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# RESEARCH MEMORANDUM

## THEORETICAL MAXIMUM PERFORMANCE OF LIQUID FLUORINE - LIQUID OXYGEN MIXTURES WITH JP-4 FUEL AS ROCKET PROPELLANTS

By Sanford Gordon and Roger L. Wilkins

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Cleveland, Ohio

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# THEORETICAL MAXIMUM PERFORMANCE OF LIQUID FLUORINE - LIQUID OXYGEN MIXTURES WITH JP-4 FUEL AS ROCKET PROPELLANTS

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## SUMMARY

Theoretical values of rocket performance parameters were calculated for JP-4 fuel and various mixtures of liquid fluorine and liquid oxygen, assuming both equilibrium and frozen composition during the expansion process. Data were calculated at several equivalence ratios for each assigned fluorine-oxygen mixture.

The parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse for a chamber pressure of 300 pounds per square inch absolute and an exit pressure of 1 atmosphere (expansion ratio, 20.41) is 299.4 pound-seconds per pound for equilibrium composition and 278.9 pound-seconds per pound for frozen composition. These values occur at 69.75 weight percent fluorine in the oxidant and 20.90 weight percent fuel in the propellant.

## INTRODUCTION

Considerable interest has been shown recently in the use of mixtures of liquid fluorine and liquid oxygen as oxidants with hydrocarbons as fuel for possible high-energy rocket propellants (refs. 1 to 3). Mixtures of fluorine and oxygen exist that give higher performance with hydrocarbons than either 100-percent oxygen or fluorine because the fluorine burns preferentially with the hydrogen and the oxygen with the carbon.

Theoretical performance calculations of a typical JP-4 fuel with various mixtures of fluorine and oxygen were made at the NACA Lewis laboratory, (1) to provide data in support of an experimental program, (2) to determine the maximum performance for any assigned fluorine-oxygen mixture as a function of equivalence ratio, and (3) to determine the maximum performance of the propellant as a function of both fluorine-oxygen mixture and equivalence ratio.

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The data were calculated on the basis of both equilibrium and frozen composition during expansion. The performance parameters included are specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

## SYMBOLS

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The following symbols are used in this report:

$A$ nozzle area, sq ft

$a$ local velocity of sound, ft/sec

$C_F$ coefficient of thrust, $Ig/c^*$

$c^*$ characteristic velocity, $gP_cA_t/w$, ft/sec

$g$ acceleration due to gravity, 32.174 ft/sec$^2$

$H_T^o$ sum of sensible enthalpy and chemical energy, cal/mole

$h$ sum of sensible enthalpy and chemical energy per unit weight, $\frac{\sum_i n_i(H_T^o)_i}{nM}$, cal/g

$I$ specific impulse, lb-sec/lb

$M$ molecular weight

$n$ number of moles

$P$ pressure

$r$ equivalence ratio, ratio of four times the number of carbon atoms plus the number of hydrogen atoms to twice the number of oxygen atoms plus the number of fluorine atoms

$T$ temperature, $^oK$

$w$ rate of flow, lb/sec

$\alpha$ ratio of equivalent oxidant formulas $OF_\beta$ to equivalent fuel formulas $CH_\gamma$

Subscripts:

c combustion chamber

e nozzle exit

i product of combustion

t nozzle throat

$\beta$ fluorine-to-oxygen atom ratio

$\gamma$ hydrogen-to-carbon atom ratio

## CALCULATION OF PERFORMANCE DATA

The computations were carried out by means of the method described in reference 4 with modifications to adapt it for use with an IBM Card-Programmed Electronic Calculator. The machine was operated with floating decimal point notation and eight significant figures. The successive approximation process which was used to calculate the desired values of the assigned parameters (mass balance and pressure or entropy balance) was continued until seven-figure accuracy was reached.

Assumptions. - The calculations were based on the following usual assumptions: perfect gas law, adiabatic combustion at constant pressure, isentropic expansion, no friction, homogeneous mixing, and one-dimensional flow. The products of combustion were assumed to be graphite and the following ideal gases: atomic carbon C, carbon monofluoride CF, carbon difluoride $CF_2$, carbon trifluoride $CF_3$, carbon tetrafluoride $CF_4$, difluoroacetylene $C_2F_2$, methane $CH_4$, carbon monoxide CO, carbon dioxide $CO_2$, atomic fluorine F, fluorine $F_2$, atomic hydrogen H, hydrogen $H_2$, hydrogen fluoride HF, water $H_2O$, atomic oxygen O, oxygen $O_2$, and hydroxyl radical OH.

Thermodynamic data. - The thermodynamic data for all combustion products except graphite, methane, the fluorocarbons, and water were taken from reference 4. Data for graphite were taken from reference 5, carbon monofluoride from reference 6, the remainder of the fluorocarbons from reference 7, and water from reference 8. Data for methane were determined by the rigid-rotator-harmonic-oscillator approximation using spectroscopic data taken from reference 9.

The dissocation energy of $F_2$ was taken to be 35.6 kilocalories per mole and the heat of sublimation of graphite at 298.16° K was taken to be 171.698 kilocalories per mole (ref. 10).



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Physical and thermochemical data. - The JP-4 fuel used in these calculations was assumed to have a hydrogen-to-carbon weight ratio of 0.163 (atom ratio $\gamma = 1.942$) and a lower heat of combustion value of 18,640 Btu per pound. Additional properties of jet fuels may be found in reference 11. Several properties of the oxidants taken from references 4, 10, 12, and 13 are listed in table I.

