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# ANALYSIS OF CAPABILITY OF NASA LAUNCH VEHICLES WITH FLUORINE-OXYGEN MIXTURES AS AN OXIDANT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# ANALYSIS OF CAPABILITY OF NASA LAUNCH VEHICLES WITH FLUORINE-OXYGEN MIXTURES AS AN OXIDANT*

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## SUMMARY

The improvement in mission performance as a result of the addition of up to 30 percent fluorine (flox) to the oxidant was calculated for several NASA launch vehicles. Results are presented primarily for the Atlas-Centaur-Surveyor mission with flox in the Atlas stage. Results are also presented for the use of flox in the first stage of the Atlas-Agena, Thor-Agena, and Saturn V vehicles for the EGO, Nimbus, and Apollo missions, respectively. The use of flox in the Atlas stage of the Atlas-Centaur vehicle is compared briefly with the use of an additional upper stage or alternate launch vehicles (Titan II - Centaur and Saturn IB - Centaur) for the Surveyor, Synchronous Orbit, and 0.20 AU Solar Probe missions.

The calculated increase in payload as a result of fluorine addition to the oxidant is dependent on the specific launch vehicle and the mission. For the Atlas-Centaur-Surveyor mission, the use of 30 percent flox in the Atlas results in a payload increase of approximately 750 pounds. This increase in mission capability is a direct function of the assumed engine performance, which is based on very limited experimental data. Even if the engine performance with flox follows frozen-expansion characteristics, however, the payload increase at 30 percent flox is 560 pounds.

## INTRODUCTION

Continuing emphasis on improving launch vehicle capability has generated an interest in the use of liquid fluorine-oxygen (flox) mixtures as an oxidant for various NASA launch vehicles. Substitution of flox for liquid oxygen (lox) in appropriate launch vehicles is potentially a very effective means of extending their mission capability. The interest in flox is presently manifested in contracts with industry to establish the compatibility of flox with existing launch vehicle hardware and to define more precisely the propulsion improvements available. Preceding this experimental effort, mission analyses were

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*Title, Unclassified.

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conducted at the Lewis Research Center to determine the increased mission capability potentially available through the use of flox. This report summarizes some of the Lewis studies.

Emphasis herein will be on the increased mission capability available through the use of flox for mixtures containing up to 30 percent fluorine in the oxidant. Results are presented principally for the Atlas-Centaur-Surveyor mission with flox in the Atlas stage. The use of flox in the first stage of the Atlas-Agena, Thor-Agena, and Saturn V vehicles is also discussed. Finally, the use of flox in launch vehicles is compared briefly to alternate approaches for conducting three specific space missions (Surveyor, Synchronous Orbit, and 0.20 AU Solar Probe missions).

The increased mission capability through the use of flox is, of course, a direct function of the assumed engine performance. The engine performance assumed herein is based primarily on theoretical engine performance calculations modified in the light of the available experimental data. Unfortunately, only very limited experimental engine-performance data are available, making the precise definition of flox engine performance difficult at this time. In view of this uncertainty, and due to its importance in establishing mission capability, the effect of fluorine addition on the performance of the Atlas propulsion system will be discussed in detail.

## SYMBOLS

| | |
|---|---|
| $A_{ex}$ | nozzle exit area, sq ft |
| $C^*$ | characteristic exhaust velocity, ft/sec |
| F | thrust, lb |
| I | specific impulse, sec |
| MF | stage propellant fraction |
| P | pressure, lb/sq ft |
| q | dynamic pressure, lb/sq ft |
| O/F | engine mixture ratio |
| $\Delta V$ | characteristic velocity, ft/sec |
| $W_G$ | gross weight, lb |
| $W_P$ | propellant weight, lb |

Subscripts:

| | |
|---|---|
| o | ambient |

[redacted]

| | |
|---|---|
| sl | sea level |
| vac | vacuum |

## PERFORMANCE OF ATLAS PROPULSION SYSTEM

Very little experimental data on the performance increases to be gained by adding fluorine to the oxidant of a lox RP-1 engine have been generated. Some tests were run at Lewis on small engines when flox was being considered as a means of increasing the capability of the Vanguard vehicle (refs. 1 to 4). In addition, in 1959 Rocketdyne ran three short-duration tests on a 150,000-pound-thrust lox RP-1 engine similar to the Atlas booster engine with mixtures of approximately 10, 15, and 20 percent fluorine in the oxidant. These data and a discussion of associated test techniques are reported in reference 5.

Data obtained by Rocketdyne for the Atlas booster engine are presented in figure 1 along with curves of theoretical equilibrium and frozen specific impulse. Similar theoretical curves are presented in figure 2 for the Atlas sustainer engine (no experimental data for the sustainer engine are available for comparison). To facilitate comparison of the theoretical and experimental data, the theoretical curves of figures 1 and 2 have been shifted so that the theoretical frozen expansion, zero-flox point, matched the actual lox engine performance. The experimental flox data were obtained by Rocketdyne on runs of 11- to 14-seconds duration with flox. For the 10- and 20-percent flox runs, an immediate transition was made at the termination of flox operation to operation with lox. These lox points are indicated in figure 1(b) at zero percent flox and allow a direct comparison between flox RP-1 and lox RP-1 operation. The experimental data in figure 1 are adjusted to standard sea-level conditions and a chamber pressure of 548 pounds per square inch absolute. The mixture ratios used by Rocketdyne in obtaining the flox data are presented in figure 1(a).

In general, lox RP-1 engines tend to follow a theoretical frozen-expansion-performance curve. Inherently, it might be expected that adding a reactive element like fluorine to the oxidizer would increase the delivered specific impulse more than that predicted by theoretical frozen-expansion calculations. In fact, the limited test data bear out this expectation. The problem is that the data are too fragmentary to assess the amount of this additional improvement with confidence. For example, the assumption of frozen-expansion characteristics for flox engine performance in the light of the Rocketdyne data would appear pessimistic. On the other hand, a literal extrapolation of the Rocketdyne data to higher percentages of fluorine would appear overly optimistic. Nonetheless, to proceed with the mission-performance calculations, some engine-performance assumptions must be made to extend the engine-performance data to higher percentages of fluorine and other mixture ratios.

The engine performance used herein is indicated by the curves labeled assumed in figures 1 and 2 and is based on the following assumptions:

(1) The $C^*$ efficiency (ratio of actual to theoretical characteristic exhaust velocity) is constant with fluorine addition.

[redacted]

(2) The nozzle thrust coefficient is constant with fluorine addition - equal to that for lox engine operation.

The second assumption requires some clarification. First, theoretical-performance calculations indicate that adding fluorine to a lox RP-1 engine will tend to decrease the nozzle thrust coefficient as a result of an increase in the effective specific-heat ratio of the exhaust gases. This partly offsets the specific-impulse improvement due to increased $C^*$. On the other hand, any increased recombination in the nozzle will tend to increase the thrust coefficient. Examination of the available test data indicated that the net effect could be represented reasonably by assuming no change in thrust coefficient from that obtained during lox engine operation. The assumed performance data of figures 1 and 2 are thus based on thrust coefficient values from lox RP-1 calculations at the mixture ratios indicated, and the increase in specific impulse results directly from the calculated improvement in $C^*$.

