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# RESEARCH MEMORANDUM

## ANALYSIS OF FLUORINE ADDITION TO THE VANGUARD FIRST STAGE

By William A. Tomazic, Harold W. Schmidt, and Adelbert O. Tischler

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
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# ANALYSIS OF FLUORINE ADDITION TO THE VANGUARD FIRST STAGE

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## SUMMARY

The effect of adding fluorine to the Vanguard first-stage oxidant was analyzed. An increase in specific impulse of 5.74 percent may be obtained with 30 percent fluorine. This increase, coupled with increased mass ratio due to greater oxidant density, gave up to 24.6-percent increase in first-stage burnout energy with 30 percent fluorine added. However, a change in tank configuration is required to accommodate the higher oxidant-fuel ratio necessary for peak specific impulse with fluorine addition.

Increased performance of this order can be obtained without tank-configuration change by addition of unsymmetrical dimethyl hydrazine (UDMH) to the fuel coincident with fluorine addition to the oxidant. With 30 percent fluorine and approximately 51 percent UDMH, the burnout energy can be increased 23.5 percent.

Fluorine addition will increase the engine heat-rejection rate about 1 percent for each 1 percent fluorine added up to 30 percent.

## INTRODUCTION

This report presents data pertinent to the problem of boosting rocket performance by adding up to 30 percent liquid fluorine to the liquid oxygen of an existing oxygen-hydrocarbon rocket engine. This engine powers the first stage of the Vanguard satellite vehicle. It develops approximately 27,000 pounds thrust at a chamber pressure of 600 pounds per square inch with a thrust-chamber specific impulse of 258 pound-seconds per pound.

Data on performance and heat rejection of rocket engines using mixtures of fluorine and oxygen with hydrocarbon fuels are digested herein. These data, primarily from 1000- and 5000-pound-thrust engines, are extrapolated to the operating conditions of the 27,000-pound-thrust Vanguard engine. These estimates of performance and heat rejection cover the range of 0 to 30 percent by weight of fluorine in the oxidant.

The effect of the increased specific impulse and mass ratio due to adding up to 30 percent fluorine on the energy of the vehicle at burnout is calculated. Simplified vertical trajectory equations are used. Several different methods of loading the propellant tanks, some with tank-configuration changes and some without, are considered. The effect of adding unsymmetrical dimethyl hydrazine (UDMH) to the fuel to compensate for the oxidant-fuel volume ratio shift otherwise necessary to keep the fluorine-oxygen-hydrocarbon system at peak specific impulse is also presented.

Operating experiences with fluorine-oxygen mixtures are discussed. Problems and experience in handling, pumping, and thrust-chamber firing are reviewed briefly.

## SYMBOLS

| | |
|---|---|
| $e_b$ | burnout energy, ft-lb force/lb mass |
| $g_c$ | gravitational conversion factor, 32.2 ft-lb mass/(lb force)(sec)$^2$ |
| $g_l$ | acceleration due to gravity, taken to be 32.2 ft/sec$^2$ |
| $h_b$ | height at burnout, ft or miles |
| $h_{max}$ | maximum height |
| $I_s$ | specific impulse, (lb force)(sec)/lb mass |
| $q$ | heat-rejection rate, Btu/(sec)(sq in.) |
| $t_b$ | time of burning, sec |
| $V_b$ | velocity at burnout, ft/sec |
| $W_e$ | empty weight of vehicle |
| $W_g$ | gross loaded weight of vehicle |
| $W_p$ | weight of propellants |

## SPECIFIC IMPULSE

Theoretical and experimental data show that significant gains can be made in the specific impulse of an oxygen-hydrocarbon rocket by the addition of fluorine to the oxygen.

## Theoretical Data

The theoretical specific impulse for oxygen-fluorine mixtures up to 30 percent fluorine burned with JP-4 is shown in figure 1. These data were computed at the NACA Lewis laboratory for equilibrium expansion from 600 pounds per square inch to atmospheric pressure. An increase in specific impulse of more than 5 percent over that with oxygen and JP-4 is indicated for 30-percent-fluorine concentration. This increase is realized fully only if the oxidant-fuel ratio is shifted to higher values with increasing fluorine content. For example, the peak theoretical specific impulse for no fluorine occurs at an oxidant-fuel ratio of 2.43. For 30 percent fluorine, the peak occurs at an oxidant-fuel ratio of 2.94.

## Experimental Data

Published experimental data for a Project Hermes engine comparable in thrust to the Vanguard first-stage engine are shown in the following table. The data are for oxygen-gasoline burned at approximately 600-pounds-per-square-inch chamber pressure (ref. 1):

| Thrust, lb | Chamber pressure, lb/sq in. abs | Oxidant-fuel ratio | Specific impulse, lb-sec/lb |
|---|---|---|---|
| 27,800 | 605 | 2.18 | 257 |
| 28,000 | 608 | 2.33 | 263 |
| 28,200 | 614 | 2.08 | 257 |

A thrust-chamber specific impulse of 258 pound-seconds per pound (91% of peak theoretical) is expected at an oxidant-fuel ratio of 2.2 in the Vanguard engine. This oxidant-fuel ratio is considerably lower than the theoretical value for peak specific impulse of 2.43. The specific impulse is typical of those currently being obtained with oxygen-hydrocarbon engines. The performance obtained at the NACA Lewis laboratory with a 1000-pound-thrust engine operated at 600-pound-per-square-inch chamber pressure with 0, 30, and 70 percent fluorine in the oxidant (ref. 2) is shown in figure 2. Peak impulse with no fluorine was approximately 258 pound-seconds per pound. This is again about 91 percent of the theoretical value. The peak impulse occurred at an oxidant-fuel ratio of 2.4. With 30 percent fluorine in the oxidant, the peak specific impulse was 278 pound-seconds per pound and occurred at an oxidant-fuel ratio of roughly 3.2. This value is about 93 percent of theoretical. With 70 percent fluorine, the peak specific impulse was 287 pound-seconds per pound, or only about 88 percent of the theoretical peak.

A 5000-pound-thrust General Electric engine similar in type to the Vanguard engine was operated with 0 and 15 percent fluorine (ref. 3) at 350-pound-per-square-inch chamber pressure. The data are shown in figure 3. The specific-impulse values obtained at the best oxidant-fuel ratio were approximately 92 percent of theoretical at that chamber pressure.

Data obtained by North American Aviation (ref. 4) with a 300-pound-per-square-inch chamber pressure are shown in figure 4. These data cover fluorine concentrations of 10, 20, 30, 50, and 70 percent fluorine in the oxidant. The performance with 10 percent fluorine is 90 percent of theoretical. With 30 percent fluorine the performance is 95 percent of theoretical. At higher fluorine concentrations the performance again drops in terms of percent of theoretical. The decrease in efficiency at high fluorine concentrations may be attributed to the preferential combustion of fluorine with hydrogen (ref. 5). As the fluorine content reaches approximately 70 percent, there is insufficient hydrogen with which the fluorine can combine, and some may even escape unreacted.

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## Extrapolation of Data to Vanguard Engine Performance

The data presented in figures 2 to 4 indicate that specific-impulse values of 90 to 95 percent of theoretical for equilibrium expansion can be achieved with oxygen-fluorine mixtures burned with hydrocarbon fuels. As fluorine concentrations in the oxidant approach 30 percent, slightly higher percentages of the theoretical performance have been realized experimentally. However, for purposes of conservative extrapolation of these data to the Vanguard engine, a value of 91 percent of the theoretical specific impulse for equilibrium expansion has been chosen.

The predicted experimental specific impulse is shown in figure 5 as a function of oxidant-fuel ratio and percent of fluorine in the oxidant. To obtain maximum specific impulse as fluorine percentage is increased requires an increase in oxidant-fuel ratio.

## Use of UDMH in Fuel

It is possible to preserve the volumetric ratio of the oxidant to the fuel by use of additives to the fuel to compensate for the effect of fluorine addition in the oxidant. Preservation of the oxidant-fuel volumetric ratio will prevent extensive modification of the pump and plumbing system. One such fuel additive is unsymmetrical dimethyl hydrazine (UDMH). This fuel is particularly attractive, because it also increases the specific impulse of the propellants.

The effect on specific impulse and oxidant-fuel ratio of adding various percentages of UDMH to the fluorine-oxygen-hydrocarbon system was calculated at the Lewis laboratory. Figure 6 shows 91 percent of peak theoretical with each propellant combination. The constant volumetric oxidant-fuel ratio corresponding to the present Vanguard configuration is shown by the dashed curve. Any point on this curve indicates the specific impulse, the fuel composition, the oxidant composition, and the oxidant-fuel weight ratio. For example, a thrust-chamber specific impulse of nearly 271 pound-seconds per pound can be obtained with fuel containing 43 percent UDMH burned with oxygen containing 20 percent fluorine at the volumetric oxidant-fuel ratio of the Vanguard configuration. These curves are theoretical only, since no experimental data for this combination of propellants are now available.

The data of figures 5 and 6 as applied to the Vanguard engine are summarized in figure 7. This figure shows the increase in specific impulse as a function of the fluorine in the oxidant for three operating conditions: no volumetric oxidant-fuel-ratio change with hydrocarbon fuel, optimum oxidant-fuel ratio with hydrocarbon fuel, and no volumetric oxidant-fuel-ratio change with UDMH-hydrocarbon mixtures. For the third condition, the amount of UDMH in the fuel for each fluorine-oxidant mixture was that corresponding to the dashed line in figure 6.

## Application of Data to Vanguard

The use of fluorine in the Vanguard vehicle offers two separate advantages in increasing performance: (1) increased specific impulse, and (2) improved mass ratio (ratio of gross to empty weight) due to higher oxidant density. Whereas the specific impulse is a function of the percent fluorine and the oxidant-fuel ratio only, the mass ratio is also influenced by the manner in which the tanks are loaded. To illustrate the advantages of using fluorine, four different cases of tank loading have been calculated:

Case 1 maintains the original tank configuration and gross weight, with the oxidant-fuel ratio for each fluorine concentration adjusted for peak specific impulse. To maintain constant gross weight, the fuel tank is only partially filled. Here, of course, there is no increase in mass ratio. The increase in vehicle performance is due solely to specific impulse.

