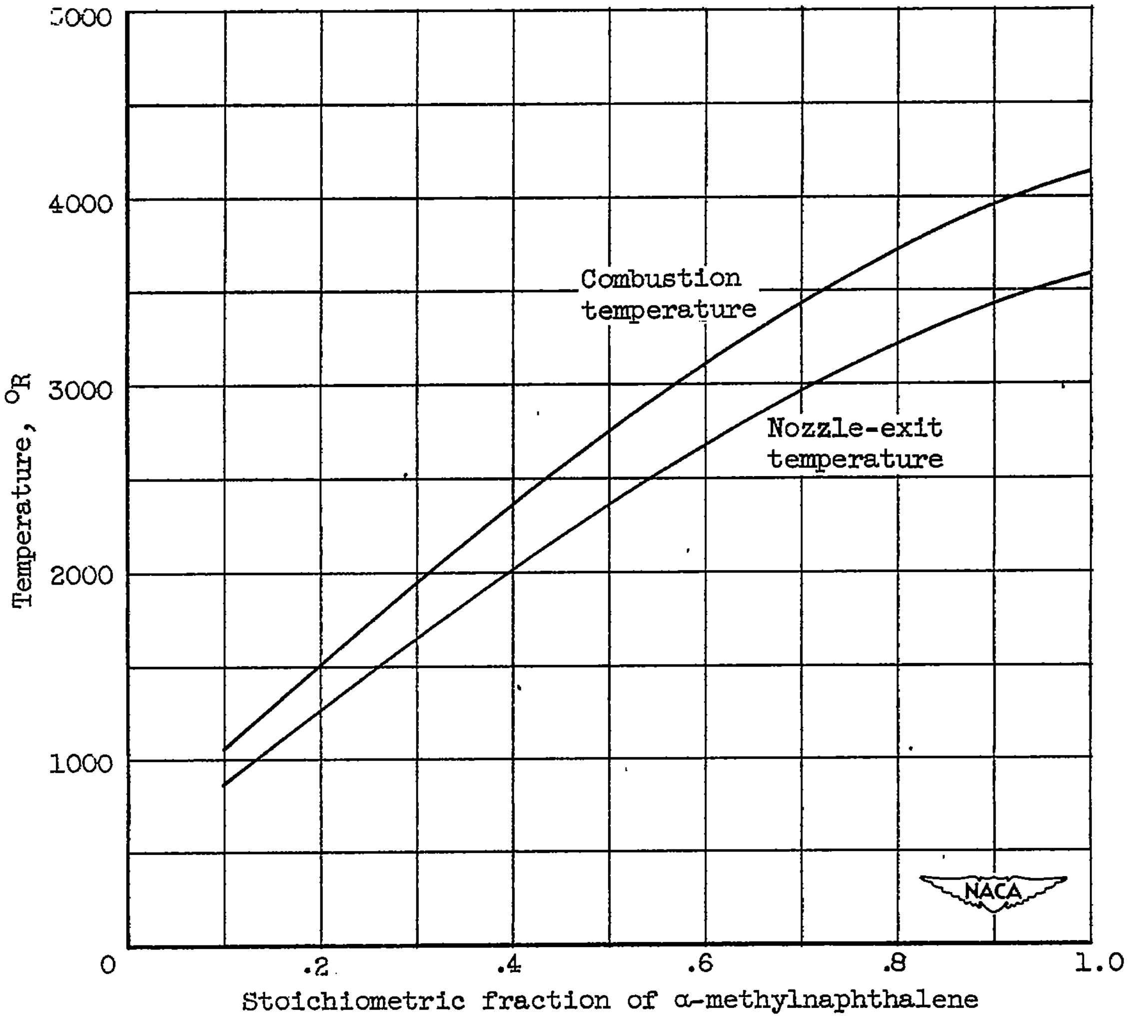
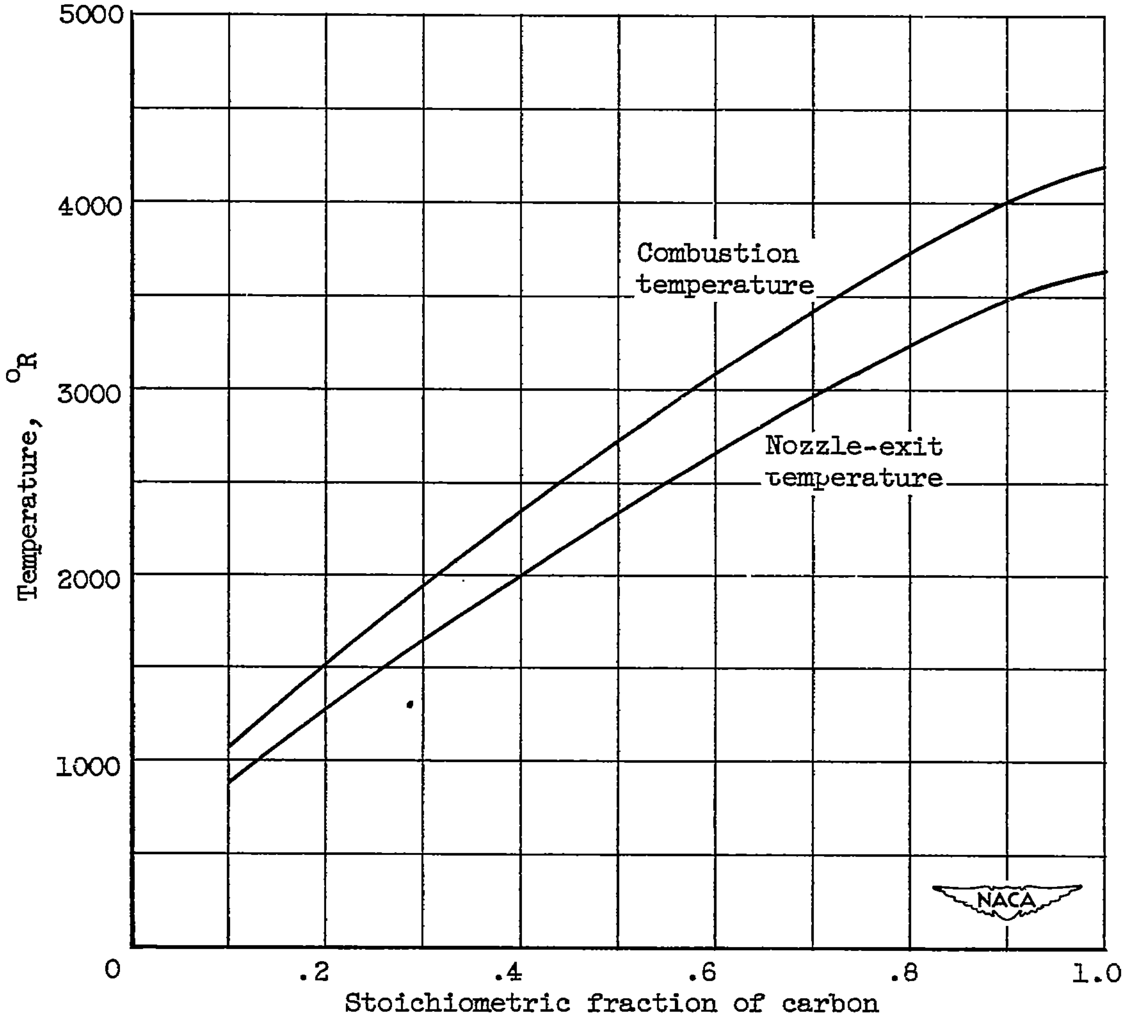