Formulas. - The formulas used in computing the various parameters are as follows:

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Specific impulse, lb-sec/lb

$$I = 294.98\sqrt{\frac{h_c - h_e}{1000}} \tag{1}$$

Throat area per unit flow rate, (sq ft)(sec)/lb (pressure in atm)

$$\frac{A_t}{w} = \frac{1.3144T_t}{P_t M_t a} \tag{2}$$

Characteristic velocity, ft/sec

$$c^* = \frac{gP_c A_t}{w} = \frac{32.174P_c A_t}{w} \tag{3}$$

Coefficient of thrust

$$C_F = \frac{Ig}{c^*} = \frac{32.174I}{c^*} \tag{4}$$

Nozzle-exit area per unit flow rate, (sq ft)(sec)/lb (pressure in atm)

$$\frac{A_e}{w} = \frac{0.040853T_e}{P_e M_e I} \tag{5}$$

Ratio of nozzle-exit area to throat area

$$\frac{A_e}{A_t} = \frac{A_e/w}{A_t/w} \tag{6}$$

## THEORETICAL PERFORMANCE DATA

The calculated values of performance parameters were obtained for 12 fluorine-oxygen ratios for a combustion pressure of 300 pounds per

square inch absolute and an exit pressure of 1 atmosphere. For each assigned fluorine-oxygen mixture, the following scheme was used to calculate an equivalence ratio for which specific impulse is near maximum:

Let the equivalent formula of the propellant be

$$CH_\gamma + \alpha(OF_\beta)$$

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Then by definition the equivalence ratio becomes

$$r = \frac{4 + \gamma}{\alpha(2 + \beta)}$$

For $\beta \leq \gamma$ and assuming products to be CO, HF, and $H_2O$,

$$\alpha = \frac{2 + \gamma}{2 + \beta} \quad \text{and} \quad r = \frac{4 + \gamma}{2 + \gamma} \tag{7}$$

For $\beta > \gamma$ and assuming products to be graphite, CO, and HF,

$$\alpha = \frac{\gamma}{\beta} \quad \text{and} \quad r = \frac{\beta(4 + \gamma)}{\gamma(2 + \beta)} \tag{8}$$

The simplified set of combustion products was used only to estimate the equivalence ratio giving near maximum specific impulse, whereas the actual calculations included all the combustion products considered in this report. For each of the 12 fluorine-oxygen mixtures, performance data were obtained for three equivalence ratios, including the one given by equation (7) or (8). The calculated values of specific impulse, with both equilibrium and frozen composition assumed during expansion, are given in table II. The values of the other performance parameters and the composition of the combustion products (corresponding to the eqivalence ratios for which equilibrium specific impulse is maximum) are given in tables III and IV for each of the 12 fluorine-oxygen mixtures. The mole fractions of $CF_4$, $CH_4$, and $F_2$ were omitted from table IV inasmuch as they were always less than 0.00001.

Parameters. - The parameters are plotted in figures 1 to 5. Figure 1 indicates the variation of specific impulse with weight percent fluorine in the oxidant for both equilibrium and frozen composition during the expansion process at the equivalence ratio for which equilibrium specific impulse is maximum. The maximum value of specific impulse is 299.4 pound-seconds per pound for equilibrium composition and 278.9 pound-seconds per pound for frozen composition. These maximum values occur at 69.75 weight percent fluorine in the oxidant and 20.90 weight percent fuel in the propellant. The oxidant mixture has the same fluorine-to-oxygen atom ratio as the hydrogen-to-carbon atom

ratio in the fuel (1.942). For this oxidant mixture, the 20.90 weight percent fuel in the propellant is the one in which the number of H atoms equals the number of F atoms and the number of C atoms equals the number of O atoms. These atom ratios may be represented by the equivalent formula $CH_{1.942} + OF_{1.942}$. This formula is consistent with the assumption that hydrogen burns preferentially with fluorine and carbon with oxygen.

A comparison of the maximum values of specific impulse for JP-4 fuel with 69.75 weight percent fluorine in the oxidant, 100 percent fluorine, and 100 percent oxygen is shown in the following table: 3473

| Composition | 69.75 percent $F_2$ 30.25 percent $O_2$ by weight | Fluorine | | Oxygen | |
|---|---|---|---|---|---|
| | Specific impulse, I | Specific impulse, I | Decrease, percent | Specific impulse, I | Decrease, percent |
| Equilibrium | 299.4 | 278.9 | 7.4 | 260.7 | 14.8 |
| Frozen | 278.9 | 264.6 | 5.4 | 250.4 | 11.4 |

The curves of $c^*$, $C_F$, $T_c$, $T_e$, $M_c$, $M_e$, and $A_e/A_t$ against weight percent fluorine in the oxidant, given in figures 2 to 5, are not necessarily the maximum values but correspond to the equivalence ratio for which equilibrium specific impulse is the maximum. The break in the curves at about 75 weight percent fluorine in the oxidant is due to the formation of graphite.

Effect of thermodynamic data on performance. - Calculations in reference 14 show that if the carbon vapor evaporating from a graphite surface is assumed to contain the three species, monatomic carbon C, diatomic carbon $C_2$, and triatomic carbon $C_3$, then $C_2$ and $C_3$ comprise a considerable part of the vapor. In order to determine the effect on specific impulse if $C_2$ and $C_3$ were included as combustion products, additional calculations were made for 74.80 weight percent fluorine in the oxidant. This percent fluorine is near the point for maximum specific impulse and contains the largest mole fraction of C (table IV). The effect on specific impulse was small as may be seen from the following table:

| Specific impulse, I, lb-sec/lb | $C_2$ and $C_3$ not included in combustion products | $C_2$ and $C_3$ included in combustion products | Decrease, percent |
|---|---|---|---|
| Equilibrium | 294.0 | 293.1 | 0.31 |
| Frozen | 272.4 | 271.1 | .48 |

The effect on specific impulse should be less than shown in the preceding table for oxidants containing less fluorine.

The thermodynamic functions for $C_2$ and $C_3$ were obtained by the rigid-rotator-harmonic-oscillator approximation using the spectroscopic data of reference 15 for $C_2$ and the spectroscopic data suggested in reference 14 for $C_3$. The heats of formation for $C_2$ and $C_3$ were taken from reference 14.

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According to reference 7, the thermodynamic functions for $CF_2$, $CF_3$, and $C_2F_2$ must be regarded as tentative. However, inasmuch as the mole fractions of these substances are small (table IV), even large changes in their thermodynamic functions are expected to have only a small effect on performance.