Case 2 retains the original tank configuration with both tanks filled. Gross weight changes in this case. The oxidant-fuel mass ratio also changes slightly because of the increasing density of the oxidant as fluorine concentration increases. The oxidant-fuel ratio is less than that required for peak specific impulse.

The third method of loading (case 3) requires a change in tank configuration to maintain total propellant volume but with individual fuel and oxidant volumes changed to give the oxidant-fuel ratio for maximum specific impulse in each case. With full tanks, this method gives the highest mass ratio.

Case 4 considers the effect of UDMH added to the fuel. As mentioned previously, a concentration of UDMH in the fuel may be chosen for each fluorine-in-oxygen concentration to give the oxidant-fuel ratio for peak specific impulse without changing the volume ratio of the tanks. Because the densities of the UDMH and the hydrocarbon are nearly identical there is negligible change in mass ratio over case 2. The improvement in vehicle performance over case 2 is due entirely to increased specific impulse.

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The effect of fluorine addition on vehicle performance can be illustrated by calculating burnout energies (maximum height) for a simplified zero-drag vertical trajectory for the first stage from the following equations:

$$e_b = h_{max} = \frac{h_b \bar{g}_l}{g_c} + \frac{V_b^2}{2g_c}$$

$$h_b = g_c t_b I_s \left(1 + \frac{W_e}{W_p} \ln \frac{W_e}{W_g}\right) - \bar{g}_l \frac{t_b^2}{2}$$

$$V_b = g_c I_s \ln \frac{W_g}{W_e} - \bar{g}_l t_b$$

Because this calculation does not give correct absolute results, the comparisons are made in terms of percent increase in vehicle energy at burnout. Engineering problems may also necessitate compromises in ratio of thrust to gross weight. Such compromises are beyond the scope of this survey. To help round out the picture, two sets of calculations for each propellant loading case were carried out: (1) for the same thrust for all cases, and (2) for a ratio of thrust to gross weight of 1.2 for all cases. This acceleration is the value of the existing Vanguard configuration (ref. 6). Constant engine thrust and specific impulse are assumed throughout a flight.

For the rated engine thrust of 27,000 pounds (ref. 6), the percentage increase in the total energy of the first stage at burnout for all cases is shown in figure 8(a) as a function of concentration of fluorine in the oxidant. With 30 percent fluorine in the oxidant the increase in first-stage final energy varied from 10.8 percent for case 2a (fixed tanks, nonoptimum oxidant-fuel ratio) to 16.7 percent for case 4a (UDMH and JP-4 burned with fluorine and oxygen at fixed volumetric oxidant-fuel ratio). In all cases the curves do not intersect the origin, because the initial or reference oxidant-fuel ratio is not at the theoretical optimum oxidant-fuel ratio.

The second set of calculations was made with the initial acceleration of each vehicle assumed to be 0.2 $g_l$ for each case. This decreases burning time as compared with the first set of calculations. The results are given in figure 8(b). In this set of calculations the percent increase in total energy varied from 11.8 percent for case 1 to 24.6 percent for case 3b with 30 percent fluorine in the oxidant. Cases 3b and 4b (i.e., the cases of the adjustable relative tank volumes and the UDMH and JP-4 with fluorine and oxygen at fixed volumetric oxidant-fuel ratio) gave very nearly identical results (23.5% increase in $e_b$ for case 4b) under the assumption of fixed initial acceleration. Results of these calculations are presented in tables I and II.

## PROBLEMS IN USING FLUORINE

### Heat Rejection

Two factors affecting the heat rejection in a rocket engine using fluorine-oxygen mixtures with hydrocarbon fuel (at constant chamber pressure) are the oxidant-fuel ratio and the percent fluorine in the oxidant. Experimental data from several rocket engines burning hydrocarbon fuel with oxygen or fluorine-oxygen mixtures are shown in figures 9(a) to (c). These figures illustrate the effect of the oxidant-fuel mixture ratio on the heat rejection. Heat-rejection data for 5000- and 18,000-pound-thrust gasoline-oxygen engines, similar in design to the Vanguard engine, are shown in figure 9(d) (ref. 7).

The values for the rate of heat rejection in figure 9(a) are for a 1000-pound-thrust engine operated at a chamber pressure of 600 pounds per square inch (ref. 2). The values in figure 9(b) are for 3000- and 5000-pound-thrust engines at chamber pressures of 300 and 500 pounds per square inch, respectively (ref. 4). The fact that the heat-rejection rates in both cases are of about the same magnitude, despite chamber-pressure differences, may be attributed to the "hotter" injectors used in the larger engines.

The difference in values of the heat rejection between 30 and 70 percent fluorine is approximately 0.6 Btu/(sec)(sq in.) and is consistent between figures 9(a) and (b) over a range of oxidant-fuel ratio, as shown by the following table:

| Oxidant-fuel ratio | Percent fluorine | Heat-rejection rate, q, Btu/(sec)(sq in.) (fig. 9(a)) | Δq, Btu/(sec)(sq in.) | Heat-rejection rate, q, Btu/(sec)(sq in.) (fig. 9(b)) | Δq, Btu/(sec)(sq in.) |
|---|---|---|---|---|---|
| 3.0 | 30 | 2.10 | 0.55 | 1.95 | 0.50 |
| | 70 | 2.65 | | 2.45 | |
| 3.2 | 30 | 2.25 | 0.50 | 2.10 | 0.50 |
| | 70 | 2.75 | | 2.60 | |
| 3.4 | 30 | 2.45 | 0.65 | 2.25 | 0.55 |
| | 70 | 3.10 | | 2.80 | |
| 3.6 | 30 | 2.70 | 0.60 | 2.45 | 0.70 |
| | 70 | 3.30 | | 3.15 | |

The rates of increase in heat rejection with oxidant-fuel ratio for fluorine-oxygen-hydrocarbon engines in figures 9(a) and (b) are also comparable. They approximate an increase of 0.1 heat-transfer unit (Btu/(sec)(sq in.)) per 0.1 oxidant-fuel-ratio unit for 30 percent fluorine. This can be shown by subtracting the heat-rejection rates at consecutive oxidant-fuel ratios in the preceding table.

A cross plot of data from faired curves of figure 9(a), illustrating the effects of fluorine content as well as oxidant-fuel ratio, is shown in figure 10. These data were considered to be most representative, since they included the widest range of fluorine content unaffected by variations in hardware. The dominating effect of oxidant-fuel ratio on heat rejection is shown by this plot.

Data from figure 10 were used to plot the predicted percent increase in heat-rejection rate for the Vanguard first-stage engine in figure 11. This figure then predicts the percent increase in heat rejection that can be expected at any oxidant-fuel ratio for fluorine concentrations up to 30 percent, in terms of the heat-rejection rate without fluorine in the oxidant. The heat-rejection rate at an oxidant-fuel ratio of 2.2 and 0 percent fluorine is taken as the reference point on this plot.

Figure 11 indicates that a 30-percent increase in heat rejection will result from using 30 percent fluorine in the oxidant with hydrocarbon fuel at the oxidant-fuel ratio for highest specific impulse.

No experimental heat-rejection data are available for simultaneous fluorine and UDMH addition to hydrocarbon-oxygen propellants.

## Operating Experience with Fluorine

The addition of fluorine introduces problems new to oxygen-hydrocarbon engine systems. Its corrosivity causes severe bearing and seal problems. It is toxic in both its elemental state and as hydrogen fluoride, the most common combustion product. However, fluorine can be handled safely with proper care.

In dilute fluorine-oxygen solutions, the effects mentioned are somewhat attenuated. In reference 3, Teflon parts were used in the flow lines exposed to a 15-percent-fluorine - 85-percent-oxygen mixture. These parts deteriorated only very slowly. Teflon exposed to a flow of pure fluorine disintegrates very rapidly. At present, however, quantitative knowledge of the corrosivity of low-concentration fluorine-oxygen mixtures is very meager.

Seals. - The problem of static and rotating seals for fluorine use has been extensively investigated (ref. 8). The behavior of a number of materials, both plastic and metallic, was studied in test rigs and also as pump-shaft seals, impellers, and volutes during rocket test firings. In general, the resistance of metallic materials to fluorine is excellent. To date, however, no plastic has been found entirely suitable for use with liquid fluorine. Materials such as Kentanium (a cermet of titanium carbide and powdered nickel), Norbide (boron carbide), nitralloy, and hard chrome plate have been found satisfactory for use in fluorine pump-shaft seals where rubbing or surface friction exists. Labyrinth-type shaft seals have been tested in liquid fluorine with satisfactory results. These consisted of soft tin and silver liners with an interference fit on a serrated stainless-steel pump shaft. Operational failures occurred, however, if the liner material was not completely free of impurities or if there was excessive mechanical interference between the pump impeller and the labyrinth liner. Pure liquid fluorine has been successfully pumped in a small centrifugal pump using these metallic seals. On the basis of this work, it would seem quite possible to pump low-concentration fluorine-oxygen mixtures in rocket-engine systems.

Handling. - Because of its toxicity, fluorine must be handled in enclosed systems. To prevent boiloff, liquid-fluorine tanks can be suspended in liquid-nitrogen baths. A transportable system capable of storing liquid fluorine indefinitely under liquid nitrogen has been developed (ref. 9), and loss experiments have been conducted (ref. 10).

In the case of missile tanks, however, nitrogen jacketing would be impractical. Here precooling of the oxidant and the use of a discardable reflux condensor on the vent line may offer an answer.

Another unsolved problem is the disposal or dispersion of toxic fluorine exhaust products at vehicle takeoff. It seems that the best solution would be to keep the surrounding area clear of personnel during takeoff and until the residual exhaust fumes have dispersed to a safe concentration. More study of this problem is needed.

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## CONCLUDING REMARKS

The predictions of specific impulse and heat-rejection rates resulting from the use of fluorine in the oxidant of an oxygen-hydrocarbon rocket system are based on limited experimental data. The experimental data indicate that specific-impulse values of 91 percent of the theoretical value of equilibrium expansion can be achieved. Predictions of Vanguard vehicle performance based on these specific-impulse values show that gains in vehicle energy at first-stage burnout up to 24.6 percent can be realized by adding fluorine to the oxidant. To fully realize the potential gain in performance necessitates operation at increasing oxidant-fuel mass ratios as the fluorine concentration is increased. This, of course, may introduce cooling problems as well as necessitate pump and plumbing redesign. The use of UDMH in the fuel in addition to the fluorine in the oxidant can reduce the necessity for extensive plumbing changes while preserving and even enhancing the performance. An increase of 6.79 percent in specific impulse can be obtained this way compared with 5.74 percent obtained at optimum oxidant-fuel ratio without UDMH.