(b) α-Methylnaphthalene.

Figure 1. - Continued. Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.



(c) Carbon.

Figure 1. - Concluded. Theoretical variation of combustion and nozzle-exit temperature with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.

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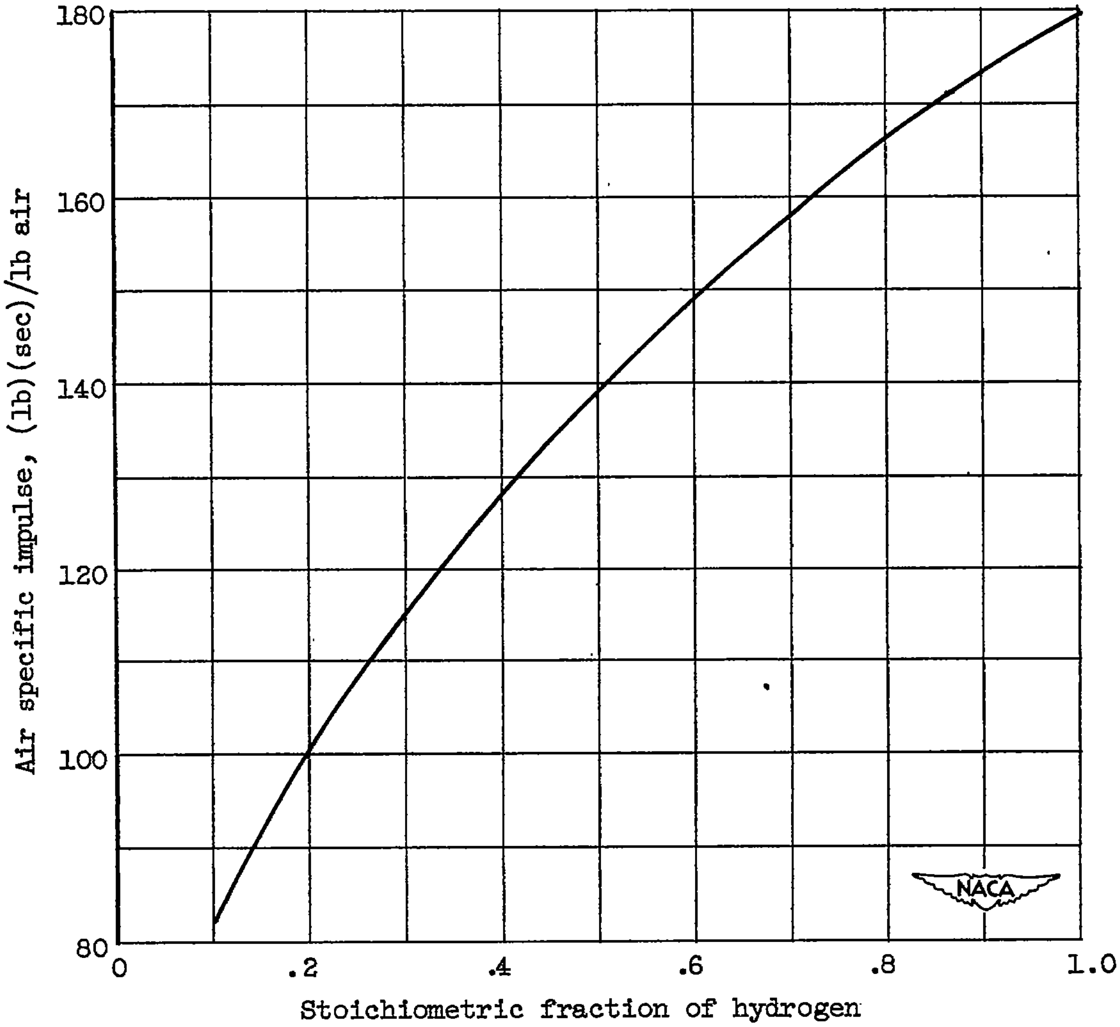
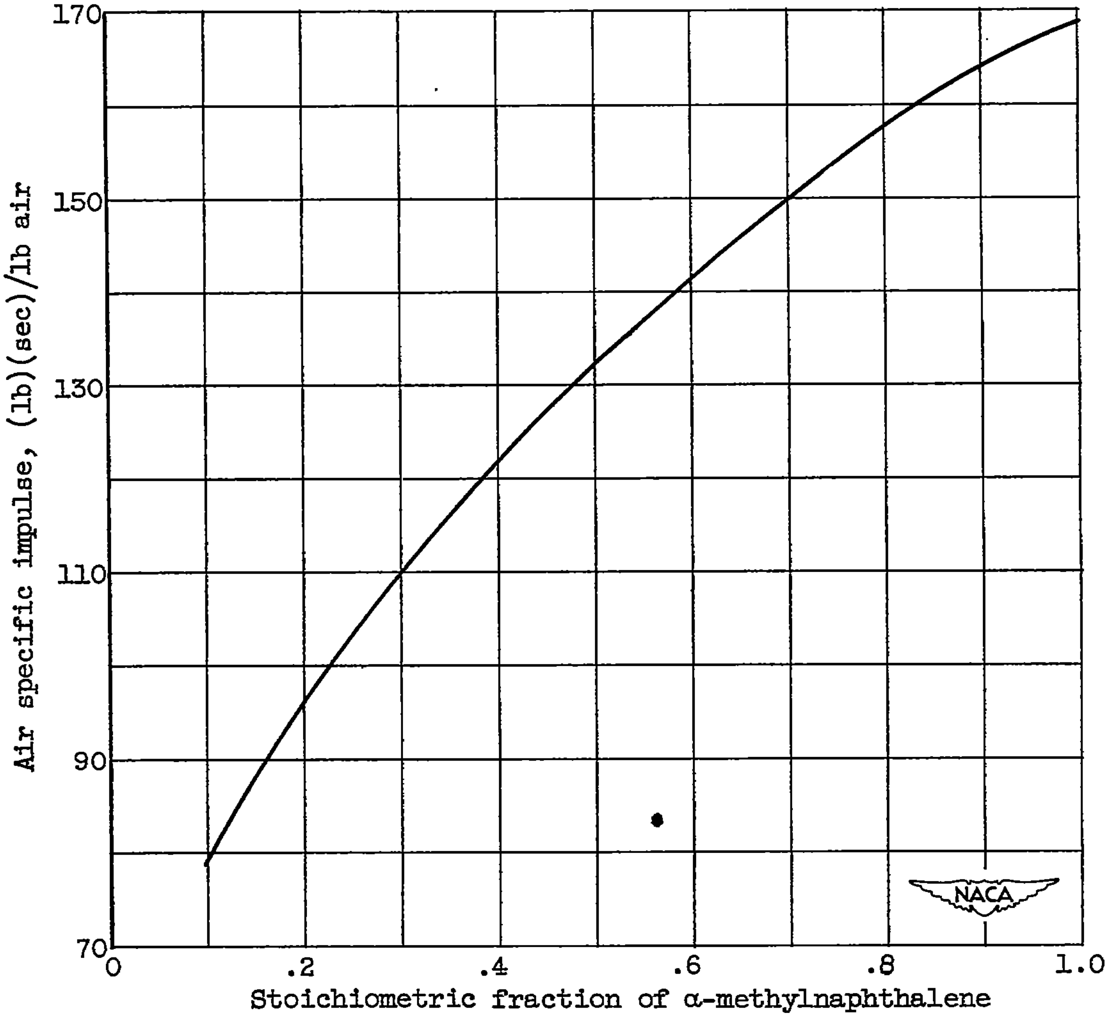