The "low" value for the heat of dissociation of $F_2$, 35.6 kilocalories per mole, and the "high" value for the heat of sublimation of graphite, 171.698 kilocalories per mole at 298.16° K, which were chosen for the calculations in this report, are still open to question. The low value for $F_2$ tends to keep the theoretical performance low, whereas the high value for graphite tends to keep it high.

## SUMMARY OF RESULTS

A theoretical investigation of the performance of JP-4 fuel with liquid fluorine - liquid oxygen mixtures for a combustion pressure of 300 pounds per square inch absolute and isentropic expansion to 1 atmosphere, assuming equilibrium and frozen composition during the expansion process, gave the following results:

1. The maximum value of specific impulse was obtained at 69.75 weight percent fluorine in the oxidant and 20.90 weight percent fuel in the propellant. The oxidant mixture is the one for which the fluorine-oxygen atom ratio equals the hydrogen-carbon atom ratio. For this oxidant mixture, the weight percent fuel in the propellant of 20.90 is the one for which the number of H atoms equals the number of F atoms and the number of C atoms equals the number of O atoms. These atom ratios may be represented by the following equivalent formula $CH_{1.942} + OF_{1.942}$.

2. The maximum value of specific impulse assuming equilibrium composition was 299.4 pound-seconds per pound. This is a 14.8 percent increase over the maximum value of 260.7 pound-seconds per pound for JP-4 fuel with liquid oxygen and a 7.4 percent increase over the maximum value of 278.9 pound-seconds per pound for JP-4 fuel with liquid fluorine.

3. The maximum value of specific impulse assuming frozen composition was 278.9 pound-seconds per pound. This is an 11.4 percent increase over the maximum value of 250.4 pound-seconds per pound for JP-4 fuel with liquid oxygen and a 5.4 percent increase over the maximum value of 264.6 pound-seconds per pound for JP-4 fuel with liquid fluorine.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 11, 1954

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TABLE I. - PROPERTIES OF LIQUID OXIDANTS

| Properties | Oxygen, $O_2$ | Fluorine, $F_2$ |
|---|---|---|
| Molecular weight, M | 32.00 | 38.00 |
| Density, g/cc | [a]1.1415 (at -182.0° C) | [b]1.54 (at -196° C) |
| Freezing point, °C | [c]-218.76 | [c]-217.96 |
| Boiling point, °C | [c]-182.97 | [c]-187.92 |
| Enthalpy required to convert liquid at boiling point to gas at 25° C | [d]3.080 | [d]3.030 |
| Enthalpy of vaporization, kcal/mole | [c]1.630 (at -182.97° C) | [c]1.51 (at -187.92° C) |
| Enthalpy of fusion, kcal/mole | [c].106 (at -218.76° C) | [c].372 (at -217.96° C) |

[a]Ref. 12.
[b]Ref. 13.
[c]Ref. 10.
[d]Ref. 4.

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TABLE II. - THEORETICAL SPECIFIC IMPULSE FOR JP-4 FUEL WITH

LIQUID FLUORINE - LIQUID OXYGEN MIXTURES

[Combustion-chamber pressure, 300 lb/sq in. abs; exit pressure, 1 atm.]

| Fluorine-to-oxygen atom ratio, β | Weight percent fluorine in oxidant | Equivalence ratio, r | Weight percent fuel in propellant | Specific impulse, I, lb-sec/lb | |
|---|---|---|---|---|---|
| | | | | Equilibrium composition | Frozen composition |
| 0 | 0 | 1.30 | 27.64 | 259.3 | 246.5 |
| | | [a]1.51 | 30.70 | 260.7 | 250.0 |
| | | 1.60 | 31.98 | 259.6 | 250.4 |
| 0.2 | 19.19 | 1.50 | 28.15 | 269.4 | 255.9 |
| | | [a]1.51 | 28.26 | 269.4 | 256.0 |
| | | 1.54 | 28.68 | 269.3 | 256.3 |
| 0.5 | 37.25 | 1.50 | 25.69 | 278.3 | 262.4 |
| | | [a]1.51 | 25.79 | 278.4 | 262.5 |
| | | 1.60 | 26.94 | 278.2 | 263.4 |
| 1.0 | 54.29 | [a]1.51 | 23.30 | 288.4 | 270.6 |
| | | 1.55 | 23.80 | 288.5 | 271.1 |
| | | 1.60 | 24.38 | 288.4 | 271.7 |
| 1.6 | 65.52 | [a]1.51 | 21.57 | 296.6 | 276.9 |
| | | 1.60 | 22.59 | 297.1 | 278.8 |
| | | 1.70 | 23.67 | 294.2 | 277.0 |
| 1.942 | 69.75 | 1.50 | 20.81 | 299.2 | 278.7 |
| | | [a]1.51 | 20.90 | 299.4 | 278.9 |
| | | 1.52 | 21.03 | 299.0 | 278.6 |
| 2.0 | 70.37 | 1.40 | 19.60 | 296.0 | 275.8 |
| | | 1.48 | 20.49 | 298.9 | 278.4 |
| | | [b]1.53 | 21.04 | 298.1 | 277.7 |
| 2.1 | 71.38 | 1.40 | 19.44 | 295.7 | 276.1 |
| | | 1.50 | 20.55 | 297.5 | 277.1 |
| | | [b]1.57 | 21.28 | 296.8 | 276.2 |
| 2.2 | 72.32 | 1.45 | 19.85 | 296.4 | 276.5 |
| | | 1.50 | 20.40 | 296.4 | 276.1 |
| | | [b]1.60 | 21.46 | 295.8 | 275.0 |
| 2.5 | 74.80 | 1.65 | 21.56 | 293.9 | 272.3 |
| | | [b]1.70 | 22.07 | 294.0 | 272.4 |
| | | 1.75 | 22.57 | 293.9 | 272.8 |
| 4.0 | 82.61 | 2.00 | 23.47 | 289.1 | 270.0 |
| | | [b]2.04 | 23.82 | 289.2 | 270.3 |
| | | 2.20 | 25.22 | 288.7 | 271.2 |
| ∞ | 100 | 3.00 | 27.07 | 278.6 | 264.2 |
| | | [b]3.06 | 27.46 | 278.9 | 264.6 |
| | | 3.50 | 30.22 | 278.0 | 266.0 |

[a]See eq. (7).
[b]See eq. (8).