The increase in heat-rejection rate as fluorine is added to the oxidant may be expected to be about 1 percent per percent of fluorine added at oxidant-fuel ratios corresponding to peak specific impulse. The increase is due primarily to shift of the optimum oxidant-fuel ratio to higher (hotter) values rather than due to the fluorine itself. There is a considerable margin of coolant heat-capacity reserve at the heat-rejection rates anticipated. No heat-rejection data are available for UDMH - JP-4 mixtures with fluorine-oxygen mixtures.

Pure liquid fluorine has been pumped previously. Therefore, the development of seals in flow systems for the dilute fluorine in oxygen solutions appears to offer no insurmountable difficulties. Storage vessels for liquid fluorine have also been developed. Loading techniques and exhaust-gas disposal are problems requiring study and development.

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## SUMMARY OF RESULTS

The vehicle performance increase resulting from the addition of fluorine to the Vanguard first-stage oxidant was calculated for a zero-drag vertical trajectory. The following table lists the burnout-energy increase for fluorine addition:

| Case | Fluorine in oxidant, percent | Increase in burnout energy, percent |
|---|---|---|
| 1 Fixed vehicle gross weight; | 10 | 4.15 |
| optimum oxidant-fuel ratio; | 20 | 7.98 |
| constant thrust and initial acceleration | 30 | 11.82 |
| 2a Fixed tank configuration; | 10 | 3.25 |
| nonoptimum oxidant-fuel ratio; | 20 | 6.93 |
| constant thrust | 30 | 10.75 |
| 2b Fixed tank configuration; | 10 | 5.16 |
| nonoptimum oxidant-fuel ratio; | 20 | 11.03 |
| fixed initial acceleration | 30 | 17.24 |
| 3a Fixed total tank volume; | 10 | 5.46 |
| optimum oxidant-fuel ratio; | 20 | 10.27 |
| constant thrust | 30 | 15.23 |
| 3b Fixed total tank volume; | 10 | 8.59 |
| optimum oxidant-fuel ratio; | 20 | 16.33 |
| fixed initial acceleration | 30 | 24.55 |

In order to avoid both the changes in tanks and the changes in volumetric flow ratio necessary for peak performance with fluorine addition to the oxidant, UDMH may be added to the fuel. The following table shows the effect of combined UDMH and fluorine addition:

| Case | Fluorine in oxidant, percent | UDMH in fuel, percent | Increase in burnout energy, percent |
|---|---|---|---|
| 4a Fixed tank configuration; | 10 | 33.8 | 6.97 |
| optimum oxidant-fuel ratio; | 20 | 43.1 | 11.78 |
| constant thrust | 30 | 51.4 | 16.67 |
| 4b Fixed tank configuration; | 10 | 33.8 | 8.78 |
| optimum oxidant-fuel ratio; | 20 | 43.1 | 16.06 |
| fixed initial acceleration | 30 | 51.4 | 23.50 |

Experiments show that fluorine addition will increase the engine heat-rejection rate about 1 percent for each 1 percent fluorine added up to 30 percent. The use of UDMH in addition will probably not substantially alter this figure, although tests have not yet been made.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 23, 1956

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TABLE I. - PERFORMANCE OF VANGUARD FIRST STAGE WITH FLUORINE ADDITION TO THE OXIDANT

| Fluorine in oxidant, percent | Oxidant specific gravity | Oxidant-fuel weight ratio | Thrust-chamber specific impulse, lb-sec/lb | Engine specific impulse used for flight calculations, lb-sec/lb | Increase in specific impulse, percent | Relative propellant weight | Ratio of gross weight to empty weight | Burning time, sec | Burnout velocity, ft/sec | Increase in burnout velocity, percent | Burnout height, miles | Increase in burnout height, percent | Energy at burnout, ft-lb/lb | Increase in burnout energy, percent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Case 1: Fixed vehicle gross weight; optimum oxidant-fuel ratio, constant thrust and initial acceleration | | | | | | | | | | | | | | |
| 0 | 1.142 | 2.200 | 258.0 | 254.0 | 0.00 | 1.00 | 3.129 | 146.0 | 4622 | 0.00 | 39.95 | 0.00 | $3901 \times 10^6$ | 0.00 |
| 5 | 1.158 | 2.493 | 261.2 | 257.2 | 1.26 | 1.00 | 3.129 | 147.8 | 4680 | 1.26 | 40.95 | 2.55 | 4000 | 2.54 |
| 10 | 1.172 | 2.567 | 263.3 | 259.2 | 2.05 | 1.00 | 3.129 | 149.0 | 4717 | 2.05 | 41.58 | 4.13 | 4063 | 4.15 |
| 15 | 1.188 | 2.663 | 265.9 | 261.8 | 3.06 | 1.00 | 3.129 | 150.5 | 4764 | 3.06 | 42.43 | 6.26 | 4145 | 6.25 |
| 20 | 1.204 | 2.746 | 268.1 | 263.9 | 3.92 | 1.00 | 3.129 | 151.7 | 4803 | 3.92 | 43.11 | 7.96 | 4213 | 7.98 |
| 25 | 1.219 | 2.834 | 270.3 | 266.1 | 4.77 | 1.00 | 3.129 | 153.0 | 4842 | 4.77 | 43.83 | 9.77 | 4282 | 9.75 |
| 30 | 1.235 | 2.940 | 272.8 | 268.6 | 5.74 | 1.00 | 3.129 | 154.4 | 4887 | 5.74 | 44.66 | 11.85 | 4362 | 11.82 |
| Case 2a: Fixed tank configuration; nonoptimum oxidant-fuel ratio; constant thrust | | | | | | | | | | | | | | |
| 5 | 1.158 | 2.230 | 259.0 | 255.0 | 0.39 | 1.0095 | 3.149 | 148.0 | 4649 | 0.58 | 40.47 | 1.35 | $3950 \times 10^6$ | 1.24 |
| 10 | 1.172 | 2.258 | 261.0 | 257.0 | 1.16 | 1.0181 | 3.168 | 150.4 | 4693 | 1.54 | 41.32 | 3.48 | 4028 | 3.25 |
| 15 | 1.188 | 2.288 | 263.0 | 258.9 | 1.94 | 1.0275 | 3.187 | 152.9 | 4734 | 2.42 | 42.15 | 5.56 | 4103 | 5.16 |
| 20 | 1.204 | 2.319 | 264.8 | 260.6 | 2.62 | 1.0372 | 3.208 | 155.4 | 4772 | 3.25 | 42.91 | 7.46 | 4172 | 6.93 |
| 25 | 1.219 | 2.348 | 266.6 | 262.5 | 3.33 | 1.0463 | 3.227 | 157.8 | 4815 | 4.18 | 43.75 | 9.57 | 4250 | 8.93 |
| 30 | 1.235 | 2.379 | 268.5 | 264.3 | 4.07 | 1.0559 | 3.248 | 160.1 | 4853 | 5.00 | 44.55 | 11.57 | 4321 | 10.75 |
| Case 2b: Fixed tank configuration; nonoptimum oxidant-fuel ratio; fixed initial acceleration | | | | | | | | | | | | | | |
| 5 | 1.158 | 2.230 | 259.0 | 255.0 | 0.39 | 1.0095 | 3.149 | 147.0 | 4679 | 1.23 | 40.57 | 1.60 | $3985 \times 10^6$ | 2.14 |
| 10 | 1.172 | 2.258 | 261.0 | 257.0 | 1.16 | 1.0181 | 3.168 | 148.5 | 4752 | 2.81 | 41.65 | 4.31 | 4103 | 5.16 |
| 15 | 1.188 | 2.288 | 263.0 | 258.9 | 1.94 | 1.0275 | 3.187 | 150.1 | 4824 | 4.37 | 42.66 | 6.84 | 4218 | 8.12 |
| 20 | 1.204 | 2.319 | 264.8 | 260.6 | 2.62 | 1.0372 | 3.208 | 151.6 | 4895 | 5.91 | 43.62 | 9.24 | 4332 | 11.03 |
| 25 | 1.219 | 2.348 | 266.6 | 262.5 | 3.33 | 1.0462 | 3.227 | 153.0 | 4970 | 7.53 | 44.66 | 11.85 | 4454 | 14.16 |
| 30 | 1.235 | 2.379 | 268.5 | 264.3 | 4.07 | 1.0559 | 3.248 | 154.6 | 5043 | 9.11 | 45.68 | 14.40 | 4574 | 17.24 |
| Case 3a: Fixed total tank volume; optimum oxidant-fuel ratio; constant thrust | | | | | | | | | | | | | | |
| 5 | 1.158 | 2.493 | 261.2 | 257.2 | 1.26 | 1.0186 | 3.168 | 150.6 | 4696 | 1.60 | 41.39 | 3.60 | $4034 \times 10^6$ | 3.39 |
| 10 | 1.172 | 2.567 | 263.3 | 259.2 | 2.05 | 1.0290 | 3.191 | 153.3 | 4741 | 2.58 | 42.26 | 5.84 | 4114 | 5.46 |
| 15 | 1.188 | 2.663 | 265.9 | 261.8 | 3.06 | 1.0408 | 3.216 | 156.6 | 4798 | 3.81 | 43.39 | 8.67 | 4218 | 8.11 |
| 20 | 1.204 | 2.746 | 268.1 | 263.9 | 3.92 | 1.0525 | 3.241 | 159.7 | 4843 | 4.78 | 44.35 | 11.02 | 4302 | 10.27 |
| 25 | 1.219 | 2.834 | 270.3 | 266.1 | 4.77 | 1.0641 | 3.265 | 162.8 | 4894 | 5.89 | 45.32 | 13.50 | 4395 | 12.65 |
| 30 | 1.235 | 2.940 | 272.8 | 268.6 | 5.74 | 1.0766 | 3.292 | 166.2 | 4947 | 7.03 | 46.43 | 16.28 | 4496 | 15.25 |
| Case 3b: Fixed total tank volume; optimum oxidant-fuel ratio; fixed initial acceleration | | | | | | | | | | | | | | |
| 5 | 1.158 | 2.493 | 261.2 | 257.2 | 1.26 | 1.0186 | 3.168 | 148.7 | 4756 | 2.90 | 41.72 | 4.48 | $4110 \times 10^6$ | 5.34 |
| 10 | 1.172 | 2.567 | 263.3 | 259.2 | 2.05 | 1.0290 | 3.191 | 150.3 | 4836 | 4.63 | 42.80 | 7.19 | 4236 | 8.59 |
| 15 | 1.188 | 2.663 | 265.9 | 261.8 | 3.06 | 1.0408 | 3.216 | 152.4 | 4934 | 6.75 | 44.18 | 10.64 | 4396 | 12.67 |
| 20 | 1.204 | 2.746 | 268.1 | 263.9 | 3.92 | 1.0525 | 3.241 | 154.2 | 5021 | 8.63 | 45.39 | 13.67 | 4538 | 16.33 |
| 25 | 1.219 | 2.834 | 270.3 | 266.1 | 4.77 | 1.0641 | 3.265 | 155.9 | 5113 | 10.62 | 46.67 | 16.88 | 4691 | 20.24 |
| 30 | 1.235 | 2.940 | 272.8 | 268.6 | 5.74 | 1.0766 | 3.292 | 158.0 | 5212 | 12.77 | 48.09 | 20.44 | 4859 | 24.55 |