Engine specific impulse values used in the subsequent mission-performance analysis are based on the foregoing assumptions. Generalized plots of assumed engine specific impulse are presented in figures 3(a) and (b) for the Atlas booster and sustainer engines, respectively. The data are based on operation of the Atlas engines at rated thrust. For this mode of engine operation, the data presented in figure 3 can be applied to both sea-level and vacuum conditions.

Normally, when a detailed mission analysis is conducted with the Atlas boost vehicle, a detailed engine simulation is used wherein engine thrust, fuel, and oxidant flow are functions of pump inlet conditions and ambient pressure. For the present study, there was insufficient data on flox performance to utilize the detailed engine model. A simplified engine model was used and applied to both the lox and the flox missions so that valid comparisons could be made. The simplified Atlas engine model was based on constant engine propellant flow rates throughout the flight. The booster and sustainer engine mixture ratios were constant and equal to the "tanked" ratio of impulse propellants. Engine thrust was varied only as a function of ambient pressure as given by the equation

$$F = F_{sl} + A_{ex}(P_{sl} - P_o)$$

For the lox calculations, values of sea-level thrust $F_{sl}$, nozzle exit area $A_{ex}$, and engine weight flow were selected on the basis of yielding the best agreement with calculations for the detailed engine model. For the flox calculations, $F_{sl}$ and $A_{ex}$ were kept the same as for the lox calculations, while engine weight flow was varied in inverse proportion to the specific-impulse improvements presented in figure 3. Table I presents a comparison of some of the values of specific impulse used in the study. The mixture ratios presented in table I are for full Atlas tanks. It should be noted that the values of specific impulse shown in table I for lox operation do not correspond precisely to the reference values normally given by Rocketdyne for the Atlas propulsion system. Rather, they were selected to give the best agreement over the entire flight with calculations based on a detailed engine simulation.

## ATLAS-CENTAUR-SURVEYOR MISSION PERFORMANCE

### Mission Performance Map

Figure 4 presents the effect of fluorine addition to the Atlas for the Atlas-Centaur-Surveyor mission. The results are based on the assumed engine performance presented in figure 3. The data presented in figure 4 are based on the use of the 165K (165,000-pound-thrust) Atlas booster engines recently incorporated on the Centaur launch vehicle. (The results were obtained by integrating the launch trajectories on the Lewis Research Center 7090 digital computer.) The Atlas engines with flox are assumed to operate at the same thrust level as the present engines, and nominal lox stage jettison weights are used throughout. (The vehicle data were taken from ref. 6.) The flox vehicle performance is presented in figure 4 relative to the performance of the nominal lox vehicle. The payload increase shown is at translunar insertion (Centaur burnout) and is presented as a function of Atlas propellant loading. The higher density of the flox allows an increase in Atlas propellant loading compared with the lox vehicle. For a given percent flox, the Atlas propellant loading in figure 4 is varied from the propellant weight of the nominal lox vehicle to a maximum loading (full tanks) corresponding to the same propellant volume as for the nominal lox vehicle.

At 30 percent flox and full tanks the injected payload increase is approximately 750 pounds. The payload calculated in this study for the nominal Atlas-Centaur-Surveyor mission is 2280 pounds; hence, the 750-pound increase in payload represents a 33-percent increase in payload for this mission. The payload increase with flox is essentially linear with percent flox over the range presented. With no increase in Atlas propellant weight, the payload improvement with 30 percent flox is 540 pounds, which is directly attributable to the increase in specific impulse. The remainder of the improvement to 750 pounds is due to increased propellant loading.

With full tanks, the engine O/F ratios are dictated by the relative volumes of the Atlas propellant tanks and the propellant densities. When the O/F ratios shown in figure 4 are compared with the data in figure 3, it can be seen that the resultant full-tank O/F ratios are near optimum in terms of specific impulse. If it is desired to launch at less than full tanks, there is a choice between off-loading either the oxidant or the fuel or some combination of the two. The off-loaded data presented in figure 4 and all subsequent figures are based on off-loading only the oxidant. To maintain the best predicted specific impulse, it would generally be somewhat better to off-load both fuel and oxidant.

As shown in figure 4, the best performance is obtained by launching the flox Atlas with full propellant tanks. Two possible problem areas associated with the resultant increased launch weight are a change in vehicle structural loads and a decreased launch acceleration. The effect on vehicle structural loads will be discussed in the section Effect of Fluorine Addition on Structural Loads. The problem of launch acceleration is one of the vehicle lateral drift prior to clearing the launch facility. The Atlas engines were assumed to operate at rated thrust levels, and as the Atlas propellant load is increased, the launch thrust-to-weight ratio decreases. The reduced launch acceleration allows more time for lateral drift prior to clearing the launch facility. Recent incorporation of 165K Atlas booster engines on the Centaur launch vehicle (in place of the 154.5K engines) should keep the flox vehicle launch acceleration to an acceptable level. With the 165K booster engines, the nominal lox launch thrust-to-weight ratio is approximately 1.27. At 30 percent flox and full tanks, the launch thrust-to-weight ratio decreases to approximately 1.22. This is, however, equal to the launch thrust-to-weight ratio previously achieved by the nominal Centaur launch vehicle with 154.5K booster engines and should, therefore, be acceptable.

## Comparison With Frozen Expansion Engine Performance

The payload increases presented in figure 4 are a direct function of the assumed Atlas engine performance. Since the assumed performance is based on very limited experimental data, it is worthwhile to examine the impact on mission performance if subsequent experimental engine data do not substantiate this performance. In figure 5 the Surveyor mission capability for the assumed Atlas engine performance is compared with that obtainable if the increase in engine specific impulse with fluorine addition follows frozen-expansion characteristics. The data in figure 5 are for rated Atlas thrust and Atlas propellant loadings corresponding to full tanks. The payload increase for the assumed Atlas engine performance is the same as that presented in figure 4. The frozen Atlas performance is based on a specific-impulse increase corresponding to theoretical frozen expansion in the exhaust nozzle (figs. 1 and 2). As discussed earlier, experimental Rocketdyne data on the Atlas booster engine indicate that the specific-impulse improvement with flox will be greater than that predicted by frozen-expansion calculations. Nonetheless, even with frozen-expansion-performance characteristics, the increase in Surveyor mission payload is substantial. The payload increase based on frozen Atlas performance at 30 percent flox is 560 pounds or about 75 percent of the improvement obtained with the assumed engine performance.

## Comparison of Engine Operating Modes

A factor that can significantly influence the mission-performance improvement with flox is the assumed engine operating mode (thrust level). The previous discussion has considered engine operation at rated thrust. To demonstrate the advantage of uprating the Atlas engine thrust, three possible Atlas operating modes are compared in figure 6 for the Surveyor mission. The results presented are for 20 percent fluorine addition to the Atlas oxidant. The three modes of operation compared in order of increasing thrust are (1) operation at nominal thrust, (2) operation at nominal propellant weight flow rate, and (3) operation at nominal volume flow rate. Nominal stage jettison weights were assumed for all three modes.

The lower curve in figure 6 demonstrates mission performance when the Atlas engines (booster and sustainer) are operated at nominal rated thrust levels. This is the same as the data previously presented in figure 4 for

20 percent flox. With this mode, the Atlas engines operate essentially at nominal chamber pressure, and the propellant weight flow rate is decreased approximately 4 percent (inversely proportional to the specific-impulse increase at 20 percent flox).