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TABLE III. - CALCULATED PERFORMANCE OF JP-4 FUEL WITH LIQUID FLUORINE - LIQUID OXYGEN MIXTURES

[Combustion-chamber pressure, 300 lb/sq in. abs; exit pressure, 1 atm; equilibrium and frozen composition assumed during expansion.]

| Weight percent fluorine in oxidant | Weight percent fuel in propellant | Equivalence ratio, r | Specific impulse, I, $\frac{\text{lb-sec}}{\text{lb}}$ | Characteristic velocity, $c^*$, ft/sec | Coefficient of thrust, $C_F$ | Combustion chamber temperature, $T_c$, °K | Nozzle exit temperature, $T_e$, °K | Ratio of nozzle-exit area to throat area, $A_e/A_t$ | Mean molecular weight in combustion chamber, $M_c$ | Mean molecular weight at nozzle exit, $M_e$ |
|---|---|---|---|---|---|---|---|---|---|---|
| (a) Equilibrium composition. | | | | | | | | | | |
| 00.00 | 30.70 | 1.51 | 260.7 | 5887 | 1.425 | 3428 | 2412 | 3.885 | 21.83 | 22.97 |
| 19.19 | 28.26 | 1.51 | 269.4 | 6076 | 1.427 | 3584 | 2570 | 3.913 | 21.37 | 22.78 |
| 37.25 | 25.79 | 1.51 | 278.4 | 6278 | 1.427 | 3767 | 2721 | 3.919 | 20.95 | 22.56 |
| 54.29 | 23.80 | 1.55 | 288.5 | 6523 | 1.423 | 4010 | 2826 | 3.852 | 20.50 | 22.13 |
| 65.52 | 22.59 | 1.60 | 297.1 | 6739 | 1.418 | 4255 | 2893 | 3.759 | 20.35 | 21.83 |
| 69.75 | 20.90 | 1.[illegible]1 | 299.4 | 6768 | 1.423 | 4351 | 3080 | 3.858 | 20.71 | 22.37 |
| 70.37 | 20.49 | 1.48 | 298.9 | 6759 | 1.423 | 4359 | 3077 | 3.849 | 20.80 | 22.47 |
| 71.38 | 20.55 | 1.50 | 297.5 | 6723 | 1.424 | 4332 | 3076 | 3.865 | 20.91 | 22.59 |
| 72.32 | 20.40 | 1.50 | 296.4 | 6697 | 1.424 | 4321 | 3064 | 3.862 | 21.04 | 22.70 |
| 74.80 | 22.07 | 1.70 | 294.0 | 6617 | 1.429 | 4204 | 3118 | 3.984 | 21.42 | 22.85 |
| 82.61 | 23.82 | 2.04 | 289.2 | 6495 | 1.433 | 4184 | 3155 | 4.040 | 22.21 | 23.61 |
| 100.00 | 27.46 | 3.06 | 278.9 | 6240 | 1.438 | 4146 | 3219 | 4.140 | 24.03 | 25.37 |
| (b) Frozen composition. | | | | | | | | | | |
| 00.00 | 30.70 | 1.51 | 250.0 | 5733 | 1.403 | 3428 | 1929 | 3.500 | 21.83 | |
| 19.19 | 28.26 | 1.51 | 256.0 | 5890 | 1.398 | 3584 | 1935 | 3.410 | 21.37 | |
| 37.25 | 25.79 | 1.51 | 262.5 | 6061 | 1.394 | 3767 | 1945 | 3.314 | 20.95 | |
| 54.29 | 23.80 | 1.55 | 271.1 | 6280 | 1.389 | 4010 | 1978 | 3.219 | 20.50 | |
| 65.52 | 22.59 | 1.60 | 278.8 | 6468 | 1.387 | 4255 | 2048 | 3.170 | 20.35 | |
| 69.75 | 20.90 | 1.51 | 278.9 | 6474 | 1.386 | 4351 | 2075 | 3.152 | 20.71 | |
| 70.37 | 20.49 | 1.48 | 278.4 | 6464 | 1.386 | 4359 | 2075 | 3.147 | 20.80 | |
| 71.38 | 20.55 | 1.50 | 277.1 | 6432 | 1.386 | 4332 | 2072 | 3.157 | 20.91 | |
| 72.32 | 20.40 | 1.50 | 276.1 | 6407 | 1.386 | 4321 | 2074 | 3.164 | 21.04 | |
| 74.80 | 22.07 | 1.70 | 272.4 | 6304 | 1.390 | 4204 | 2105 | 3.249 | 21.42 | |
| 82.61 | 23.82 | 2.04 | 270.3 | 6228 | 1.396 | 4184 | 2218 | 3.369 | 22.21 | |
| 100.00 | 27.46 | 3.06 | 264.6 | 6047 | 1.408 | 4146 | 2435 | 3.597 | 24.03 | |

TABLE IV. - EQUILIBRIUM COMPOSITION IN COMBUSTION CHAMBER FOR JP-4 FUEL WITH LIQUID FLUORINE - LIQUID OXYGEN MIXTURES

[Combustion-chamber pressure, 500 lb/sq in. abs.]

