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SOME FUEL LOSS RATE AND WEIGHT ESTIMATES OF AN OPEN-CYCLE GAS-CORE NUCLEAR ROCKET ENGINE

by Robert G. Ragsdale
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
Sixth Propulsion Joint Specialists Conference sponsored by the
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

An analysis is carried out to estimate engine weight and to show the effect on engine weight of engine thrust, specific impulse, and uranium loss rate for a gaseous fueled nuclear rocket engine. The analysis incorporates recent results from laboratory experiments on two-gas mixing, and from theoretical predictions of uranium plasma composition and opacity. Engine weights are calculated for engine thrust ranging from 100,000 to 1,000,000 lbs, for specific impulse ranging from 1000 to 1800 sec, and for hydrogen-to-uranium flow rate ratio ranging from 25 to 200. Critical mass is treated as a parameter; values of 25, 50, and 100 kg are used. All calculations are based on a 12 ft diameter cavity that is surrounded by 120,000 lbs of moderator-reflector. The total engine weight is composed of that of the moderator-reflector, pressure shell, nozzle, and turbopump. It is shown that engine weight is a relatively weak function of uranium loss rate. A reference engine with a thrust of 400,000 lbs, a specific impulse of 1800 sec, a hydrogen-to-uranium flow rate ratio of 100, and a critical mass of 50 kg is estimated to weigh 281,000 lbs.

I. Introduction

No one would argue that a specific impulse of 1800 sec or higher and a thrust level of 500,000 lbs potentially available from an open-cycle gas-core nuclear rocket engine are not desirable features. The real question to be answered is whether these obvious advantages outweigh the disadvantages of such an engine. The two main disadvantages are that an open-cycle gas-core nuclear engine would be heavy and would lose unfissioned uranium during firing. It turns out, however, that these two undesirable characteristics are interrelated, and one may be exchanged for the other. That is, engine weight can be reduced by increasing the flow rate of uranium fuel through the engine, without changing either the thrust or the specific impulse. Conversely, the uranium loss rate can be reduced by operating with a heavier engine, again without changing the thrust or the specific impulse, This paper presents the results of an analysis of this trade-off between engine weight and uranium loss rate.

The engine weight is determined by more than just the uranium loss rate. In the present study these other variables were either assigned fixed values, or else they were treated as parameters in the calculations. The total engine weight is composed of the individual weights of the moderator, the pressure shell, the turbopump, and the nozzle. This system is illustrated in Figure 1. In this study, the cavity diameter and moderator thickness were held constant. Thus moderator weight is a constant. Engine weight variations are caused by variations in the weights of the pump, nozzle, or the pressure shell.

The three independent variables of the calculations are engine thrust, specific impulse, and the hydrogen-to-uranium flow rate ratio. Reactor critical mass is treated as a parameter throughout the calculations. Thus curves of engine weight versus the various independent variables are given for three values of critical mass-25, 50, and 100 kg. Recent calculations[1] indicate that 50 kg is the best current estimate of critical mass for the configuration used in this study.

The main intermediate variable of the calculations is the engine pressure. It varies throughout the calculations, although it is not actually plotted as a dependent variable. As one of the independent variables changes, the reactor pressure changes so as to maintain a constant (critical) mass of uranium within the engine cavity. Thus the present calculations require an interrelationship among reactor pressure, engine thrust, specific impulse, reactor cavity diameter, the hydrogen-to-uranium flow rate ratio, and the required critical mass. Such a relationship was presented in Reference 2, and is used in the study reported here.

The present work has two purposes. One purpose is to present some preliminary engine weight estimates for an open-cycle gas-core nuclear rocket engine. The second purpose is to show to what extent that weight can be varied by selecting various values for engine thrust, specific impulse, and uranium loss rate.

II. Analysis

Calculation Procedure

The calculations reported here involved estimates of each of the engine component weights for a number of engine operating conditions. An engine operating condition was determined by selecting values for engine thrust, specific impulse, and the hydrogen-to-uranium flow rate ratio. The total engine weight was taken to be the sum of the individual weights of the moderator, the hydrogen turbopump, the pressure shell, and the nozzle:

$$W_e = W_m + W_p + W_s + W_n \tag{1}$$

These components are shown in a conceptual engine drawing in Figure 1.