The middle curve in figure 6 displays the effect on mission performance if the Atlas engines are operated at their nominal weight flow rate. The improvement in mission performance is due to the uprated thrust for this mode, which amounts to approximately a 4-percent thrust increase at 20 percent flox. This mode also requires an approximate 4-percent increase in chamber pressure.

The top curve in figure 6 displays the effect of operating the Atlas engines at their nominal propellant volume flow rate. Attendant with this mode is an increased weight flow rate over the nominal weight flow rate as a result of the increased propellant density. The increased thrust (about 8 percent over rated thrust) accompanying the flow-rate increase results in the mission-performance improvement shown. This mode results in approximately an 8-percent increase in chamber pressure.

Selection of an acceptable flox engine operating mode requires a careful evaluation of engine cooling and turbopump limits and structural limits on the thrust chamber, nozzle, and thrust structure. Such an evaluation was not carried out as part of the present analysis. Hence, the mission results presented in the report are based on operating the flox engines only at nominal rated thrust.

## Effect of Fluorine Addition on Structural Loads

In order to determine whether significant structural changes were necessary, the flight loads for a full tank 30-percent flox Atlas were compared with those for a nominal lox Atlas for the Atlas-Centaur-Surveyor mission. Two flight conditions, maximum dynamic pressure (q) and booster engine cutoff were examined.

Rigid body-bending-moment and axial load distributions were calculated at maximum q for the flox Atlas with the assumption that it would be required to fly at the same maximum allowable angle of attack calculated for the lox vehicle. This limiting angle of attack (maximum permitted by structural limitations) was determined for the lox Atlas vehicle by a trial-and-error computation. For both the lox and flox vehicles, rigid body-bending moments were increased by 40 percent to account for the additional loads due to wind gusts, aeroelastic effects, beam columning, and dispersions in flight conditions. Also, the calculated moments were multiplied by a safety factor of 1.25 to produce ultimate design loads. The allowable bending-moment distribution reflects the existence of compression due to axial forces and considers the propellant tanks to be pressurized to minimum vent valve settings. The comparison between ultimate applied and ultimate allowable moment distributions for the two configurations is shown in figure 7. The applied moment for the flox Atlas vehicle is seen to be less than that for the lox Atlas vehicle and less than the allowable value. Consequently, the flox Atlas vehicle is capable of flying the same angle of attack at maximum q as the lox Atlas vehicle without requiring an increase in structural strength. The lower loads are attributed principally to the fact that the maximum q for the flox Atlas trajectory is less than that for the lox Atlas trajectory.

At booster engine cutoff, both the flox and lox Atlas vehicles experience the same axial load factor, since in both cases the cutoff was assumed to occur at an axial thrust-to-weight ratio of 5.8. The increased payload weight for the flox vehicle causes slightly larger axial loads on the structure. These loads, however, remain within the present capability of both Atlas and Centaur stages. The operational interstage adapter design has not been established at this time. It will experience a larger axial load of about 2 percent in the flox version of the vehicle; consequently, the change in interstage structural requirements, if any, will be small.

## AGENA MISSION PERFORMANCE

To illustrate the advantages of fluorine addition to Agena launch vehicles, a typical mission was investigated for both the Atlas-Agena and the Thor-Agena.

### Atlas-Agena-EGO Mission

The effect of fluorine addition to the Atlas for the Atlas-Agena-EGO mission is presented in figure 8. This mission-performance map is similar to the one presented in figure 4 for the Atlas-Centaur-Surveyor mission. The mission performance presented in figure 8 is again based on the assumed Atlas engine performance presented in figure 3. Atlas engine thrusts were held to rated values (154.5K Atlas booster engines), and nominal Atlas and Agena jettison weights were assumed.

At 30 percent flox and full tanks the payload increase for the EGO mission is approximately 570 pounds. Nominal payload capability for the present EGO mission is approximately 1120 pounds (ref. 7). At lower percentages of flox the payload increase is proportionally lower. The launch thrust-to-weight ratio for the nominal EGO launch vehicle is approximately 1.33. With 30 percent flox and full tanks, this ratio decreases to about 1.26.

The effect of obtaining a lower specific-impulse increase (corresponding to frozen expansion) or the effect of uprating flox engine thrust has not been investigated for the EGO mission. The trends should, however, be similar to those presented previously for the Atlas-Centaur-Surveyor mission.

### Thor-Agena-Nimbus Mission

The effect of fluorine addition to the Thor for the Thor-Agena-Nimbus mission is presented in figure 9. Since the Thor engine is similar to the Atlas booster engine, the Thor engine performance with flox was taken from figure

3(a). Nominal Thor engine thrust and nominal Thor and Agena stage jettison weights were assumed. At 30 percent flox and full tanks, a payload increase of 375 pounds is achieved. Nominal payload capability for the present Nimbus mission is 893 pounds (ref. 7).

Compared with the Atlas-Centaur-Surveyor mission and the Atlas-Agena-EGO mission, off-loading flox for the Thor-Agena-Nimbus results in a larger relative payload penalty. This is principally a result of off-loading only the oxidant rather than a combination of oxidant and fuel to achieve an optimum mixture ratio. The Thor is more sensitive to off-loading since it has a lower nominal mixture ratio than the Atlas, and off-loading only the oxidant results in a further departure from the optimum mixture ratio for the Thor than for the Atlas. At 30 percent flox, off-loading flox to the nominal Thor propellant load results in an O/F ratio of 2.09 and a payload increase of only 215 pounds (fig. 9). Examination of figure 3(a) shows that the resultant mixture ratio of 2.09 results in a specific impulse significantly below that for an optimum mixture ratio (approx. 2.55). If, at 30 percent flox, both fuel and oxidant were off-loaded to achieve a mixture ratio of 2.55, the payload increase of 215 pounds presented in figure 9 would be increased to 296 pounds.

## SATURN V-APOLLO MISSION PERFORMANCE

To determine the potential advantage of fluorine addition to the Saturn class launch vehicles, the addition of fluorine to the S-IC stage of the Saturn V vehicle was investigated for the Apollo mission.

### F-1 Engine Performance With Fluorine Addition to the Oxidant

The S-IC stage incorporates five F-1 engines that use lox RP-1 propellants. No experimental data on fluorine addition to lox for the F-1 exists. Since the F-1 uses the same propellant combination as the Atlas, the theoretical engine data for the F-1 were modified in the same manner as that previously discussed for the Atlas engines. The resultant assumed F-1 engine performance with flox is presented in figure 10.

### Apollo Mission Performance

The effect of fluorine addition to the S-IC stage on Apollo mission performance is presented in figure 11. The payload increase shown is at translunar insertion of the Apollo spacecraft (S-IVB burnout). The full-tank limit is based on the same propellant volume used in the nominal Apollo launch vehicle with a launch thrust-to-weight ratio of 1.25. Rated F-1 engine thrust and nominal S-IC, S-II, and S-IVB stage jettison weights were assumed.

At 30 percent flox and full tanks, the payload increase at translunar insertion is 11,200 pounds. This is an increase of about 12 percent over the payload capability of approximately 90,000 pounds for the present Saturn V launch vehicle. The nominal Saturn V launch vehicle has a launch thrust-to-weight ratio of 1.25, and with 30 percent flox and full tanks, this ratio decreases to 1.20.