| Weight percent fluorine in oxidant | 0 | 19.19 | 37.95 | 54.29 | 65.52 | 69.75 | 70.37 | 71.58 | 72.32 | 74.80 | 82.61 | 100.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight percent fuel in propellant | 30.70 | 28.28 | 25.79 | 23.80 | 22.59 | 20.90 | 20.48 | 20.56 | 20.40 | 22.07 | 25.82 | 27.48 |
| Equivalence ratio, $\tau$ | 1.508 | 1.508 | 1.508 | 1.550 | 1.600 | 1.508 | 1.480 | 1.500 | 1.500 | 1.700 | 2.040 | 3.060 |
| Equilibrium composition (mole fraction) | | | | | | | | | | | | |
| C | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00019 | 0.00004 | 0.00288 | 0.00375 | 0.00784 | 0.00638 | 0.00428 |
| Graphite | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .01138 | .11272 | .88354 |
| CF | .00000 | .00000 | .00000 | .00000 | .00000 | .00017 | .00004 | .00287 | .00403 | .00698 | .00625 | .00504 |
| $CF_2$ | .00000 | .00000 | .00000 | .00000 | .00000 | .00001 | .00000 | .00010 | .00015 | .00021 | .00021 | .00020 |
| $CF_3$ | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00001 | .00002 | .00002 | .00002 | .00002 |
| $C_2F_2$ | .00000 | .00000 | .00000 | .00000 | .00000 | .00001 | .00000 | .00230 | .00475 | .02414 | .02366 | .02269 |
| CO | .37285 | .35502 | .33841 | .33045 | .32741 | .30940 | .30486 | .29721 | .28979 | .25989 | .16314 | .00000 |
| $CO_2$ | .10707 | .07740 | .04840 | .01877 | .00168 | .00003 | .00017 | .00000 | .00000 | .00000 | .00000 | .00000 |
| F | .00080 | .00138 | .00563 | .02023 | .05696 | .10288 | .11393 | .10948 | .11205 | .06810 | .05716 | .04861 |
| H | .03959 | .05110 | .06431 | .08022 | .09040 | .07428 | .06910 | .06606 | .06259 | .07322 | .06694 | .05609 |
| $H_2$ | .12903 | .10623 | .07981 | .05031 | .02876 | .01453 | .01330 | .01217 | .01187 | .02235 | .02218 | .02176 |
| HF | .00000 | .15352 | .29921 | .42602 | .48614 | .49834 | .49858 | .50702 | .51159 | .53187 | .54133 | .55775 |
| $H_2O$ | .29805 | .19089 | .09500 | .02447 | .00124 | .00001 | .00006 | .00000 | .00000 | .00000 | .00000 | .00000 |
| O | .00808 | .01359 | .02094 | .02287 | .00490 | .00015 | .00077 | .00001 | .00001 | .00000 | .00000 | .00000 |
| $O_2$ | .00709 | .00932 | .00961 | .00426 | .00008 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| OH | .03829 | .04216 | .03930 | .02840 | .00248 | .00005 | .00022 | .00000 | .00000 | .00000 | .00000 | .00000 |