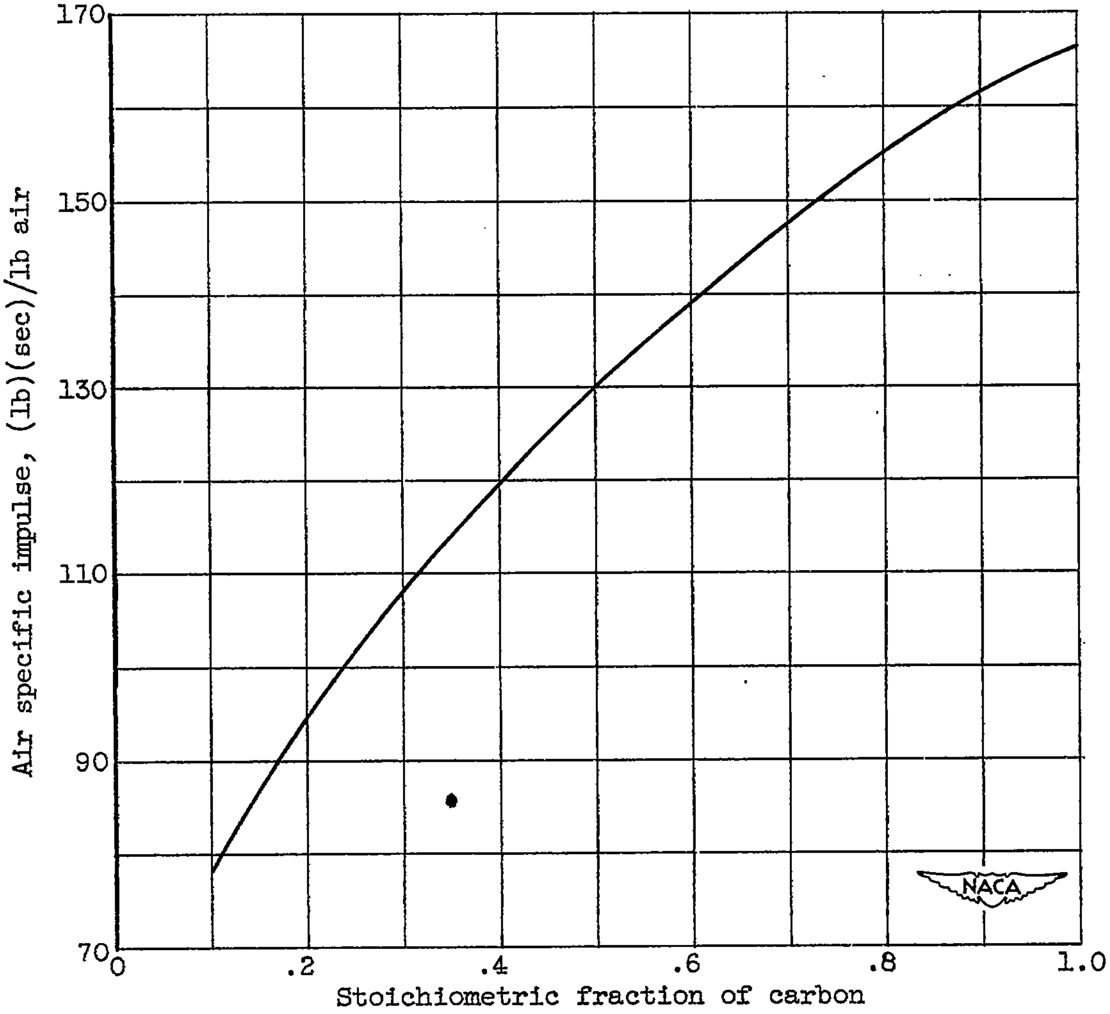
(a) Hydrogen.