TABLE II. - PERFORMANCE OF VANGUARD FIRST STAGE WITH FLUORINE ADDITION TO OXIDANT AND UDMH ADDITION TO THE FUEL

| Fluorine in oxidant, percent | UDMH in fuel, percent | Oxidant specific gravity | Thrust-chamber specific impulse, $\frac{\text{lb-sec}}{\text{lb}}$ | Engine specific impulse used for flight calculations, $\frac{\text{lb-sec}}{\text{lb}}$ | Increase in specific impulse, percent | Relative propellant weight | Ratio of gross weight to empty weight | Burning time, sec | Burnout velocity, ft/sec | Increase in burnout velocity, percent | Burnout height, miles | Increase in burnout height, percent | Energy at burnout, $\frac{\text{ft-lb}}{\text{lb}}$ | Increase in burnout energy, percent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Case 4a: Fixed tank configuration; optimum oxidant-fuel ratio; constant thrust | | | | | | | | | | | | | | |
| 10 | 33.8 | 1.172 | 265.5 | 261.4 | 2.91 | 1.0181 | 3.168 | 152.9 | 4775 | 3.27 | 42.74 | 7.04 | $4167\times10^6$ | 6.79 |
| 20 | 43.1 | 1.204 | 270.6 | 266.4 | 4.90 | 1.0372 | 3.208 | 158.9 | 4879 | 5.56 | 44.85 | 12.32 | 4361 | 11.78 |
| 30 | 51.4 | 1.235 | 275.5 | 271.2 | 6.79 | 1.0559 | 3.248 | 164.7 | 4981 | 7.77 | 46.92 | 17.50 | 4552 | 16.67 |
| Case 4b: Fixed tank configuration; optimum oxidant-fuel ratio; fixed initial acceleration | | | | | | | | | | | | | | |
| 10 | 33.8 | 1.172 | 265.5 | 261.4 | 2.91 | 1.0181 | 3.168 | 151.1 | 4833 | 4.56 | 43.08 | 7.89 | $4244\times10^6$ | 8.78 |
| 20 | 43.1 | 1.204 | 270.6 | 266.4 | 4.90 | 1.0372 | 3.208 | 155.0 | 5005 | 8.29 | 45.59 | 14.18 | 4528 | 16.06 |
| 30 | 51.4 | 1.235 | 275.5 | 271.2 | 6.79 | 1.0559 | 3.248 | 158.6 | 5176 | 11.99 | 48.11 | 20.49 | 4818 | 23.50 |

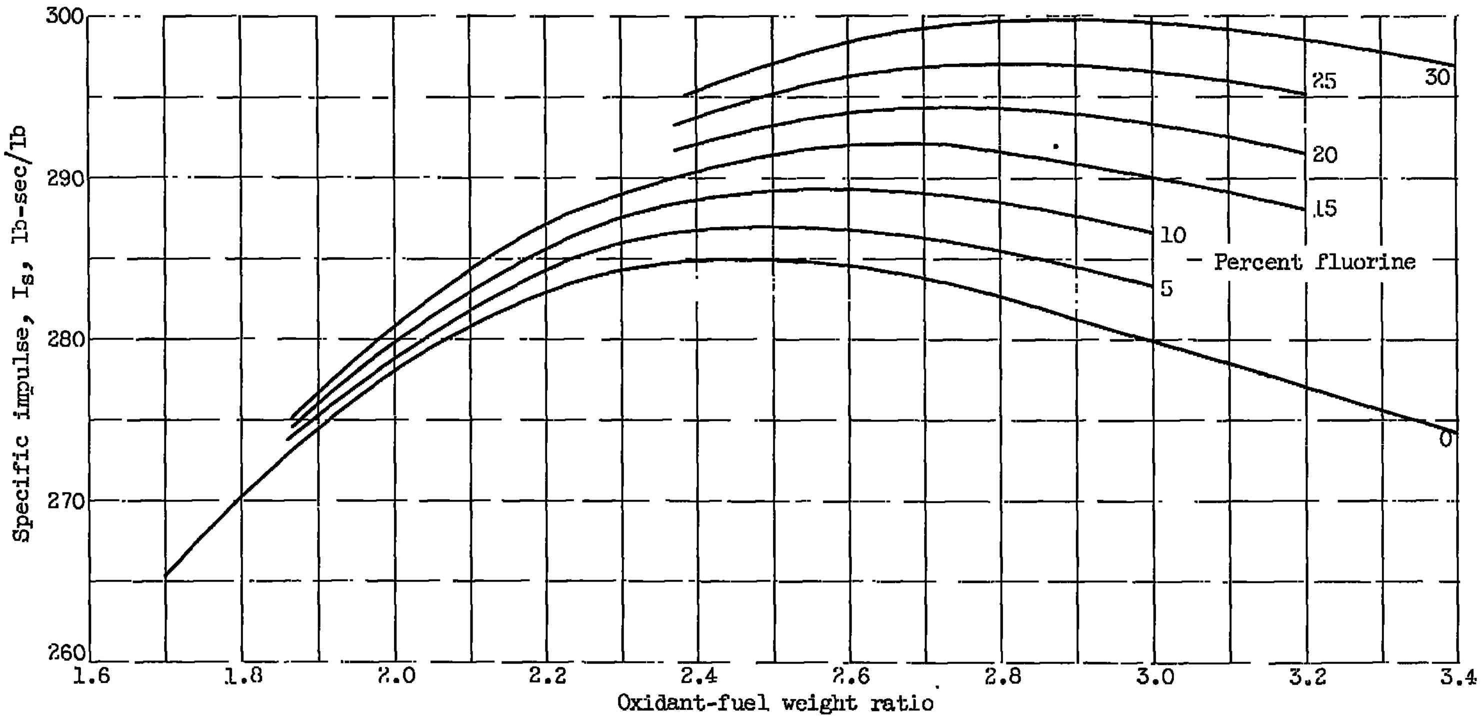


Figure 1. - Theoretical specific impulse (equilibrium composition during expansion from 600 lb/sq in. to atm. pressure) for fluorine-oxygen mixtures with JP-4 fuel.

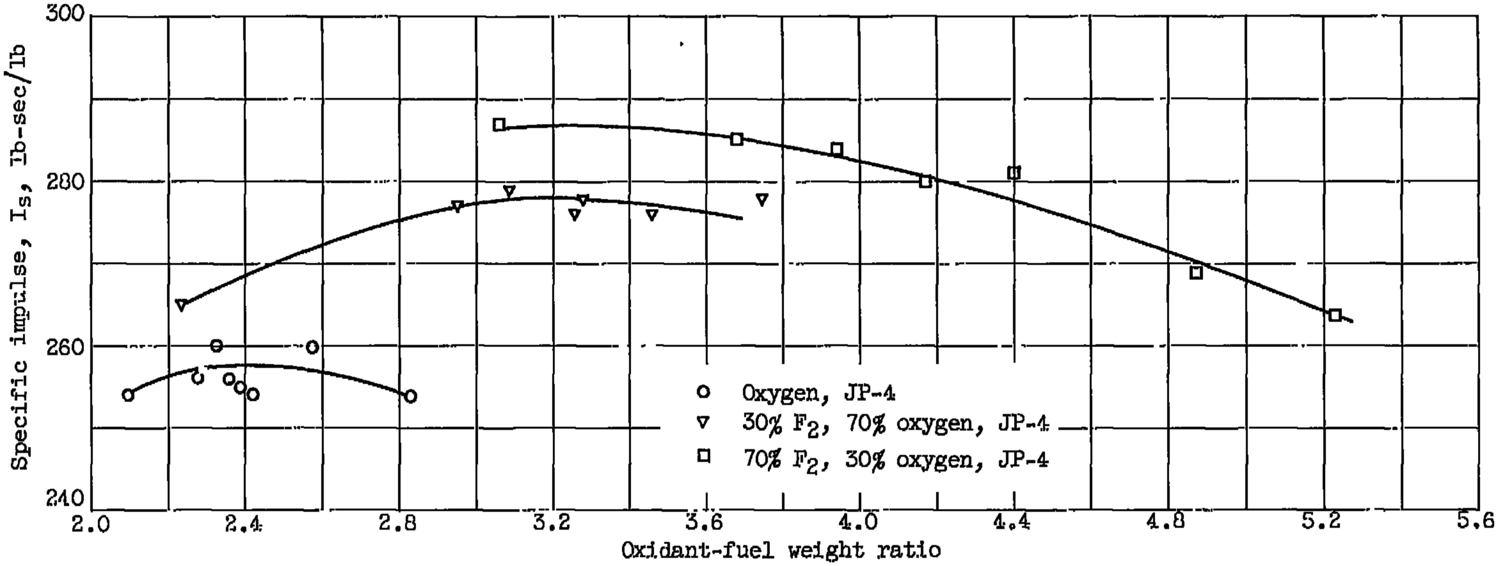


Figure 2. - Specific impulse as function of oxidant-fuel weight ratio for an NACA 1000-pound-thrust engine at 600-pound per-square-inch-absolute chamber pressure using: (1) oxygen and JP-4, (2) 30 percent fluorine, 70 percent oxygen, and JP-4, and (3) 70 percent fluorine, 30 percent oxygen, and JP-4 (ref. 2).