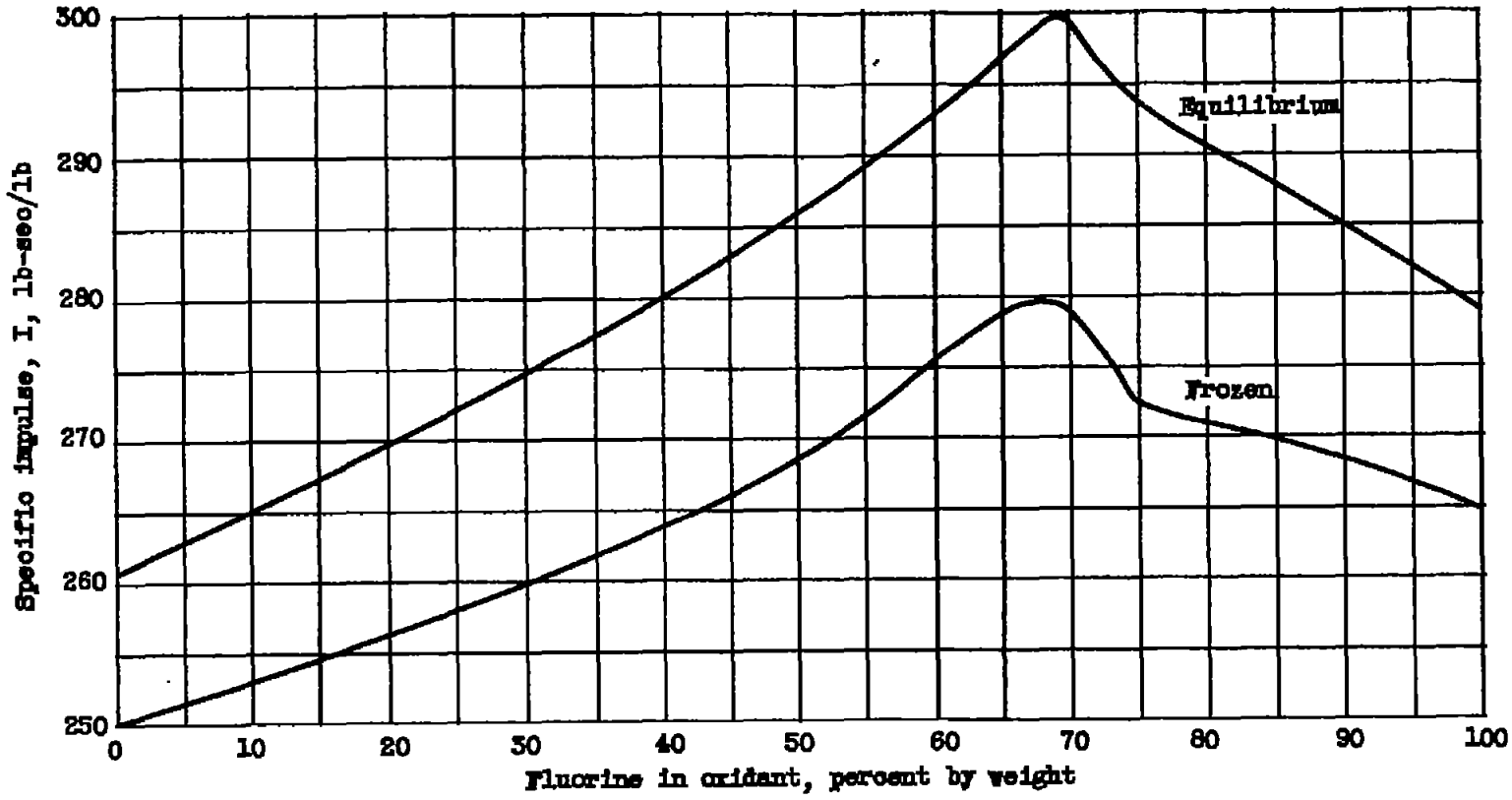


Figure 1. - Theoretical specific impulse of JP-4 fuel with liquid fluorine - liquid oxygen mixtures at equivalence ratios for which equilibrium specific impulse is maximum. Isentropic expansion from 300 pounds per square inch absolute to 1 atmosphere assuming equilibrium and frozen composition.

[redacted]

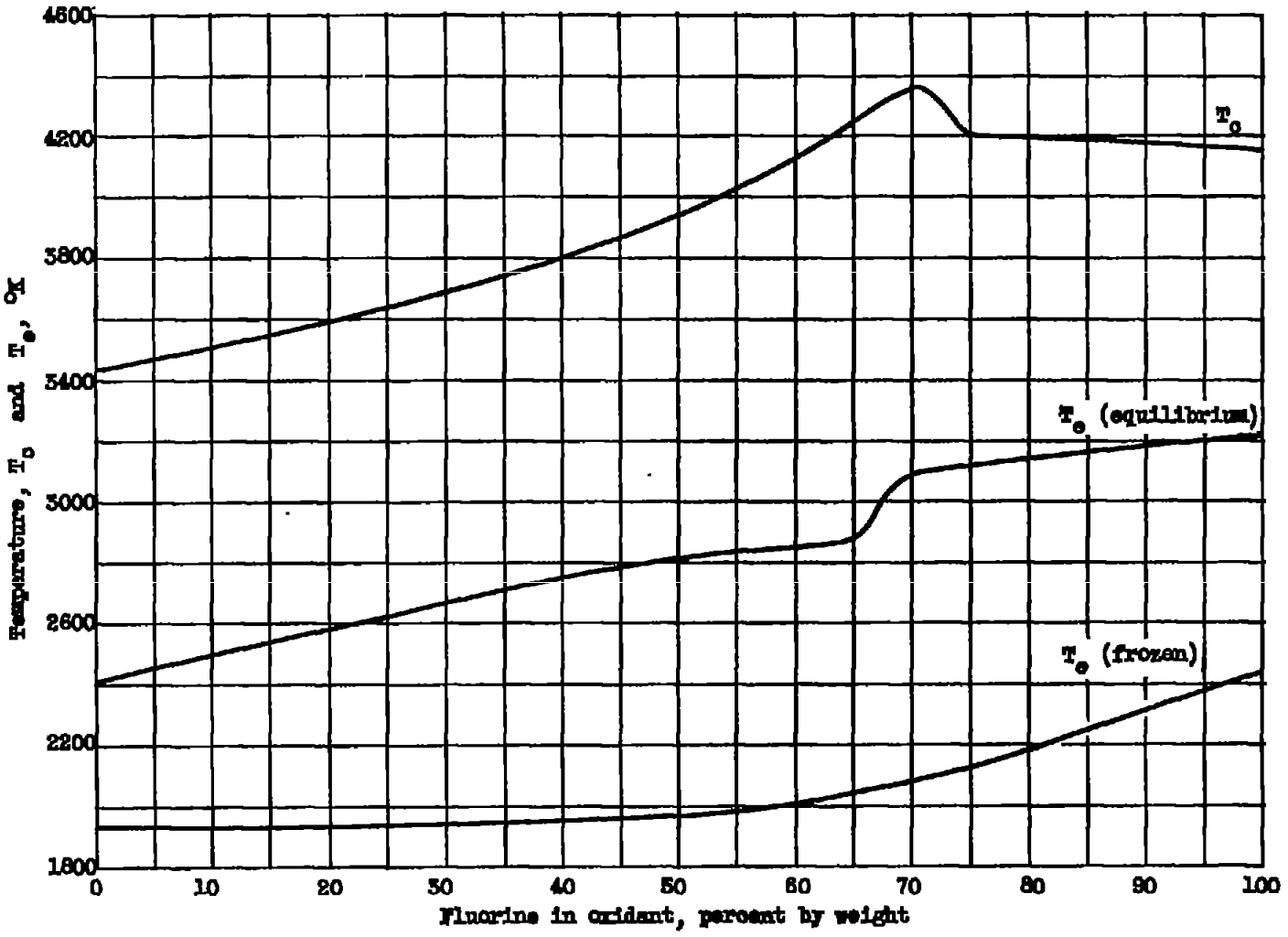


Figure 2. - Theoretical combustion-chamber temperature and nozzle-exit temperature of JP-4 fuel with liquid fluorine - liquid oxygen mixtures at equivalence ratios for which equilibrium specific impulse is maximum. Isentropic expansion from 300 pounds per square inch absolute to 1 atmosphere assuming equilibrium and frozen composition.