On a percentage basis, the payload improvement with flox for the Saturn V is considerably less than the improvement obtained for the launch vehicles discussed earlier. For example, both the Atlas-Centaur and Saturn V deliver their respective spacecraft to almost Earth escape velocity. Yet, 30 percent flox at full tanks offers approximately a 33-percent payload improvement for Atlas-Centaur and only a 12-percent improvement for Saturn V. The reason for this is that flox is used over a larger portion of the mission in the case of the Atlas vehicle. The characteristic velocity $\Delta V$ of the Atlas stage is almost 16,000 feet per second compared with about 11,600 feet per second for the SI-C. Furthermore, the payload of the Atlas-Centaur in comparison with its gross weight is less than half that for the Saturn V. Thus, the Atlas-Centaur is more sensitive to an improvement in vehicle performance than is the Saturn V.

## LAUNCH VEHICLE COMPARISON

The preceding discussion included a demonstration of the potential performance improvement in the Surveyor mission due to the addition of fluorine to the Atlas stage. In this section the use of flox in the Atlas stage of the Atlas-Centaur vehicle will be discussed for several missions. Also, the competitive position of the Atlas using flox will be compared with the use of other possible launch vehicles. Three missions with increasing energy levels will be considered: the Surveyor mission, the 24-hour Synchronous Equatorial Orbit mission, and the 0.2 AU Solar Probe mission. Performance of both the Titan II - Centaur and the Saturn IB - Centaur launch vehicles will be compared with the lox and the flox Atlas-Centaur vehicle. For the Synchronous Orbit and the Solar Probe missions, an upper (kick) stage will also be considered to augment the boost vehicle performance. It should be noted that, in this comparison, all Centaur vehicles employ at least a two-burn capability. When the specified boost vehicles are used without a kick stage to perform the Synchronous Orbit mission, a three-burn Centaur capability is required. The results of this phase of the study are based on only a preliminary analysis of vehicle performance and mission profiles, particularly in the case of the Synchronous Orbit and the Solar Probe missions. Thus, the payload values presented should be used only for comparative purposes.

The first mission to be discussed is the Surveyor mission. The payload performance for the various boost vehicles are shown in table II. The payload values tabulated are calculated for the lox Atlas-Centaur with the vehicle weight status reported in reference 6. The same Centaur stage was used on the Titan II. The present capability of the Atlas-Centaur vehicle, though adequate for the present direct-ascent Surveyor mission, does not provide a large growth capability for future unmanned lunar missions. The most likely candidate boosters for a future Surveyor are the 30 percent flox Atlas-Centaur and the Titan II - Centaur, both showing a payload greater than 3000 pounds.

When consideration is given to a more energetic mission such as the Synchronous Orbit mission shown in table III, the relative performance improvement found with the addition of flox in the Atlas-Centaur vehicle has increased markedly. For this mission, a three-burn Centaur is required if a kick stage is not used. Both the 30 percent flox Atlas and the Titan II boosters deliver a payload significantly in excess of 1000 pounds. The use of a storable propellant kick stage on the standard Atlas-Centaur vehicle also provides a comparable payload capability. Values of the kick stage gross weight, propellant loading, and mass fraction are listed in table III. The specific impulse assigned to the storable propellant stage was 305 seconds. The kick-stage mass fractions were taken as a function of propellant loading based on unpublished Lewis design studies. The Saturn IB - Centaur booster vehicle payload indicated is representative of the capability of larger NASA boost vehicles and is shown for comparison purposes only. It is interesting to note, however, that a storable propellant kick stage on this vehicle for this mission is actually a detriment to performance, whereas it improved performance for all other boosters considered. Since the three-stage Saturn IB - Centaur presently uses hydrogen-oxygen as the propellant in the two upper stages, the improvement due to additional staging is offset by the lower specific impulse of the storable propellant kick stage.

The last mission to be considered is the 0.2 AU Solar Probe mission. Performance data are tabulated in table IV for the various boost vehicles. All use a hydrogen-fluorine kick stage except the Saturn IB - Centaur where both storable propellant and hydrogen-fluorine kick stages were considered. The specific impulse of the hydrogen-fluorine kick stage was taken as 445 seconds, and the stage mass fractions were taken from unpublished Lewis design studies. This is one of the most energetic missions presently under study by NASA, and, as indicated by the payloads, it severely tries all but the Saturn IB - Centaur boost vehicle. It is doubtful that either the Atlas or the Titan II booster could be used for this mission. As can be seen from the payloads listed, the use of a kick stage tends to equalize the payload capabilities of all the boost vehicles that use the Atlas or Titan II.

## CONCLUDING REMARKS

The use of flox as an oxidant has been studied for several combinations of launch vehicles and space missions. The potential rewards for appropriate launch vehicles and missions have been shown to be substantial. For example, with the Atlas engine performance assumed herein, the use of 30 percent flox in the Atlas for the Surveyor mission results in a payload increase of approximately 750 pounds. Even if the engine performance with flox follows frozen-expansion characteristics, the payload increase at 30 percent flox is approximately 560 pounds.

Achievement of this increased payload capability is, of course, dependent on the establishment of the compatibility of flox with existing launch vehicle hardware. Also, throughout the present study, nominal lox vehicle hardware weights and residuals were assumed. A preliminary analysis of the Atlas structure (Surveyor mission) at 30 percent flox and full tanks indicated that the Atlas structural loads should not, however, increase significantly above those for the present lox vehicle.

Most important, the increased payload capabilities presented herein are a direct function of the assumed engine performance with flox. The engine-performance assumptions used are based on three short-duration runs obtained by Rocketdyne on an engine similar to the Atlas booster engine. The data extend to only 20 percent flox, and no data are available for the Atlas sustainer engine. To increase the confidence in the performance assumed, additional performance data are required for both the Atlas booster and sustainer engines. In particular, definitive data are required to at least 30 percent flox and over a range of appropriate mixture ratios.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 2, 1964

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## TABLE I. - ASSUMED ATLAS BOOSTER AND SUSTAINER ENGINE SPECIFIC IMPULSE AT VARYING PERCENTAGES OF FLUORINE ADDITION TO OXIDANT

[Rated thrust operation; engine mixture ratios based on full propellant tanks.]

| Percent flox | Engine mixture ratio, O/F | Sea-level specific impulse, $I_{sl}$ | Vacuum specific impulse, $I_{vac}$ |
|---|---|---|---|
| Atlas booster engine | | | |
| 0 | 2.287 | 254.5 | 289.3 |
| 10 | 2.345 | 259.4 | 294.9 |
| 20 | 2.406 | 264.6 | 300.7 |
| 30 | 2.468 | 269.5 | 306.4 |
| Atlas sustainer engine | | | |
| 0 | 2.287 | 216.4 | 305.4 |
| 10 | 2.345 | 220.7 | 311.5 |
| 20 | 2.406 | 224.9 | 317.4 |
| 30 | 2.468 | 229.2 | 323.5 |

## TABLE II. - PERFORMANCE DATA FOR SURVEYOR MISSION

| Booster | Percent flox | Upper stage | Payload, lb |
|---|---|---|---|
| Atlas | -- | Centaur | 2280 |
| | 20 | ↓ | 2770 |
| | [a]20 | | 2650 |
| | 30 | | 3035 |
| | [a]30 | | 2845 |
| Titan II (two stages) | -- | Centaur | 3230 |

[a] Specific-impulse improvement based on frozen expansion.