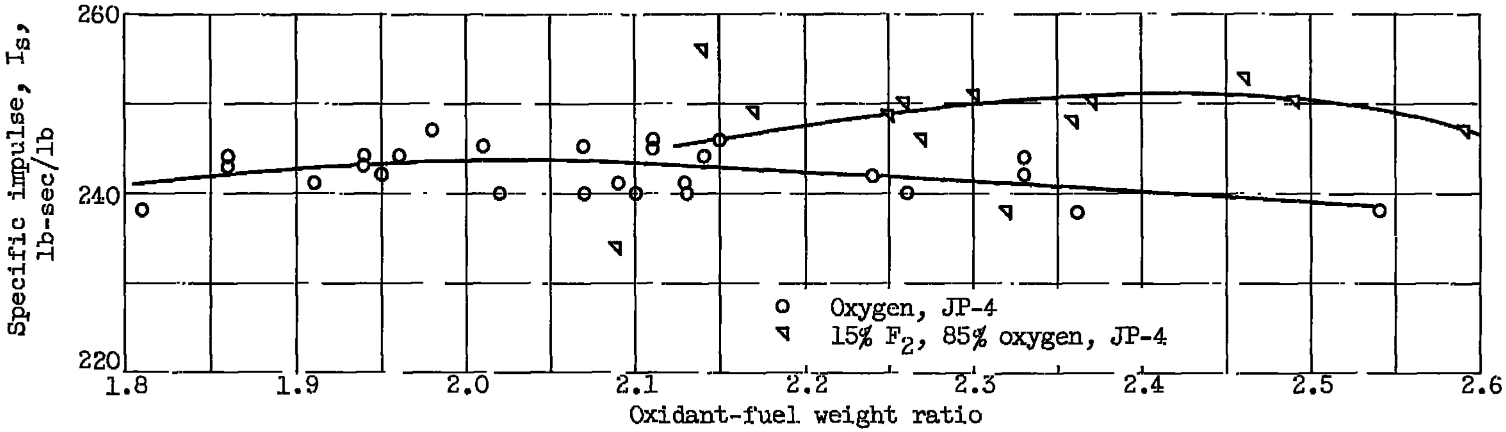


Figure 3. - Specific impulse as function of oxidant-fuel weight ratio for a General Electric 5000-pound-thrust engine at 350-pound-per-square-inch absolute chamber pressure using: (1) oxygen and JP-4 and (2) 15 percent fluorine, 85 percent oxygen, and JP-4 (ref. 3).

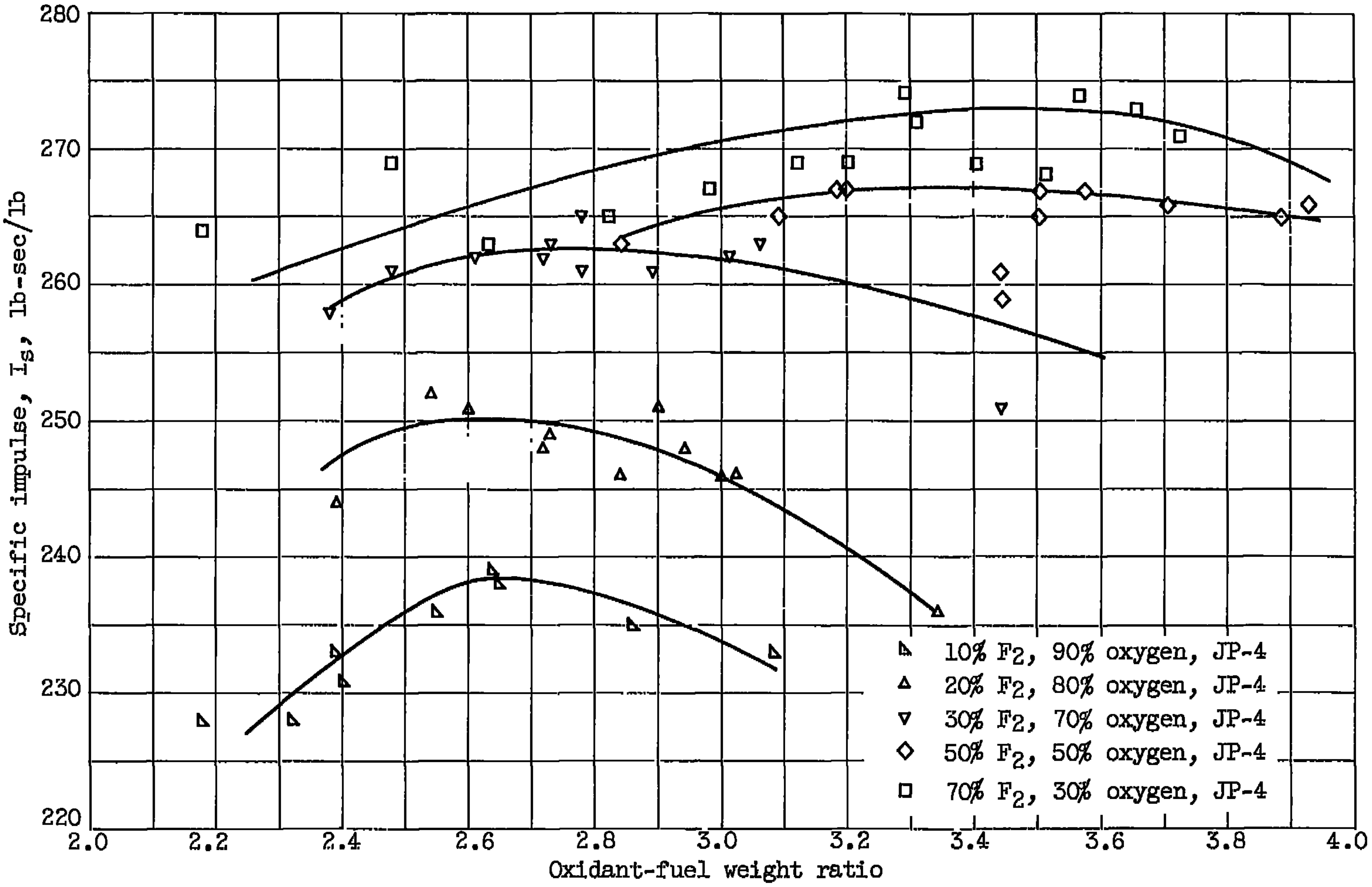


Figure 4. - Specific impulse as function of oxidant-fuel weight ratio for a North American Aviation 3000-pound-thrust engine operated at 300-pound-per-square-inch-absolute chamber pressure using a series of oxygen-fluorine mixtures with JP-4 (ref. 4).

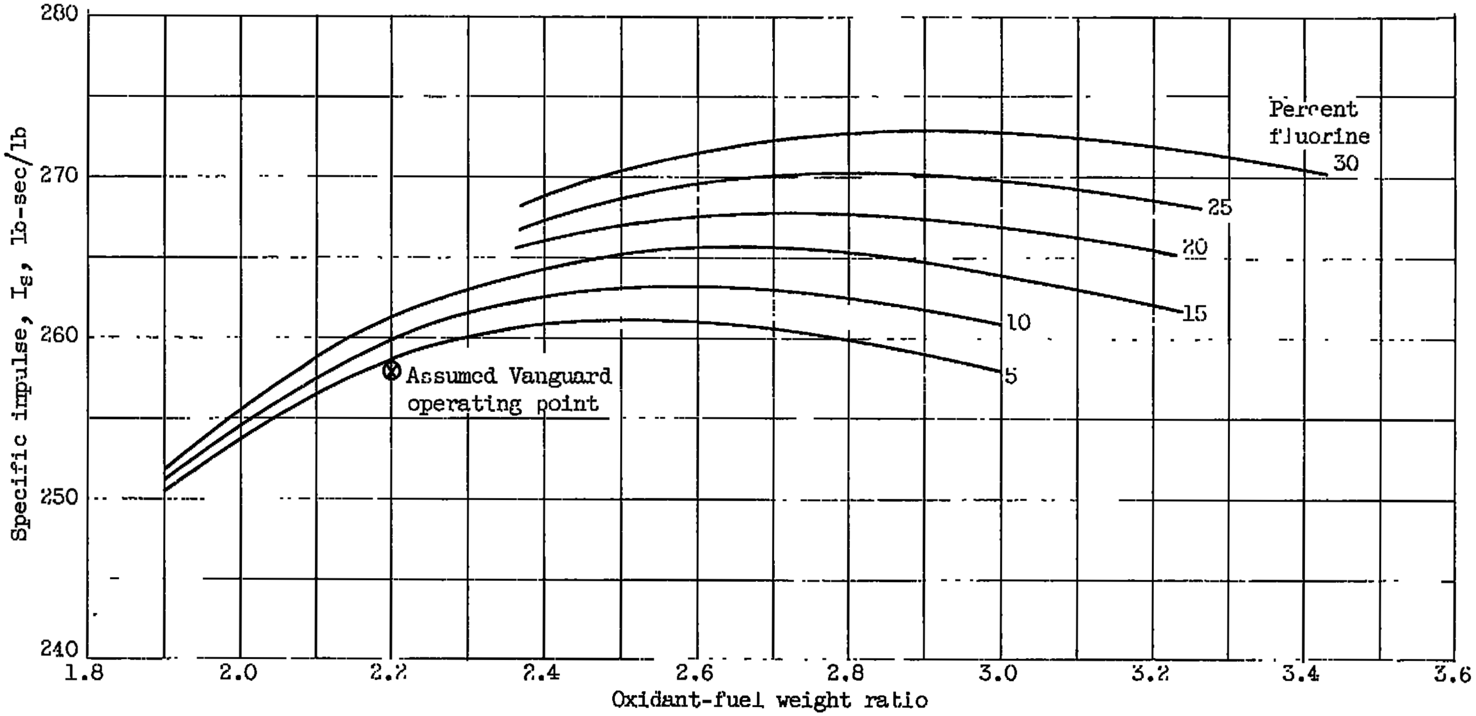


Figure 5. - Predicted experimental specific impulse for Vanguard first-stage engine with fluorine addition (91% of equilibrium theoretical specific impulse at 600 lb/sq in. absolute chamber pressure assumed).