[redacted]

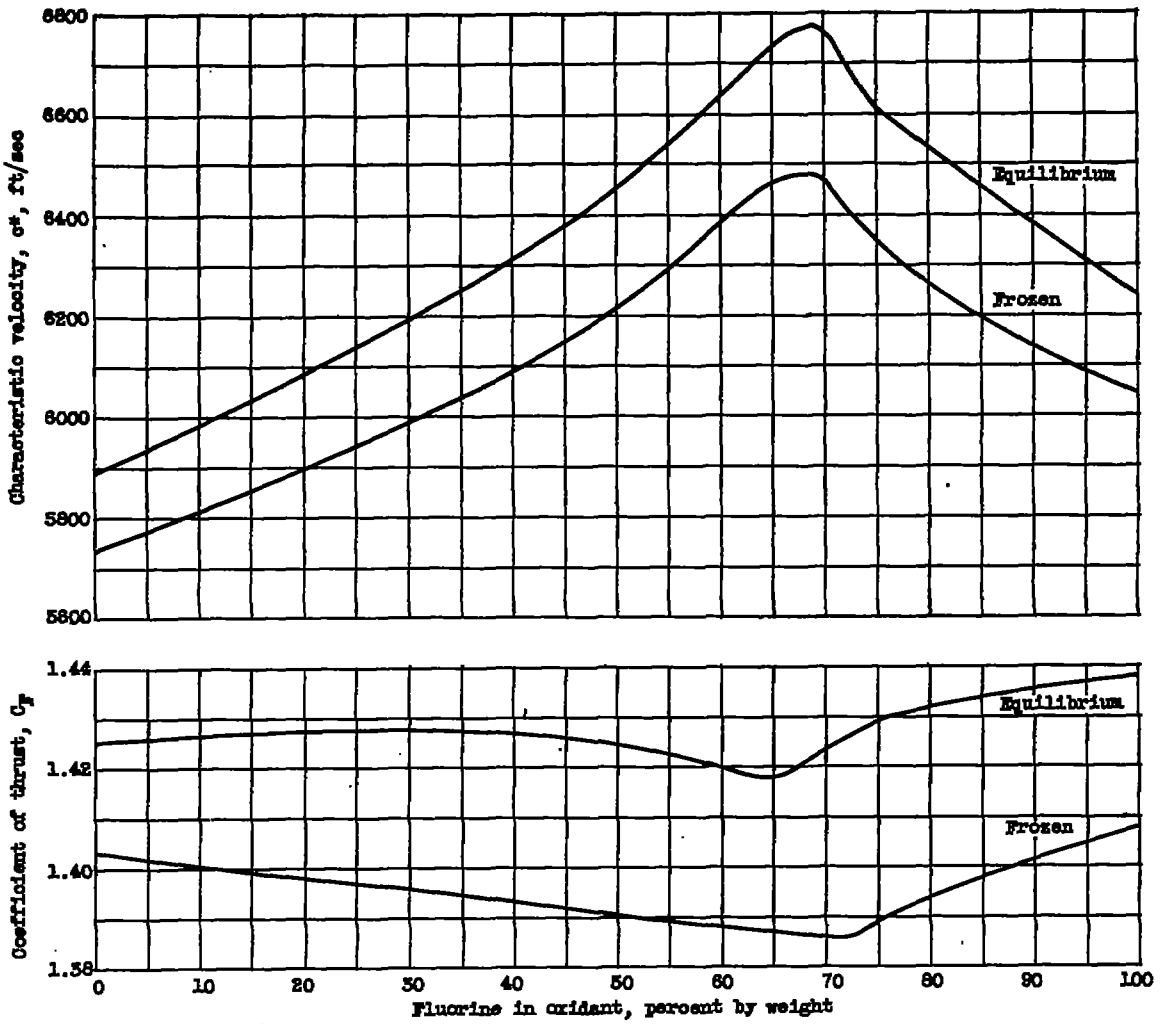


Figure 3. - Theoretical characteristic velocity and coefficient of thrust of JP-4 fuel with liquid fluorine - liquid oxygen mixtures at equivalence ratios for which equilibrium specific impulse is maximum. Isentropic expansion from 500 pounds per square inch absolute to 1 atmosphere assuming equilibrium and frozen composition.