[redacted]

[redacted]

## TABLE III. - PERFORMANCE DATA FOR TWENTY-FOUR-HOUR EQUATORIAL SYNCHRONOUS ORBIT MISSION

| Booster | Percent flox | Upper stage | Kick stage (one-burn) | | | | Payload, lb |
|---|---|---|---|---|---|---|---|
| | | | Propellant | Stage propellant fraction, MF | Propellant weight, $W_P$, lb | Gross weight, $W_G$, lb | |
| Atlas | -- | Centaur | None | ----- | ---- | ---- | 675 |
| | | | Storable | 0.804 | 1665 | 3555 | 1484 |
| Atlas | 20 | Centaur | None | ----- | ---- | ---- | 1022 |
| | | | Storable | 0.817 | 1882 | 4018 | 1714 |
| Atlas | 30 | Centaur | None | ----- | ---- | ---- | 1212 |
| | | | Storable | 0.823 | 2013 | 4296 | 1850 |
| Titan II (two stages) | -- | Centaur | None | ----- | ---- | ---- | 1403 |
| | | | Storable | 0.824 | 2033 | 4342 | 1875 |
| Saturn IB (S-IB and S-IVB) | -- | Centaur | None | ----- | ---- | ----- | 7712 |
| | | | Storable | 0.894 | 7309 | 15604 | 7429 |

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TABLE IV. - PERFORMANCE DATA FOR 0.20 AU SOLAR PROBE MISSION

| Booster | Percent flox | Upper stage | Kick stage (one-burn) | | | | Payload, lb |
|---|---|---|---|---|---|---|---|
| | | | Propellant | Stage propellant fraction, MF | Propellant weight, $W_P$, lb | Gross weight, $W_G$, lb | |
| Atlas | -- | Centaur | Hydrogen-fluorine | 0.862 | 4500 | 5465 | 245 |
| Atlas | 20 | Centaur | Hydrogen-fluorine | 0.862 | 4500 | 5540 | 320 |
| Atlas | 30 | Centaur | Hydrogen-fluorine | 0.862 | 4500 | 5568 | 348 |
| Titan II (two stages) | -- | Centaur | Hydrogen-fluorine | 0.862 | 4500 | 5578 | 358 |
| Saturn IB (S-IB and S-IVB) | -- | Centaur | Storable | 0.873 | 4000 | 5440 | 860 |
| Saturn IB (S-IB and S-IVB) | -- | Centaur | Hydrogen-fluorine | 0.876 | 7000 | 9861 | 1870 |

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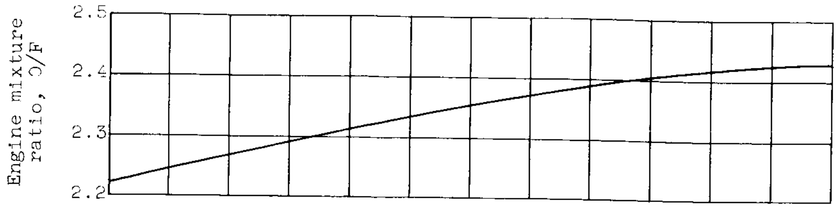
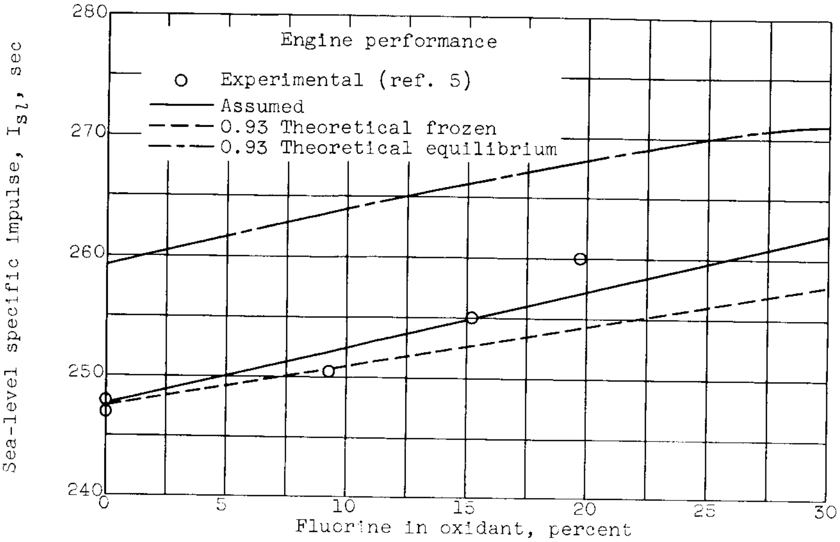


(a) Engine mixture ratios used in obtaining experimental data.



(b) Effect of fluorine addition on specific impulse.

Figure 1. - Effect of fluorine addition on Atlas booster engine performance. Sea-level conditions; chamber pressure, 548 pounds per square inch absolute; nozzle area ratio, 8.

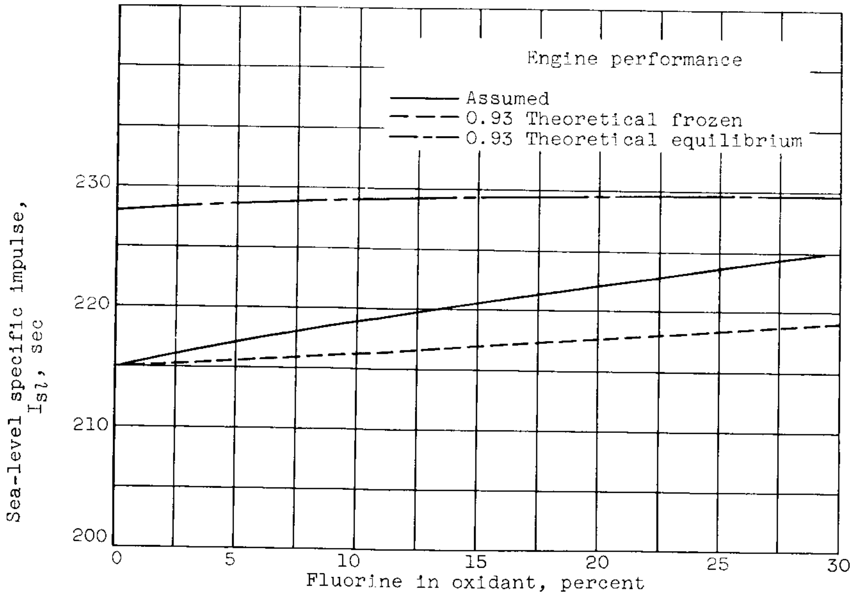


Figure 2. - Effect of fluorine addition on Atlas sustainer engine performance. Sea-level conditions; chamber pressure, 700 pounds per square inch absolute; nozzle area ratio, 25; mixture ratio, 2.27.