Figure 2. - Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



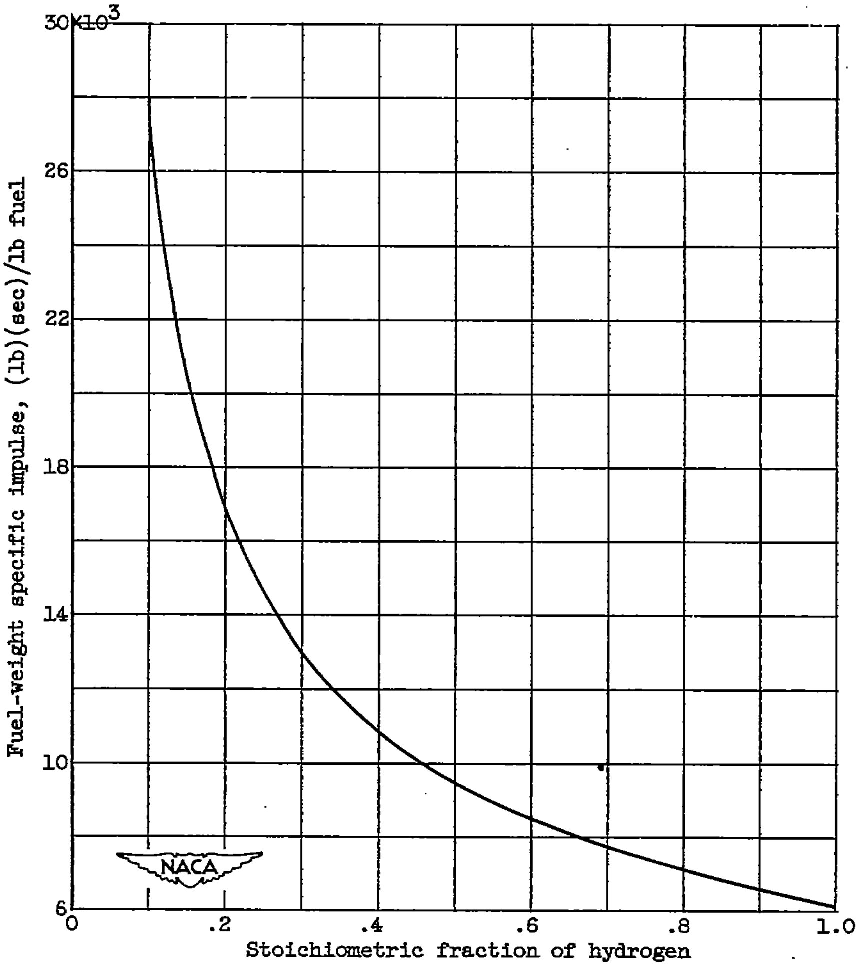
(b) α-Methylnaphthalene.

Figure 2. - Continued. Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(c) Carbon.

Figure 2. - Concluded. Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(a) Hydrogen.