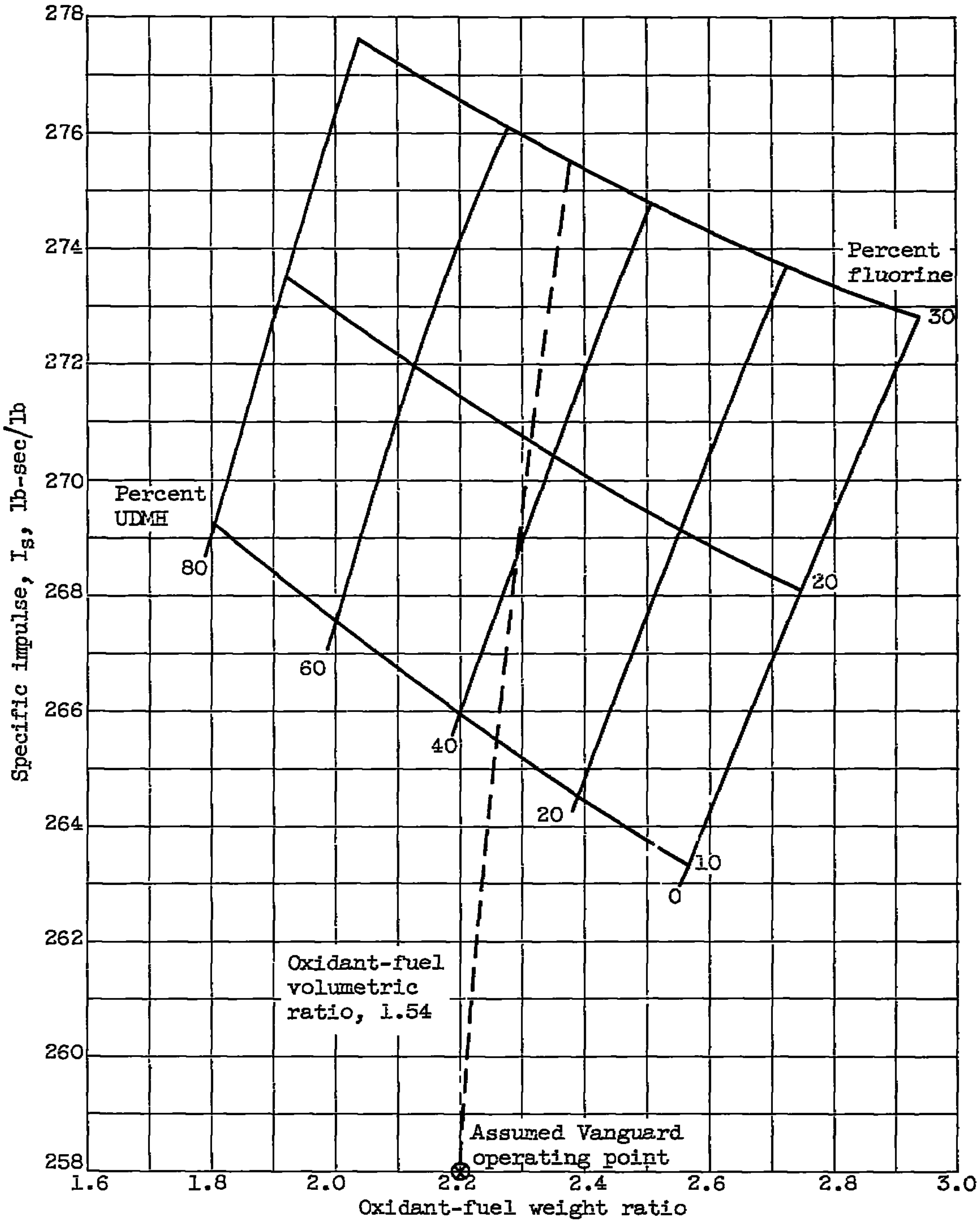


Figure 6. - Predicted specific impulse as function of oxidant-fuel ratio with fluorine and UDMH addition to Vanguard first-stage thrust chamber (91% specific-impulse efficiency assumed).

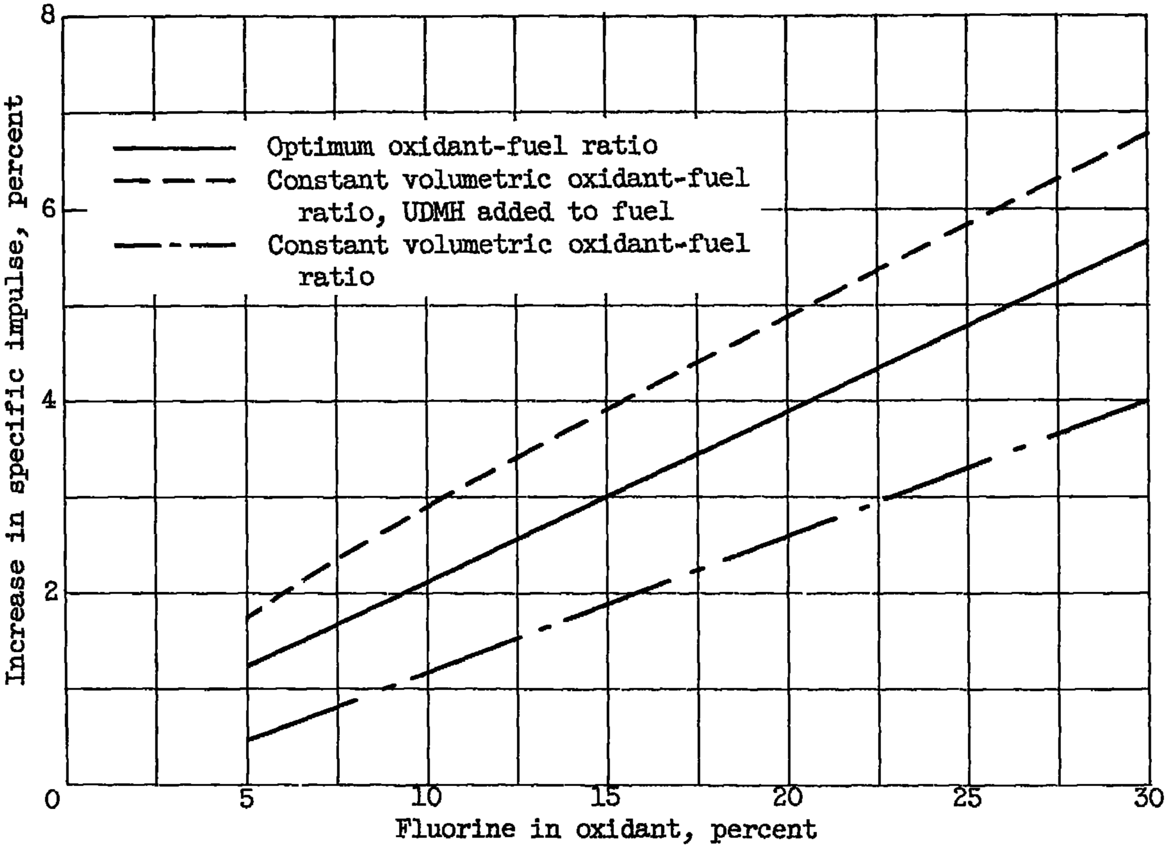
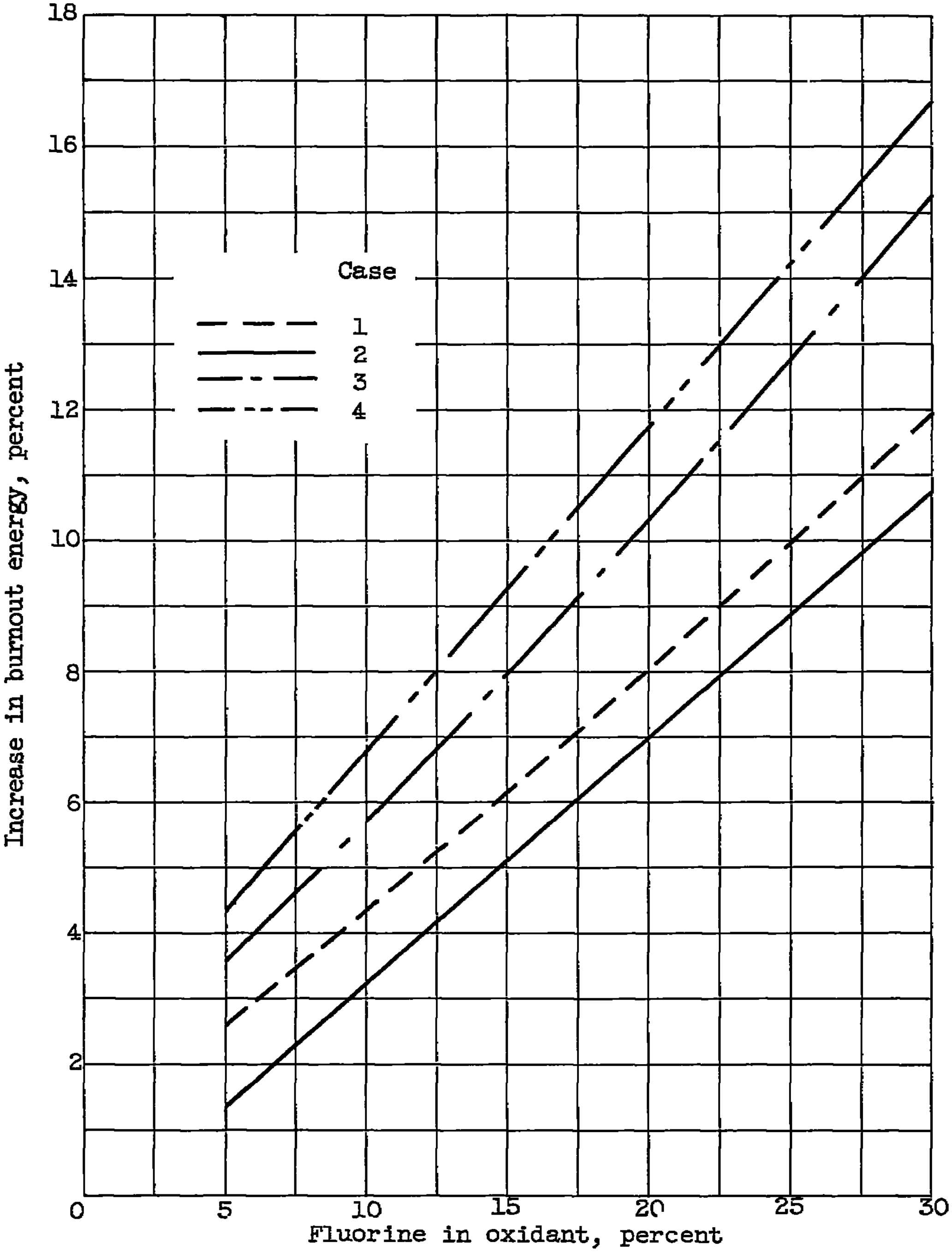


Figure 7. - Predicted increase in experimental specific impulse with fluorine addition for Vanguard first stage.