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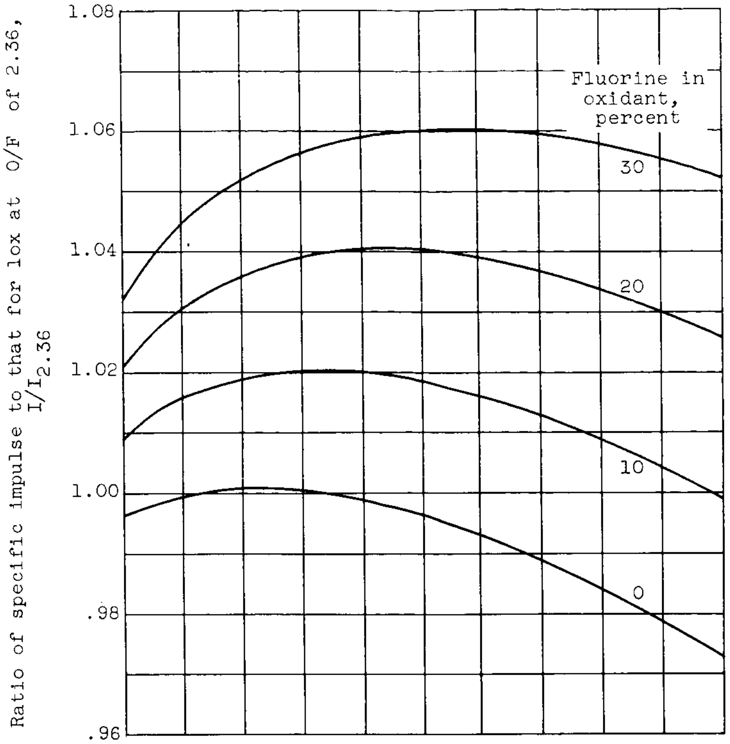
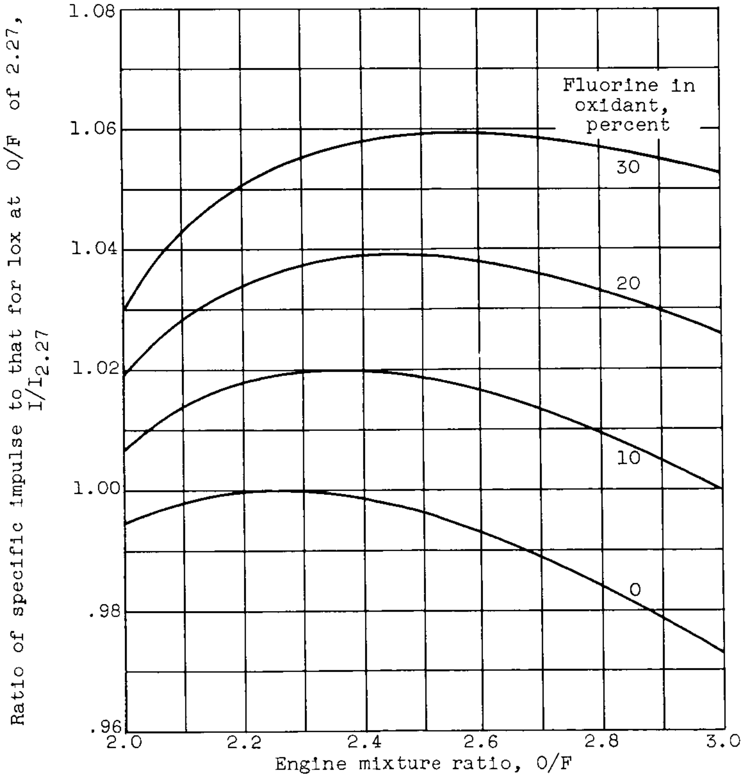


(a) Atlas booster engine.



(b) Atlas sustainer engine.

Figure 3. - Assumed effect of fluorine addition on performance.

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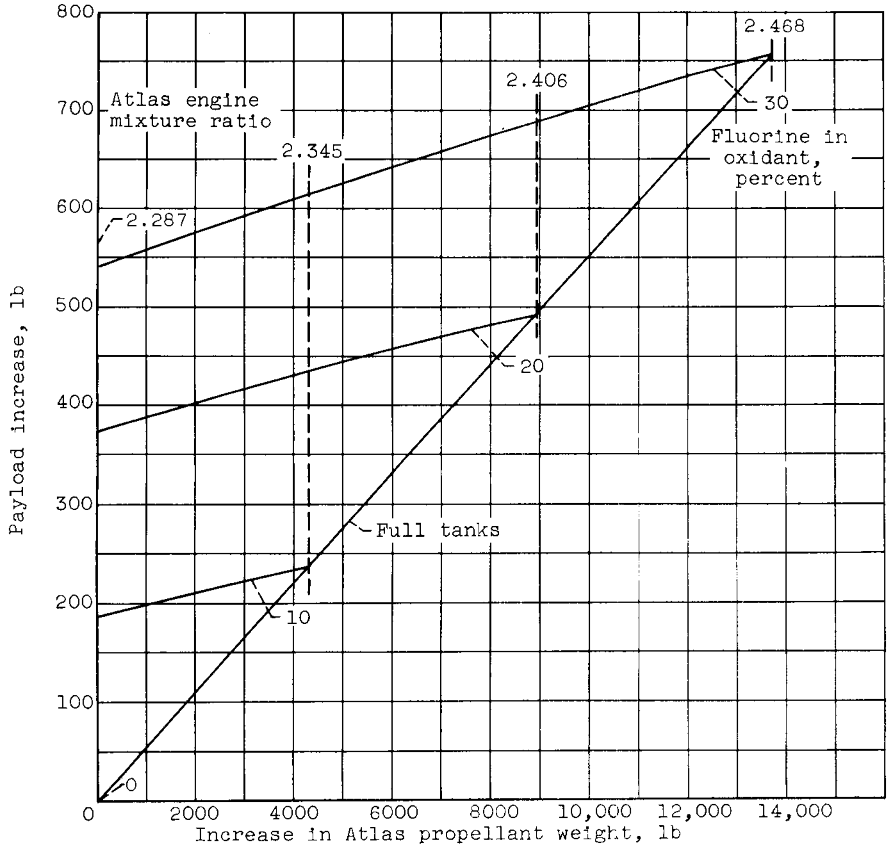

Figure 4. - Performance for Atlas-Centaur-Surveyor mission with flox in Atlas. Nominal Atlas thrust; 165K Atlas booster engines; nominal Atlas and Centaur jettison weights.

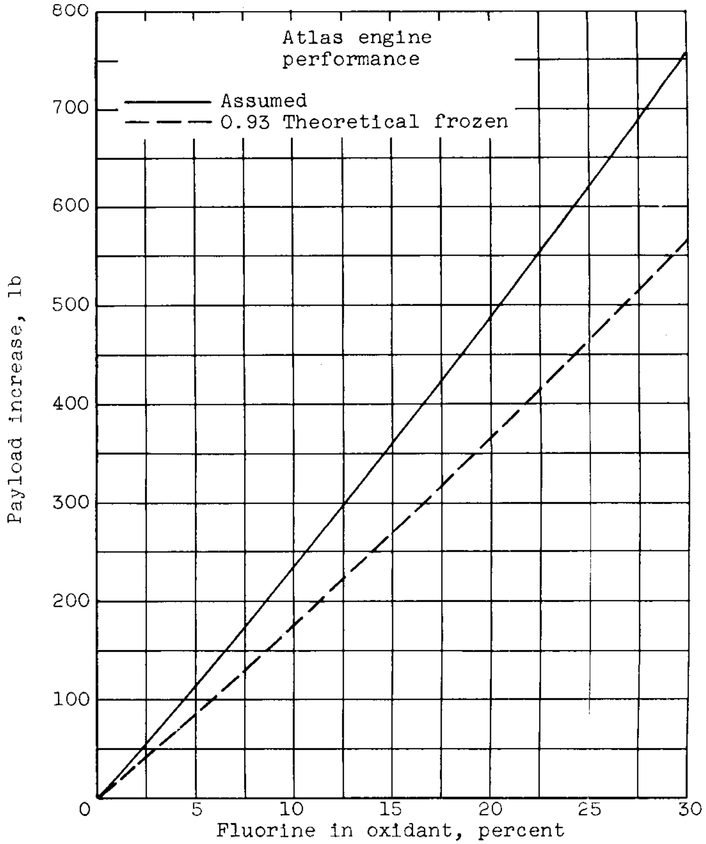

Figure 5. - Effect of Atlas engine performance assumptions on Surveyor mission capability. Full tanks; nominal Atlas thrust; 165K Atlas booster engines.