The moderator weight W_m, was not a variable in this study. The moderator weight was determined by a

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basic engine configuration that is described in the following subsection of Analysis. In order to calculate the weights of the other three engine components, it was necessary to determine the reactor pressure required for criticality. The pressure calculation was done using the following expression presented in Reference 2:

$$M_f = 0.14 \frac{D_c^{3.3} P^{0.7}}{F^{0.28} I_{sp}^{0.28} \left(\frac{\dot{w}_{H_2}}{\dot{w}_f}\right)^{0.36}} \qquad (2)$$

Equation (2) gives the fuel mass M_f in kilograms in the engine as a function of the cavity diameter D_c in feet, the reactor pressure P in atmospheres, the engine thrust F in pounds, the specific impulse I_{sp} in seconds, and the hydrogen-to-uranium flow rate ratio $\dot{w}_{H_2}/\dot{w}_f$. For the 12 ft diameter cavity used in this study, Equation (2) becomes:

$$P = 1.7\times10^{-4} M_f^{1.4} F^{0.4} I_{sp}^{0.4} \left(\frac{\dot{w}_{H_2}}{\dot{w}_f}\right)^{0.5} \qquad (3)$$

Equation (3) was used to obtain the reactor pressure necessary to have a critical mass M_f in the engine for the various thrusts, specific impulses, and hydrogen-to-uranium flow rate ratios investigated.

Basic Engine Configuration

The spherical engine geometry used as a basis for the calculations is shown in Figure 1. The central reactor cavity contains the fissioning uranium plasma ball surrounded by flowing hydrogen propellant. This cavity is enclosed by concentric spherical regions of moderator materials. The moderator is in turn contained by an outer pressure vessel that is also spherical. The pressure shell is pierced by a supersonic exhaust nozzle at the downstream end of the reactor cavity. A turbopump system is used to pressurize the hydrogen from a tank pressure of 1 or 2 atmospheres up to the reactor cavity pressure level of approximately 1000 atmospheres.

The present calculations were based on a cavity diameter of 12 ft. This is surrounded by successive layers of (1) hot heavy water, 6 in. thick, (2) beryllium metal, 4 in. thick with 25 percent voids, and (3) cold heavy water, 26 in. thick. The total moderator thickness is 2.5 ft. The moderator weight is 120,000 lbs. The critical mass of this configuration is a little less than 50 kg[1], for U-233 fuel and with some of the hydrogen "by-passing"[3] the main portion of the reactor cavity.

Schedule of Calculations

The three variables of the calculations were engine thrust, specific impulse, and hydrogen-to-uranium flow rate ratio. Critical mass was treated as a parameter in the calculations, with values of 25, 50, and 100 kg. Table I shows the numerical values used for each of the variables.

A reference case was selected to represent a "reasonable" set of values. The reference engine has the following characteristics:

Thrust	400,000 lb
Specific impulse	1800 sec
Hydrogen-to-uranium flow ratio	100
Critical mass	50 kg

These values were chosen on the following basis. The thrust is high enough to be approximately equal to the engine weight. The specific impulse is far enough beyond a solid-core level to be of interest. The uranium loss rate is low enough so as to not be prohibitive. The critical mass represents the best current estimate. These values result in an engine weight that is not intolerably large, and in a reactor pressure that is high, but not unbelievably so. Thus, the reference engine is a sort of compromise engine that has attractive performance without excessive weight or pressure.