Figure 3. - Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

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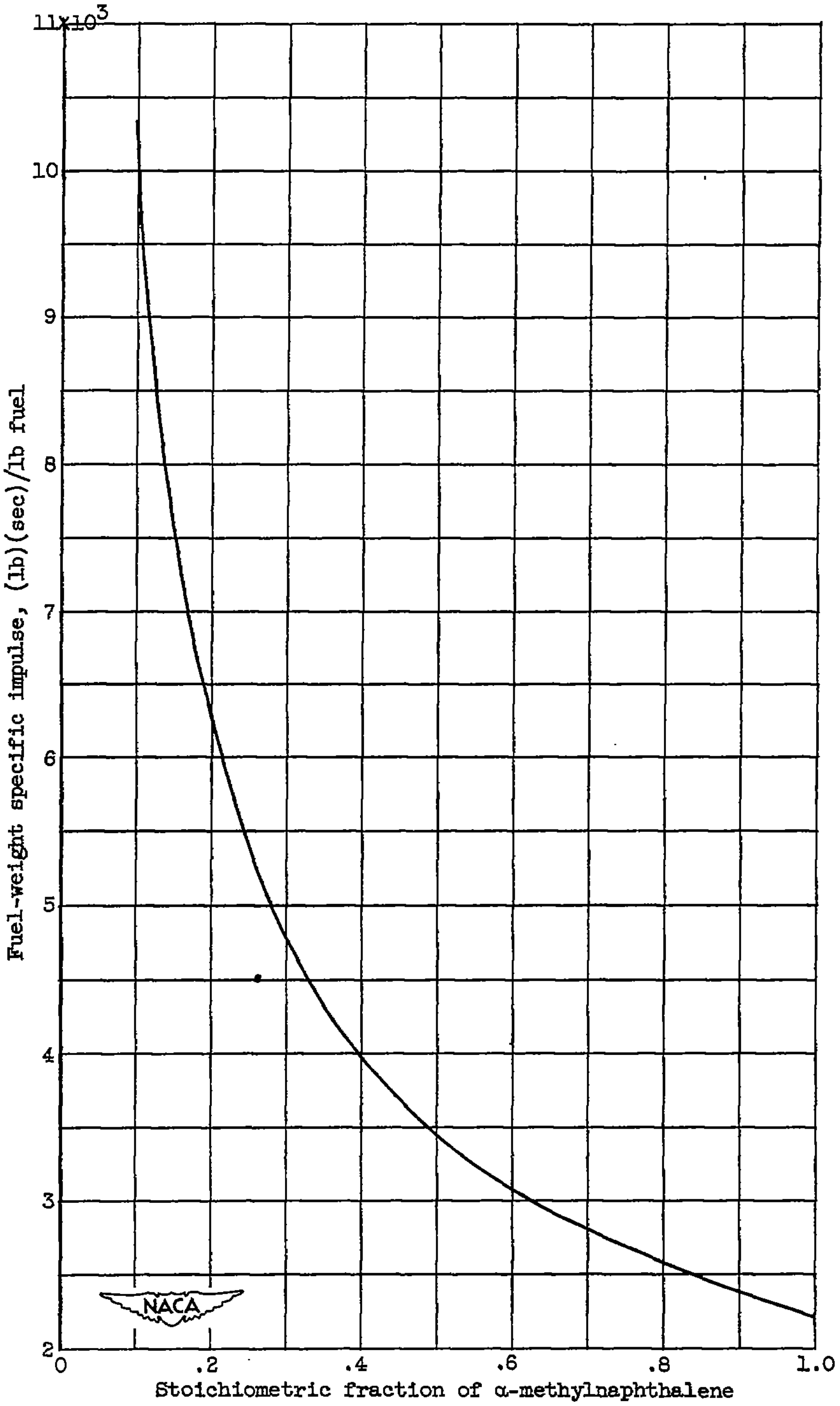
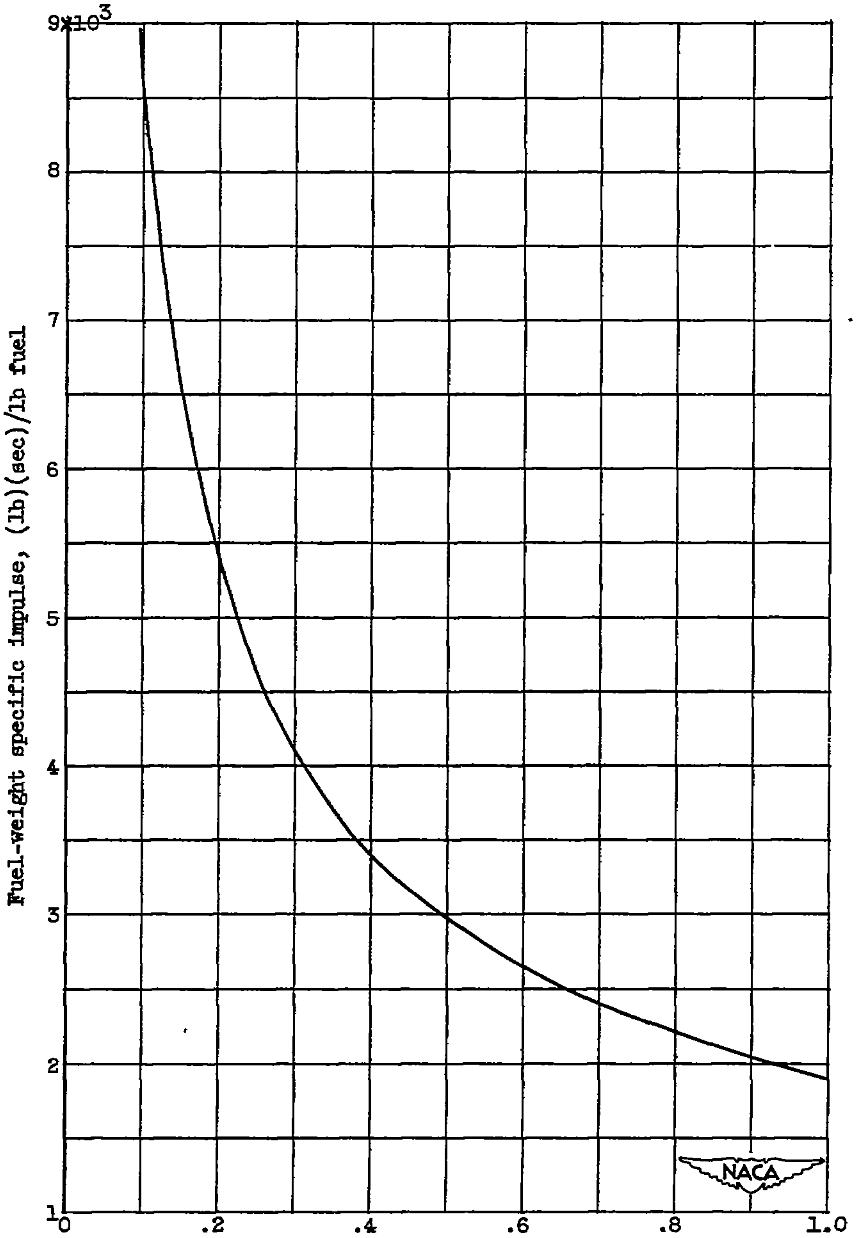