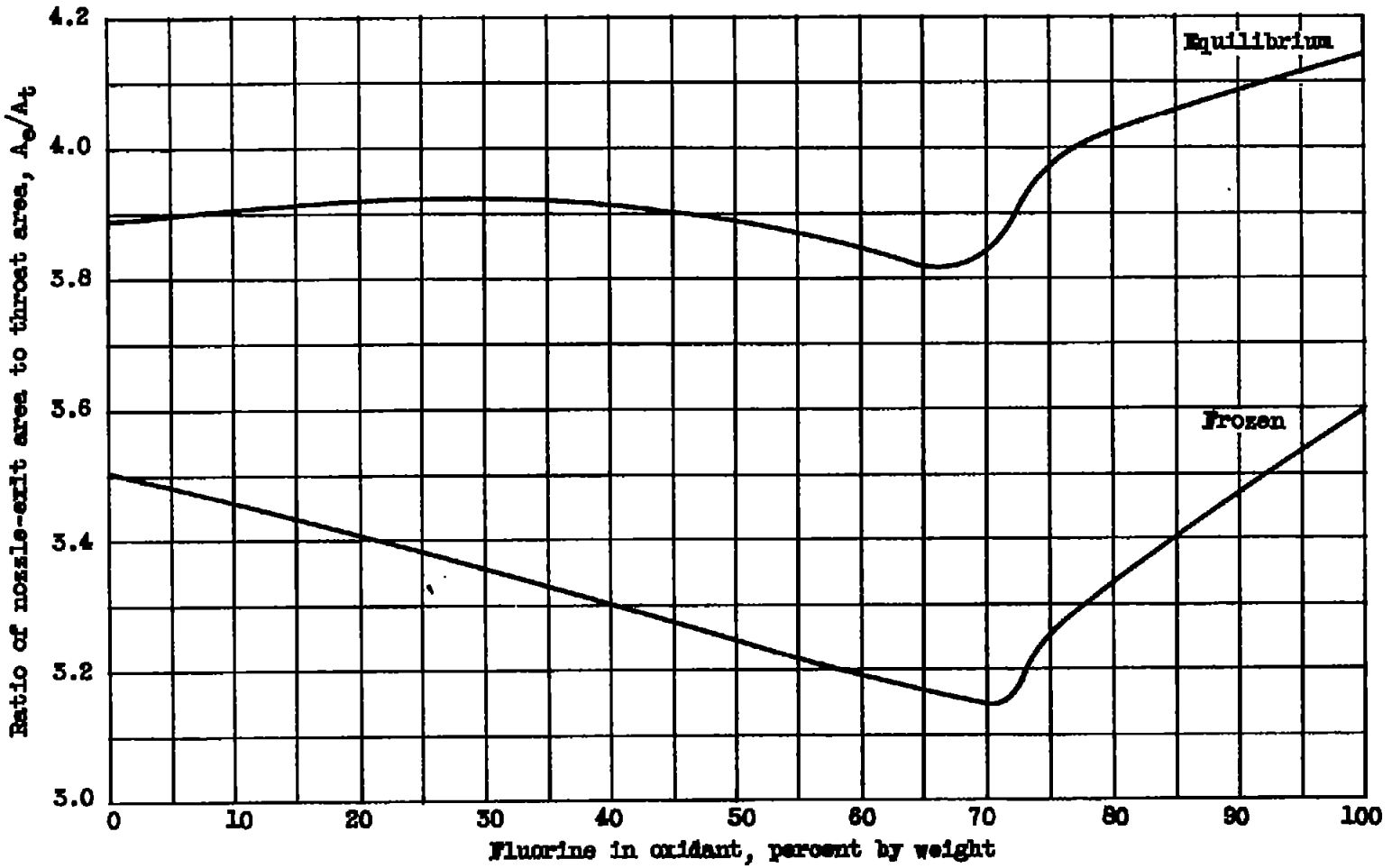


Figure 4. - Theoretical ratio of nozzle-exit area to throat area of JP-4 fuel with liquid fluorine - liquid oxygen mixtures at equivalence ratios for which equilibrium specific impulse is maximum. Isentropic expansion from 300 pounds per square inch absolute to 1 atmosphere assuming equilibrium and frozen composition.

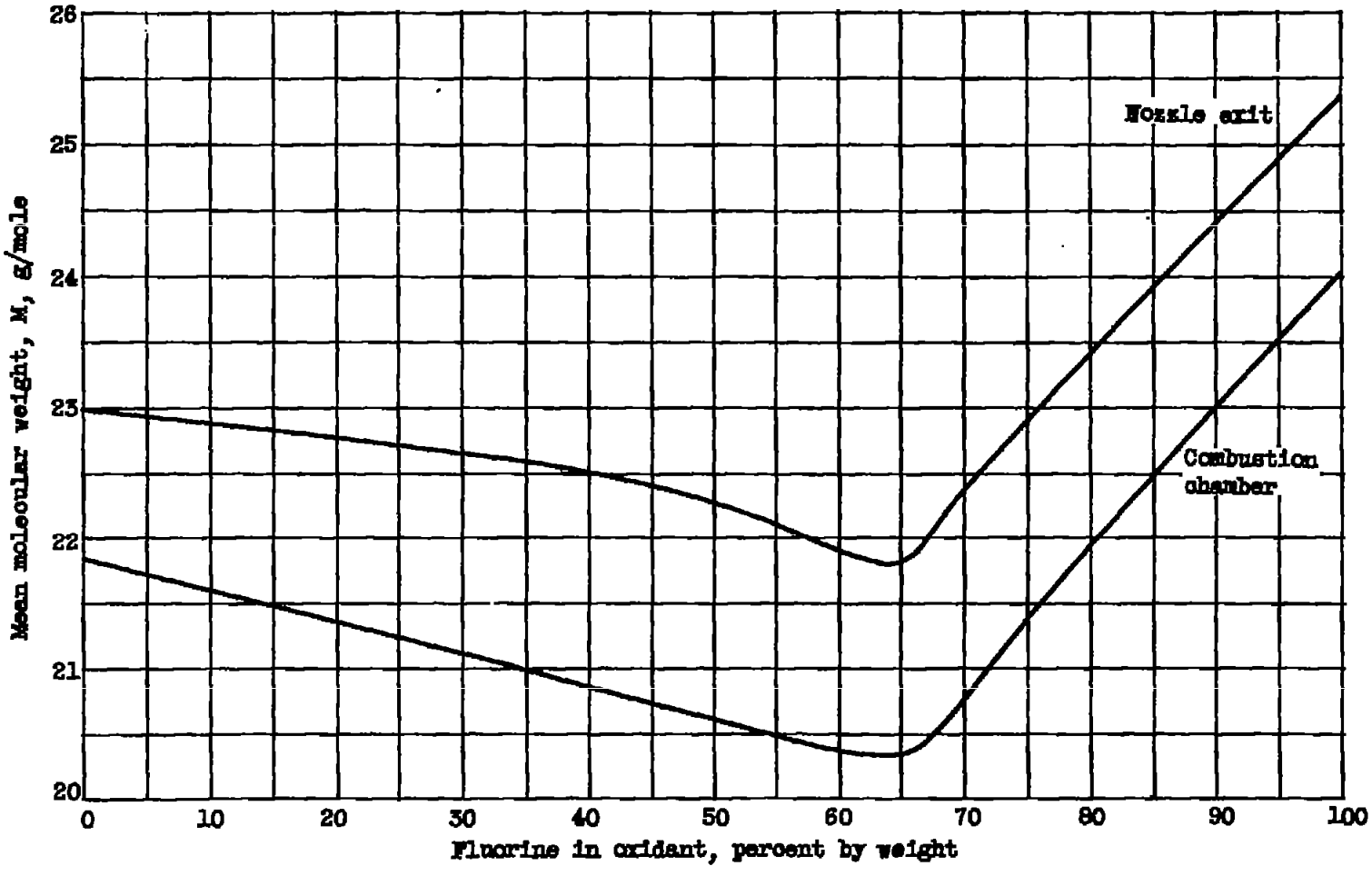


Figure 5. - Theoretical mean molecular weight in combustion chamber and at nozzle exit of JP-4 fuel with liquid fluorine - liquid oxygen mixtures at equivalence ratios for which equilibrium specific impulse is maximum. Isentropic expansion from 300 pounds per square inch absolute to 1 atmosphere assuming equilibrium composition.