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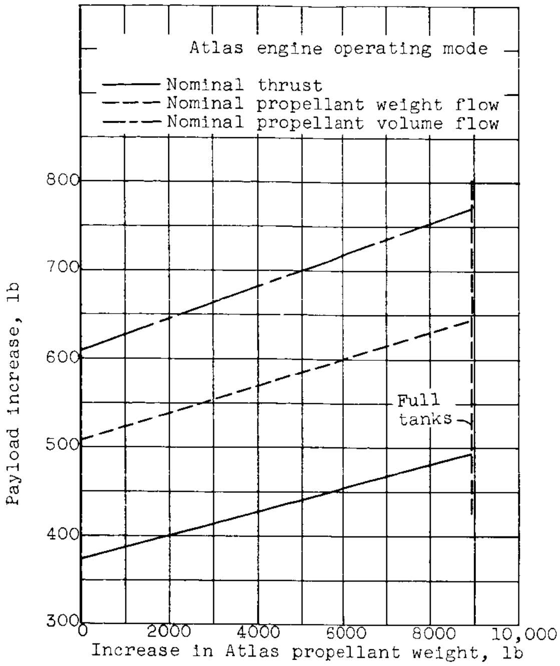

Figure 6. - Comparison of Atlas engine operating modes for Surveyor mission. Fluorine in oxidant, 20 percent.

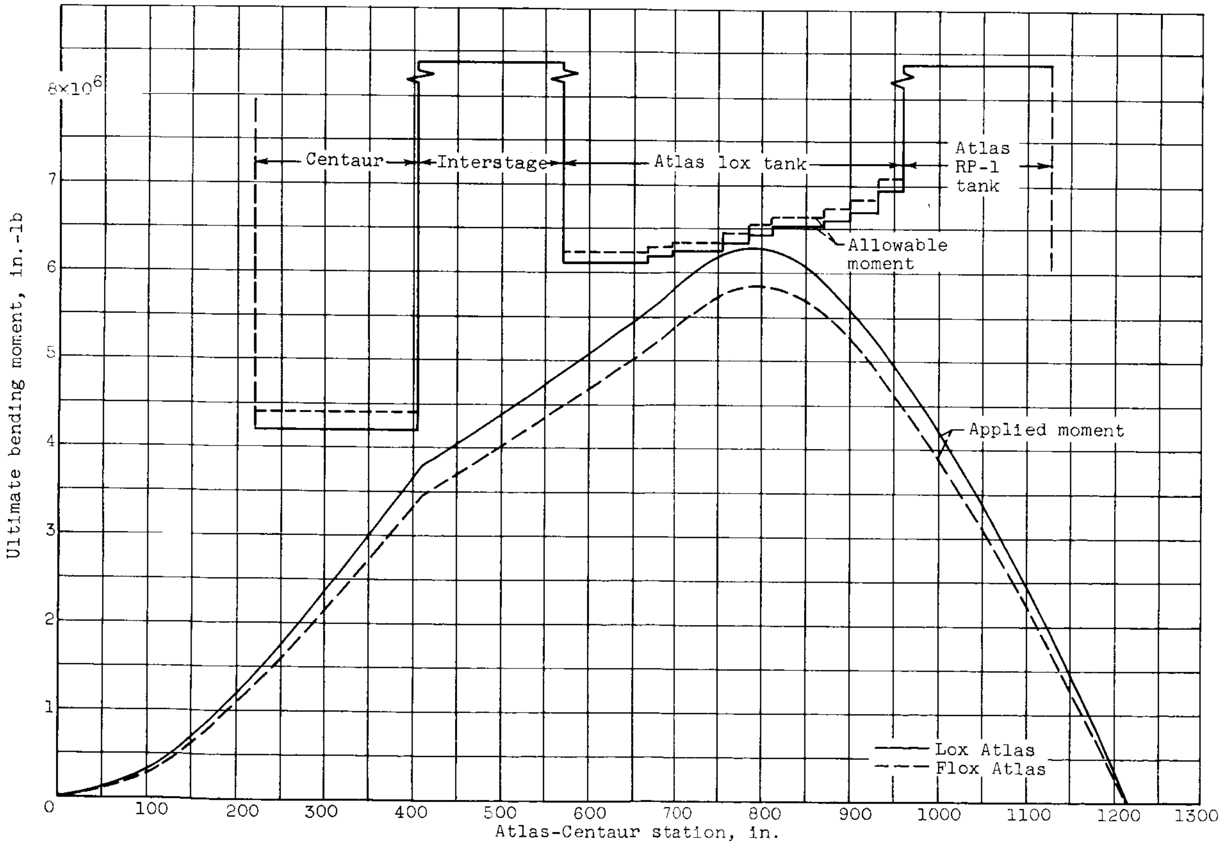

Figure 7. - Bending-moment comparison at maximum dynamic pressure of lox and flox Atlas-Centaur vehicles.

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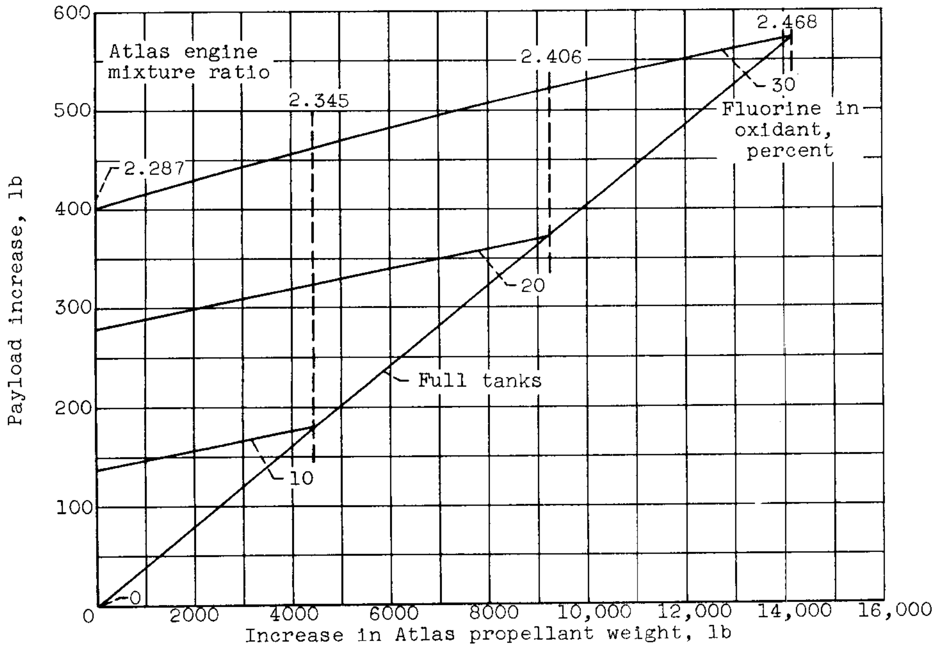

Figure 8. - Atlas-Agena-EGO mission performance with flox in Atlas. Nominal Atlas thrust; 154.5K Atlas booster engines; nominal Atlas and Agena jettison weights.