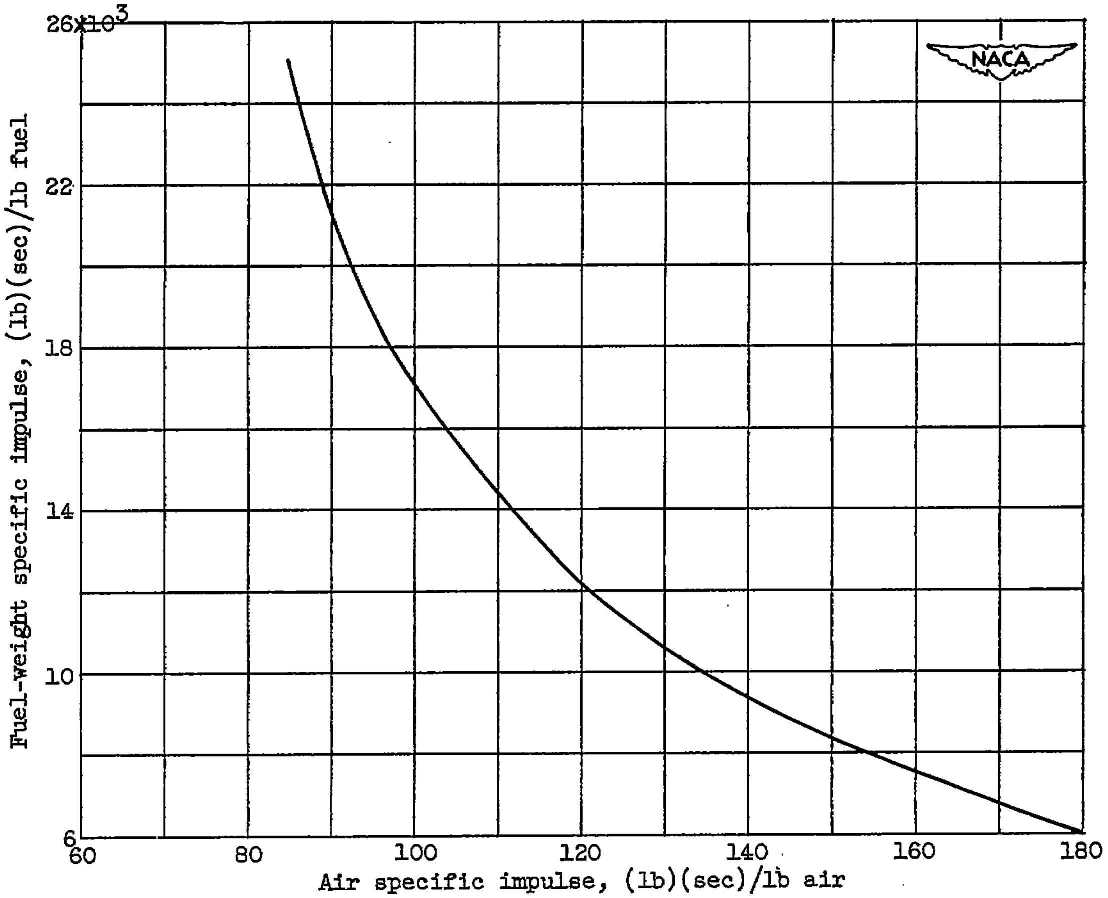
(b) α-Methylnaphthalene.

Figure 3. - Continued. Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



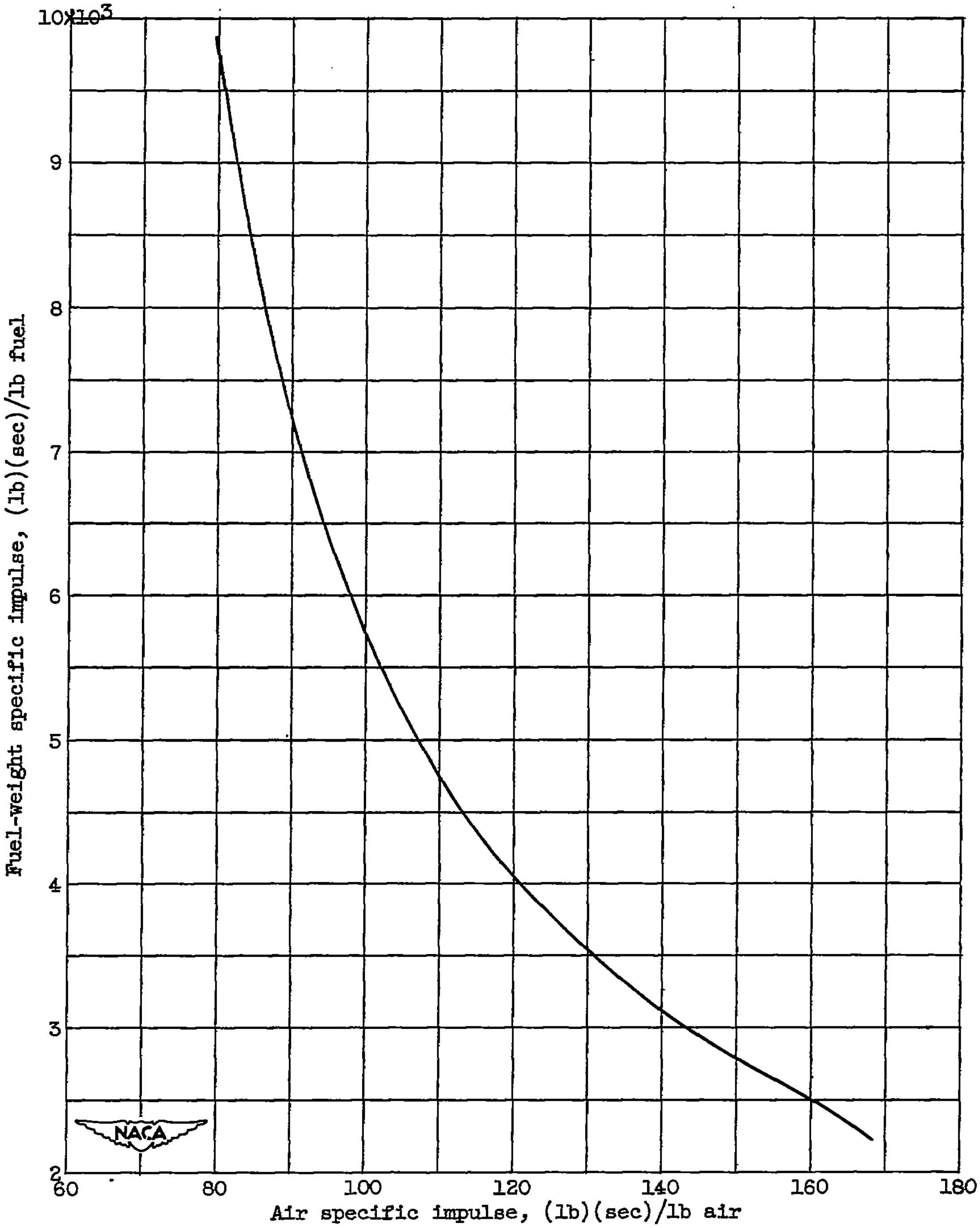
(c) Carbon.

Figure 3. - Concluded. Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(a) Hydrogen.