(a) Thrust constant at 27,000-pound rated value.

Figure 8. - Predicted increase in burnout energy with fluorine addition for Vanguard first stage.

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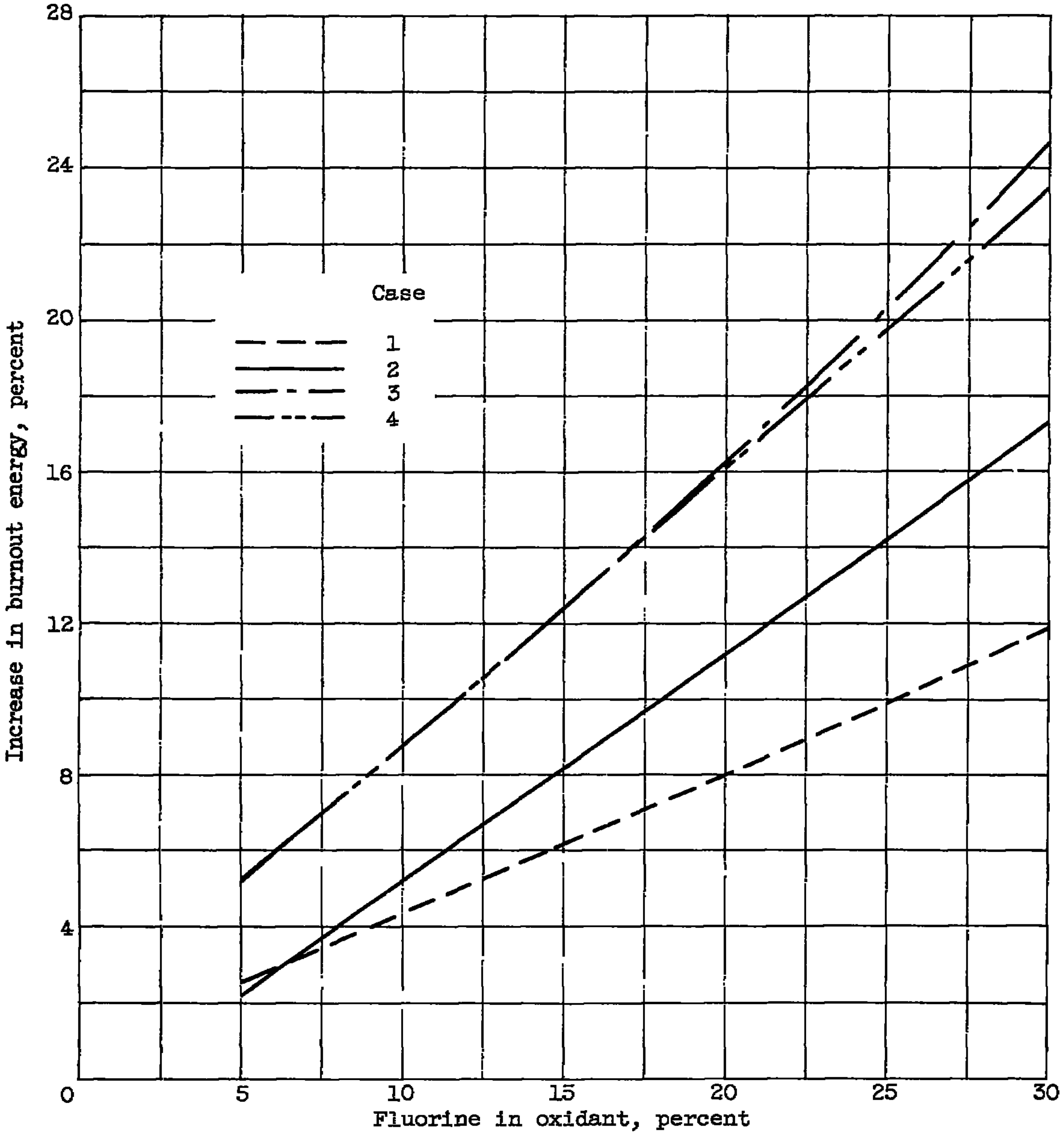
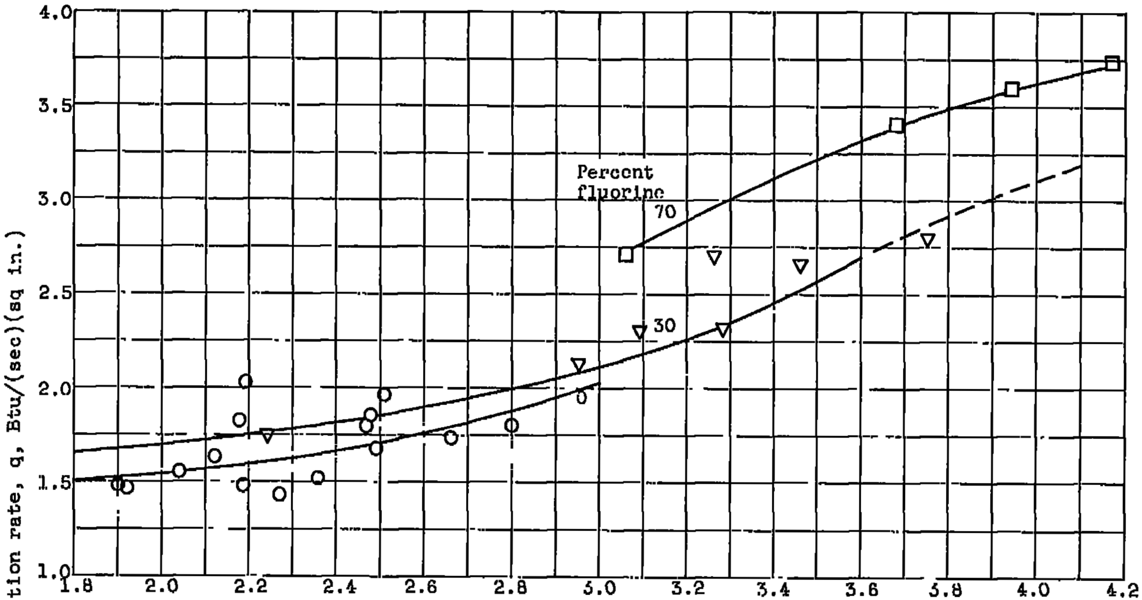
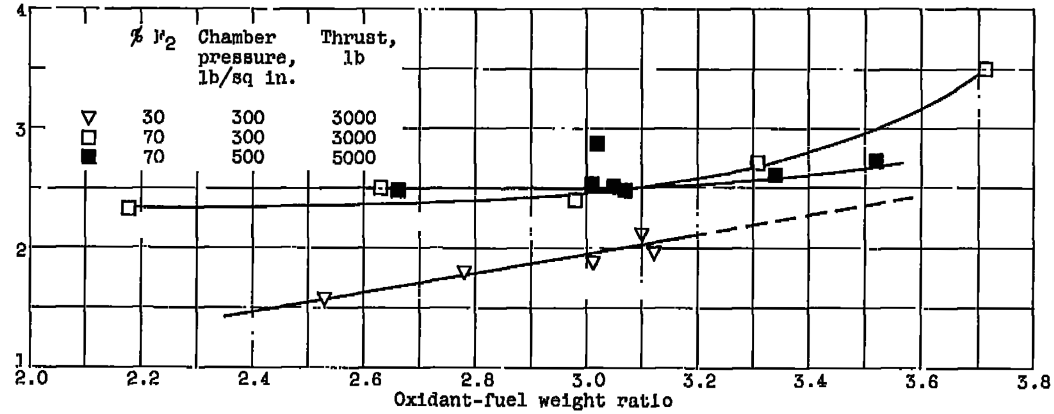


(b) Ratio of thrust to gross weight constant at 1.2.

Figure 8. - Concluded. Predicted increase in burnout energy with fluorine addition for Vanguard first stage.

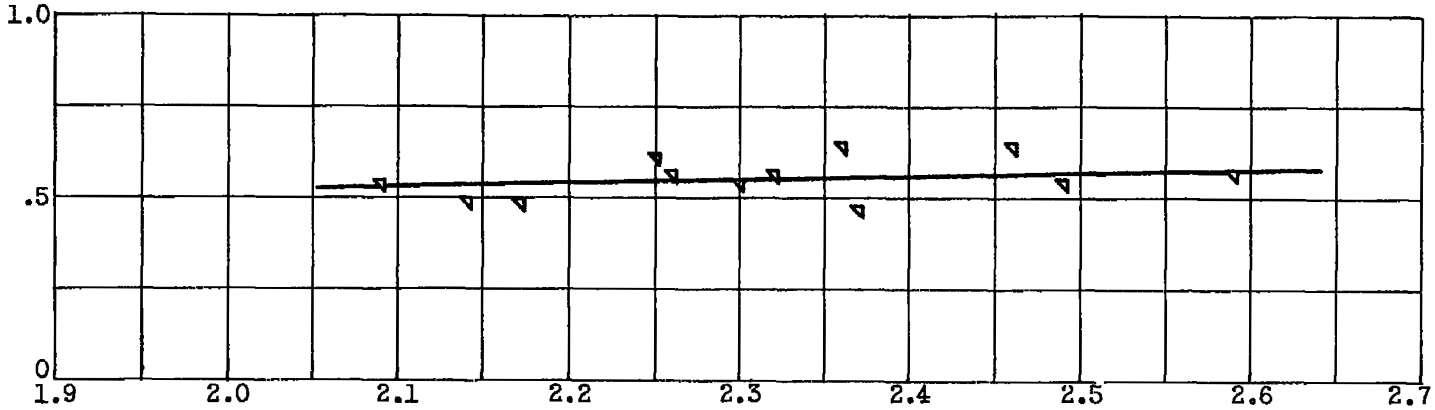


(a) Fluorine-oxygen mixtures with JP-4; thrust, 1000 pounds; chamber pressure, 600 pounds per square inch (ref. 2).