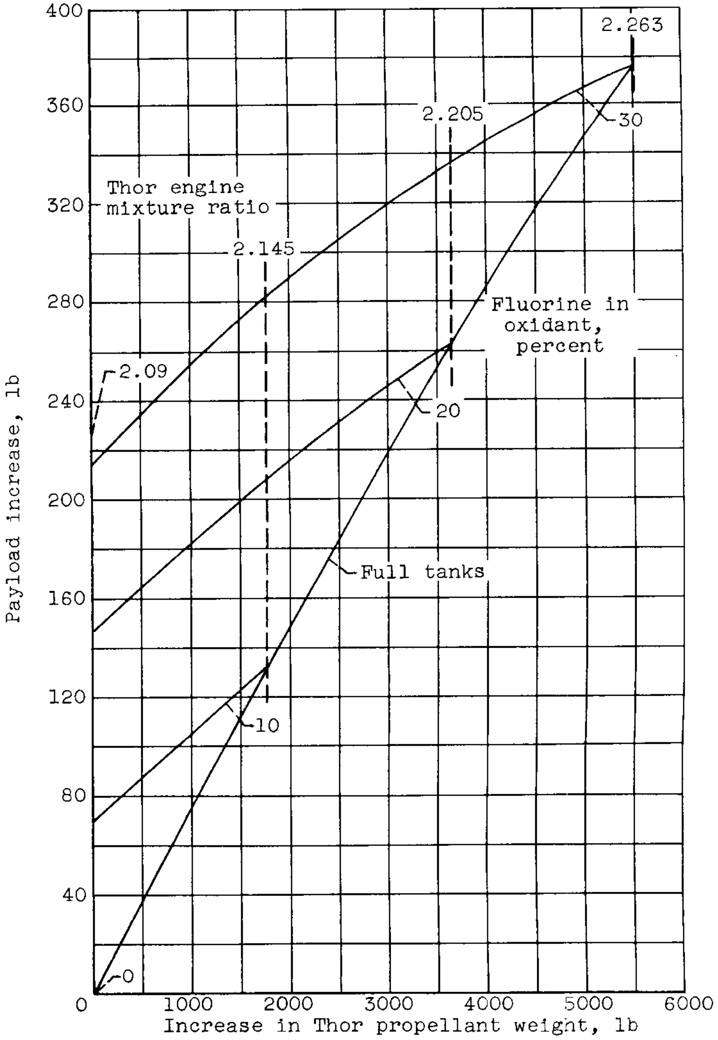

Figure 9. - Thor-Agena-Nimbus mission performance with flox in Thor. Nominal Thor thrust; 165K Thor engine; nominal Thor and Agena jettison weights.

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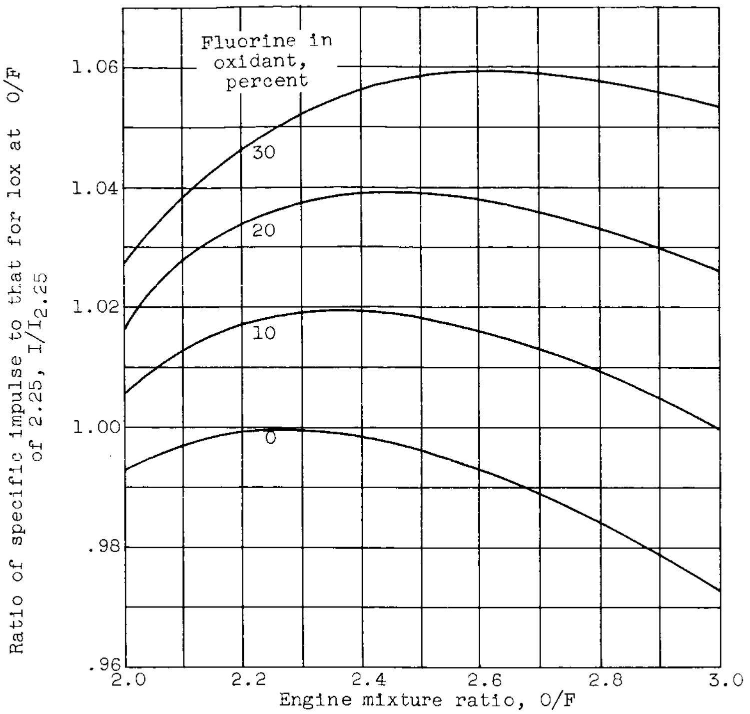

Figure 10. - Assumed effect of fluorine addition on F-1 engine performance.

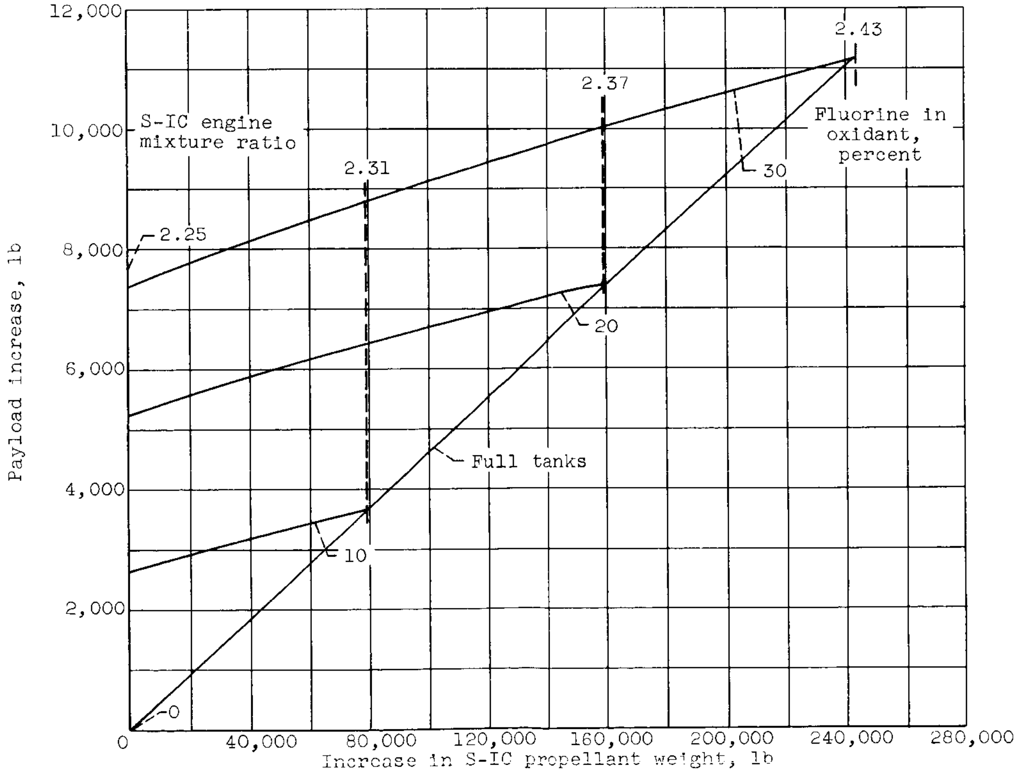

Figure 11. - Saturn V - Apollo mission performance with flox in S-IC. Nominal F-1 thrust; nominal Saturn V stage jettison weights.

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