Figure 4. - Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(b) α-Methylnaphthalene.

Figure 4. - Continued. Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

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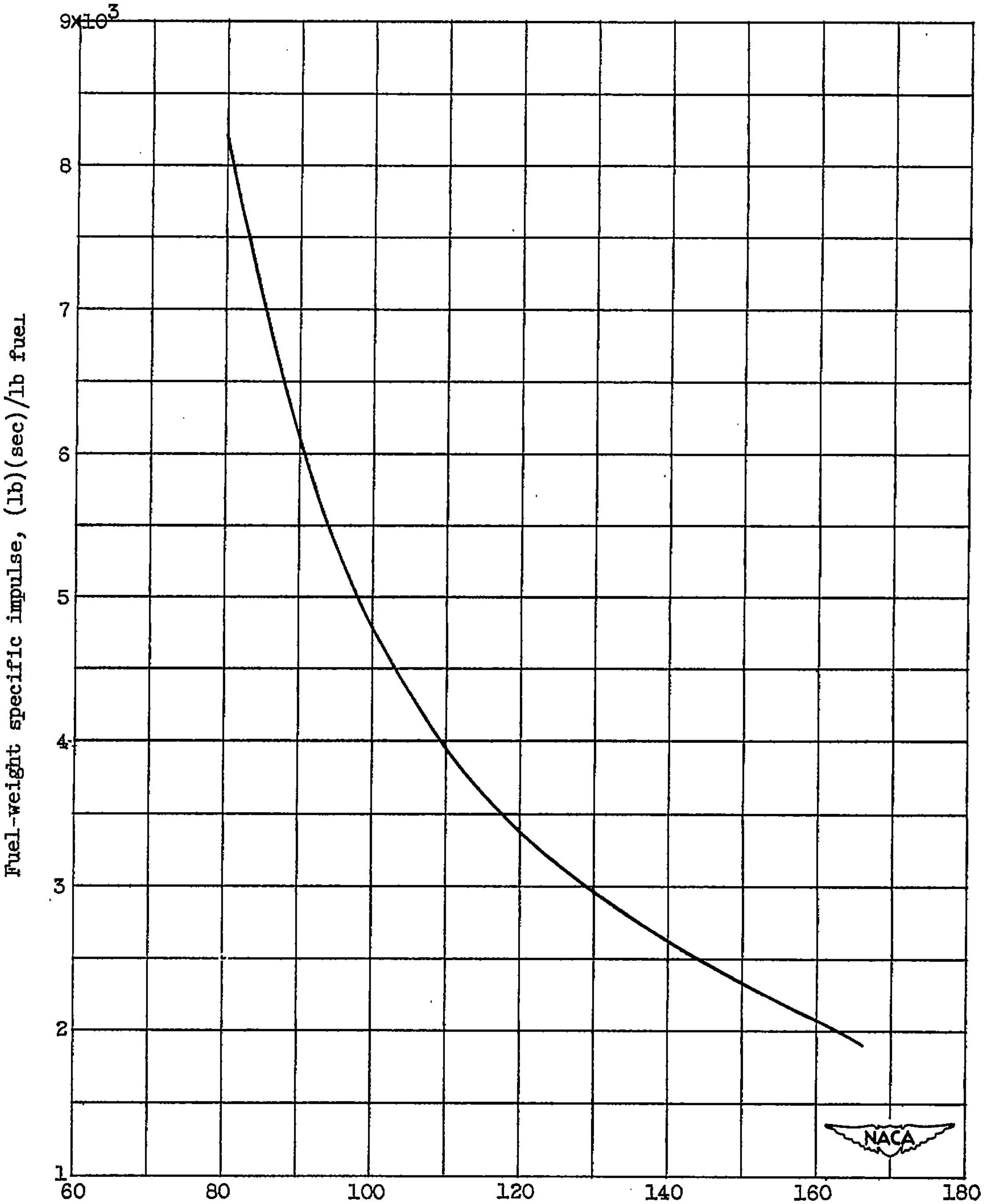

(c) Carbon.

Figure 4. - Concluded. Variation of fuel-weight specific impulse with air specific impulse for several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