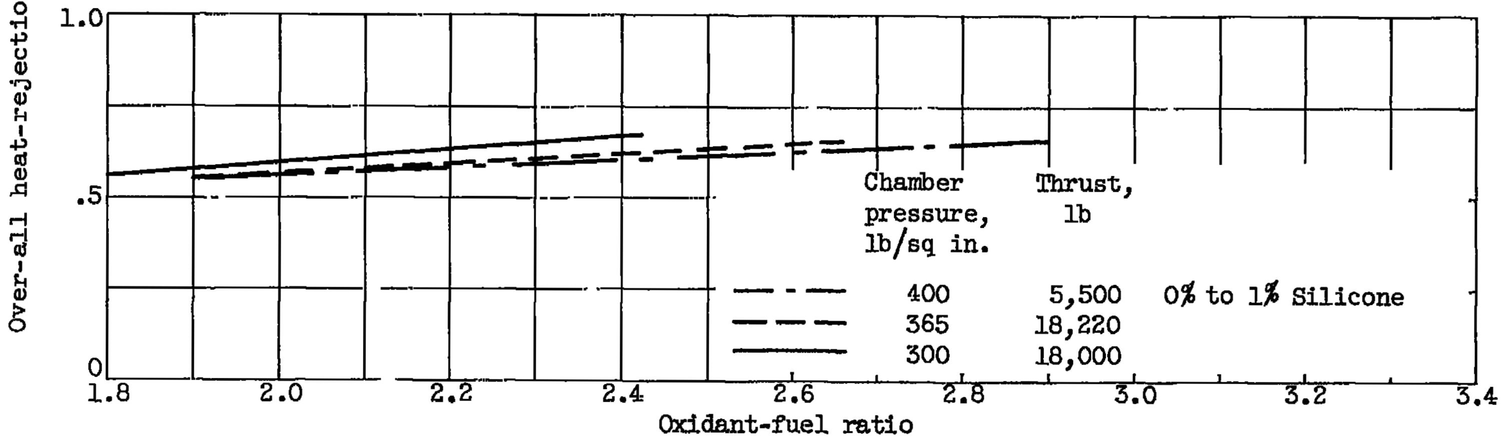


(b) Fluorine-oxygen mixtures with JP-4 (ref. 4).

Figure 9. - Experimental heat-rejection rate as function of oxidant-fuel weight ratio.



(c) 15 Percent fluorine and 85 percent oxygen and JP-4; chamber pressure, 350 pounds per square inch; thrust, 5000 pounds (1% silicone in fuel) (ref. 3).



(d) Hydrocarbon fuels and oxygen (ref. 7).

Figure 9. - Concluded. Experimental heat-rejection rate as function of oxidant-fuel weight ratio.

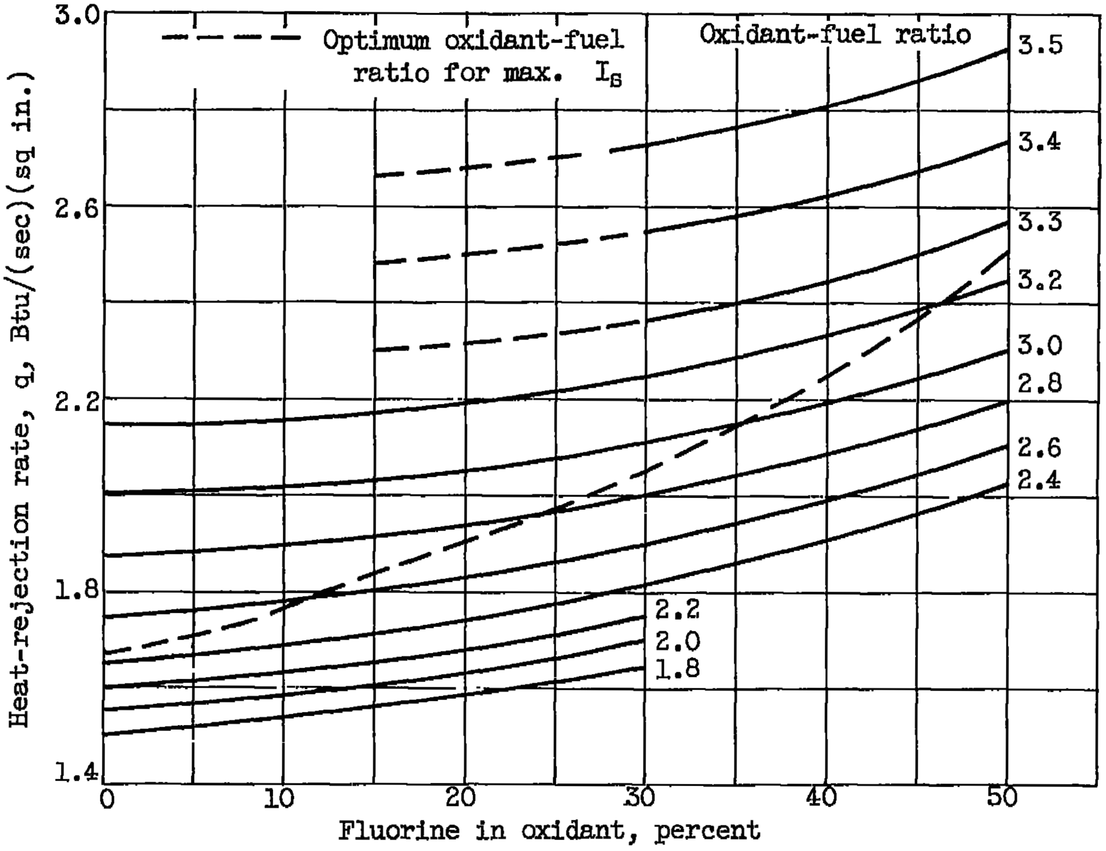


Figure 10. - Heat-rejection rate as function of percent fluorine in oxidant. Chamber pressure, 600 pounds per square inch; thrust, 1000 pounds. (Based on data at 0, 30, and 70% fluorine, ref. 3).

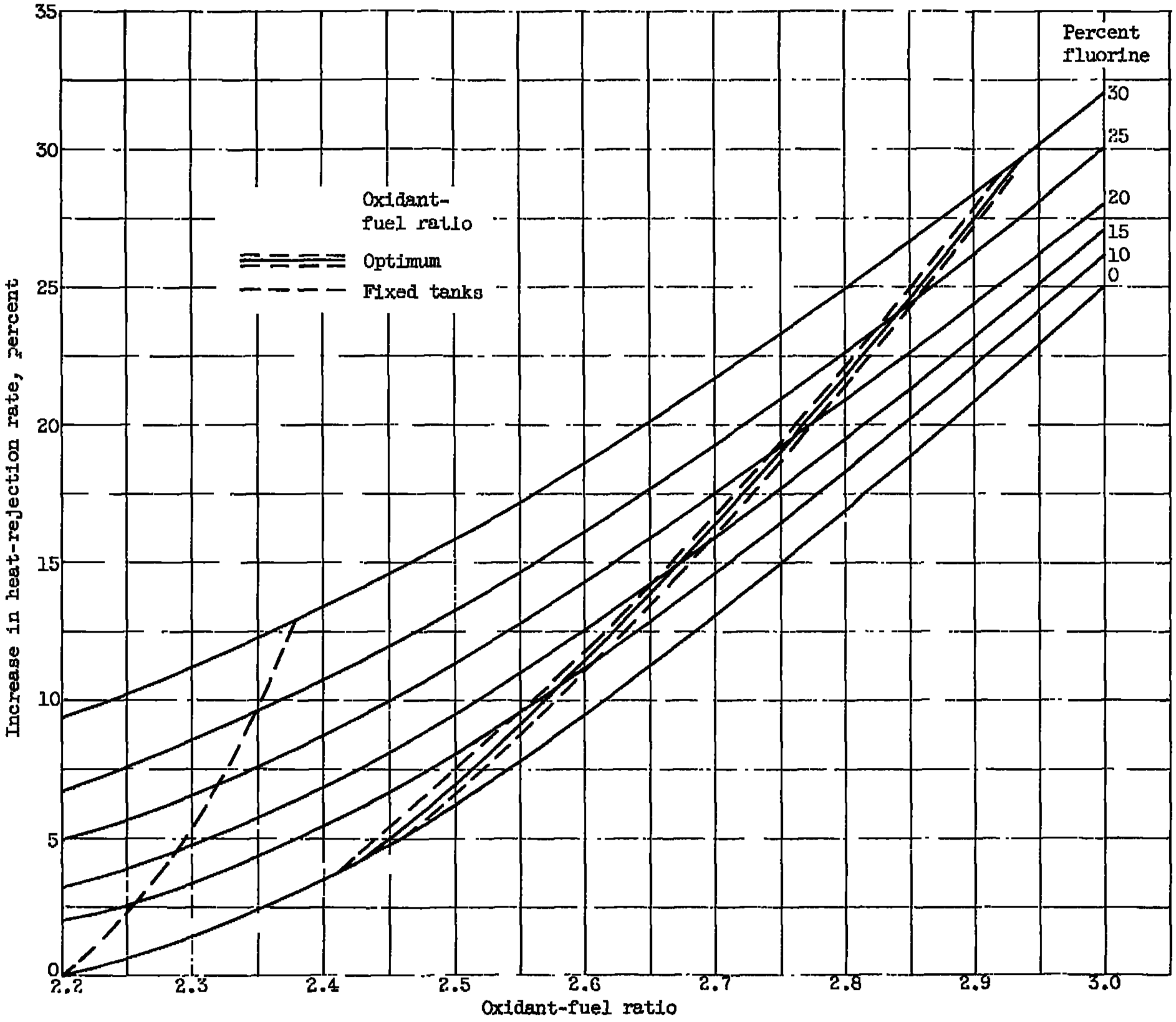


Figure 11. - Predicted increase in experimental heat-rejection rate with fluorine added to oxidant in Vanguard first stage.

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