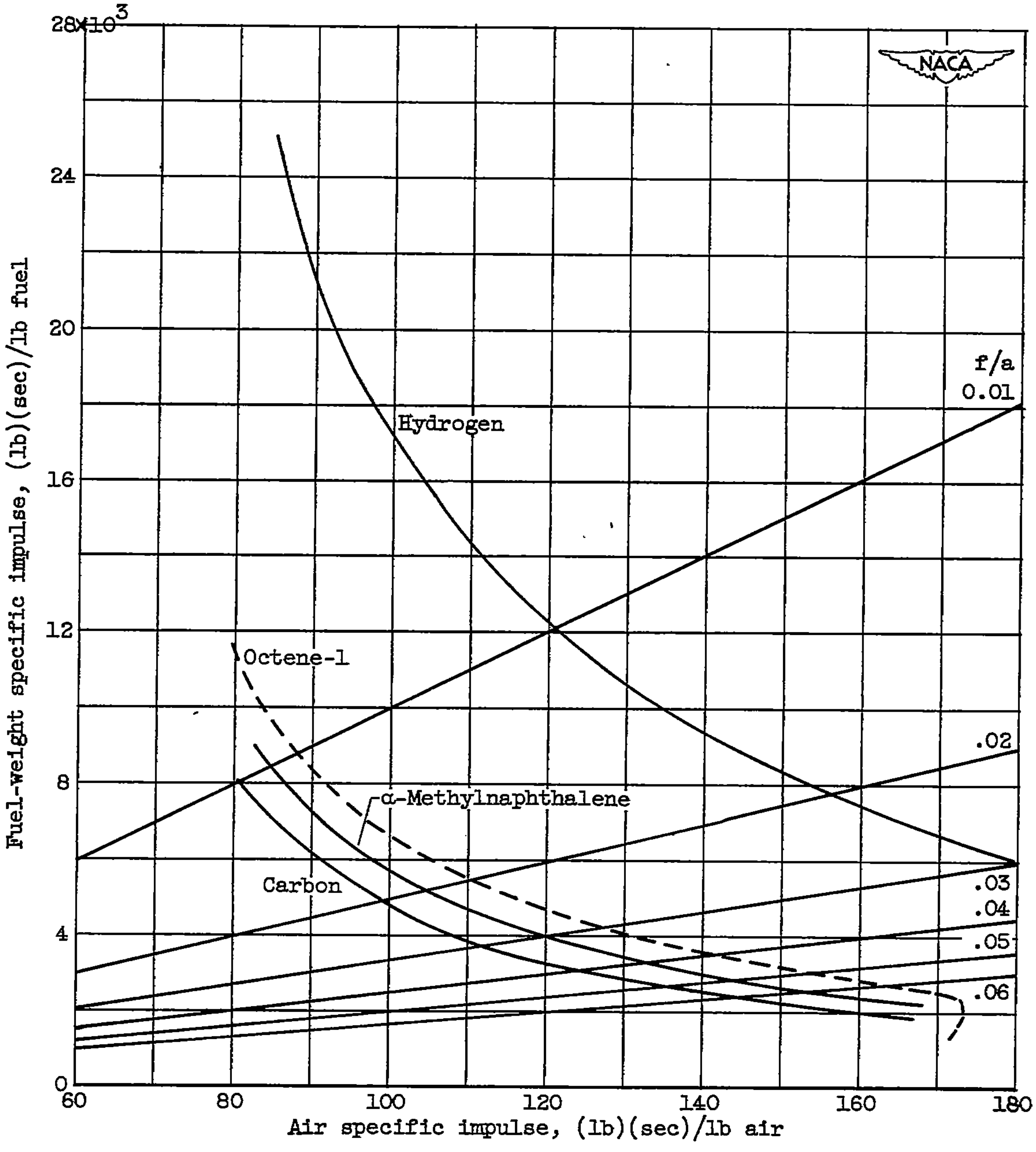

Figure 5. - Comparison of air and fuel-weight specific-impulse characteristics of hydrogen, α-methylnaphthalene, and graphite carbon with octene-1.

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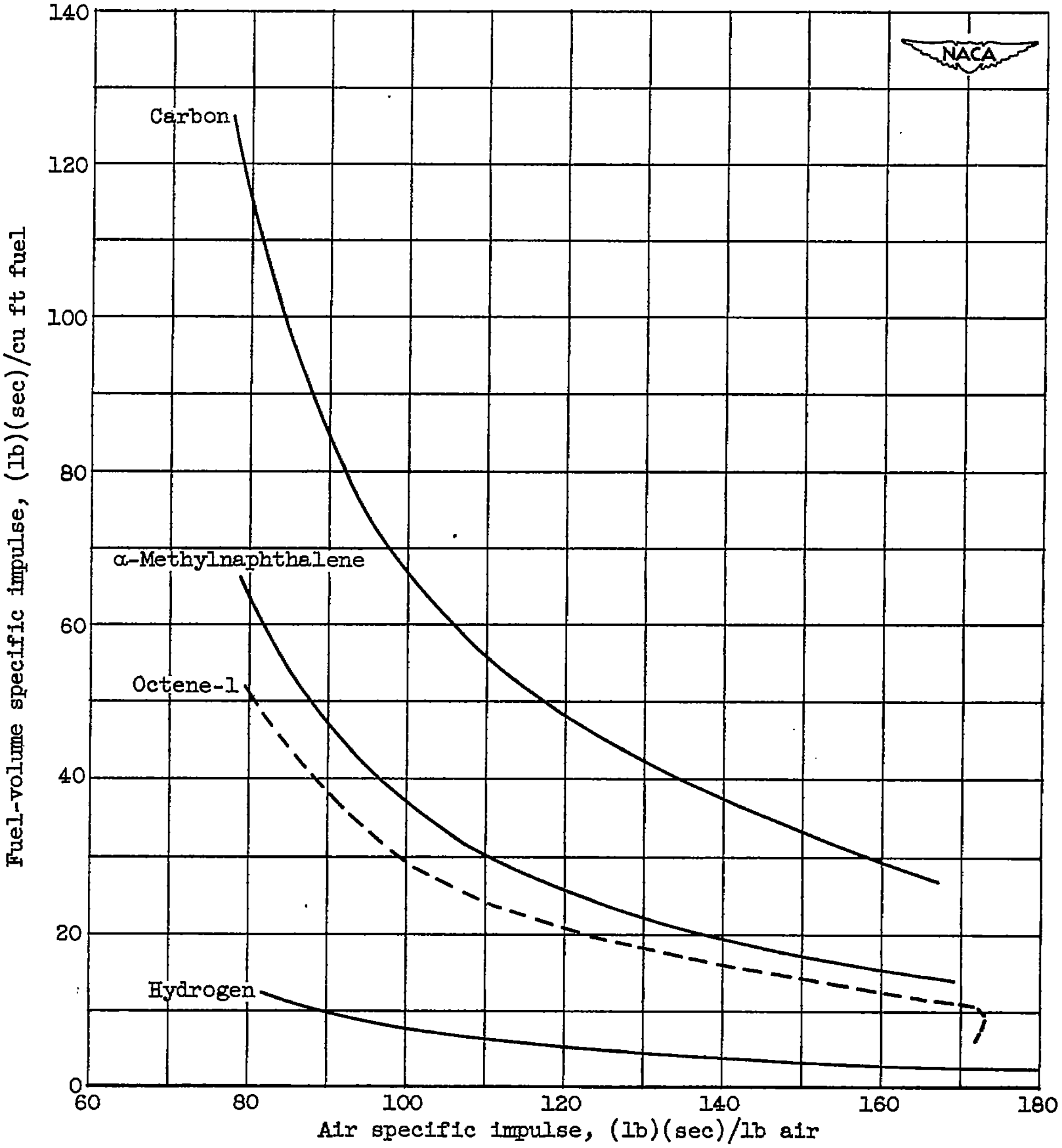

Figure 6. - Comparison of air and fuel-volume specific-impulse characteristics of hydrogen, α-methylnaphthalene, and graphite carbon with octene-1.

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