Pressure Shell

The pressure shell weight was obtained by using the equation for mechanical stress in a thin walled sphere. This gives the thickness of the shell in terms of the allowable stress σ, the radius of the sphere R_s, and the engine pressure P as:

$$t_s = \frac{PR_s}{2\sigma} \qquad (4)$$

This equation can be rewritten to obtain the weight of the shell material with a density ρ_s as:

$$W_s = \frac{2\pi R_s^3}{(\sigma/\rho_s)} \qquad (5)$$

For the fixed engine configuration of this study R_s had a constant value of 8.5 ft. The shell material strength to density ratio (σ/ρ_s) was taken to be 0.7×10^6 in. For a steel density of 0.29 lbs/in.^{3}, this ratio corresponds to a strength of 200,000 psi. Values higher than this are available in base metals, and weldment strengths above 150,000 psi have been reported.[4] Certainly in an actual design of a nuclear engine pressure vessel, complicated factors such as thermal stress, radiation activation and damage, and shell penetrations would have to be considered. More detailed studies[5-7] based on filament wound fiberglass designs ($\sigma/\rho_s = 2.5\times10^6$ in.), produced shell weights comparable to the ones obtained in this study.

For the numerical values used here, Equation (5) becomes:

$$W_s = 140\ P \quad (6)$$

This equation gives the pressure shell weight W_s in pounds in terms of the engine pressure P in atmospheres. This equation is shown plotted in Figure 2. A reactor pressure of 1000 atmospheres requires a pressure shell weighing 140,000 lbs.

Hydrogen Turbopump

The turbopump must provide the driving force to move the hydrogen propellant from its storage tank through the regeneratively cooled regions of the engine into the high pressure reactor cavity. Turbopump weight was calculated in this study from an equation given in Reference 8:

$$W_p = 3\ \frac{\dot{w}_{H_2}}{\rho_{H_2}}\ P_d^{2/3} \quad (7)$$

This gives the turbopump weight W_p in pounds in terms of the hydrogen flow rate $\dot{w}_{H_2}$ in pounds per second, the hydrogen density ρ_{H_2}, in pounds per cubic foot, and the pump discharge pressure P_d, in atmospheres. The pump discharge pressure was assumed to be 1.5 times the reactor cavity pressure P. The hydrogen density was taken to be 4.5 lbs/ft^3.

These values give Equation (7) as:

$$W_p = 0.875\ \dot{w}_{H_2} P^{2/3} \quad (8)$$

The hydrogen flow rate is obtained from the following relation:

$$\dot{w}_{H_2} = \frac{F}{I_{sp}} \quad (9)$$

Turbopump weight is shown in Figure 3 for a specific impulse of 1800 sec. For a thrust of 400,000 lbs and a reactor pressure of 1000 atmospheres, the turbopump weight is 19,000 lbs. A more complicated set of equations given in Reference 9 gave a weight of 24,000 lbs for this same case. Scaling pump weight estimates given in References 5 and 6 to these conditions gives values between 5000 and 6000 lbs.

Nozzle

The weight of the exhaust nozzle was obtained from the following equation:[10]

$$W_n = C\ \frac{\epsilon F}{14.7\ P} \quad (10)$$

The nozzle weight W_n is in pounds, the thrust F is in pounds, and the reactor pressure P is in atmospheres. The area ratio ϵ was taken to be 300. Reference 10 gives C values ranging from 0.05 to 0.25; 0.25 was used in the present calculations. These values give:

$$W_n = 5\ \frac{F}{P} \quad (11)$$

For a thrust of 400,000 lbs and a reactor pressure of 1000 atmospheres, the nozzle weight is 2000 lbs. Equation (11) is shown plotted in Figure 4.

Shield

A reactor shield was not included as a component in this analysis because it appears possible that little, if any, additional weight of material would be required beyond that already present as moderator and pressure shell. To really prove that this is so would, of course, require shield design calculations of detail and complexity considerably beyond the scope of the present study. However, the results of rather extensive and sophisticated shielding studies already done for the NERVA solid-core nuclear engine were used to estimate gas-core engine shielding requirements.

It is currently estimated that a 1575 MW NERVA engine would require an internal shield that weighs 3300 lbs, and perhaps an additional disk shield that might weigh up to a maximum value of 8300 lbs.[11] The actual amount of disk shield required would depend on a number of specific, mission related factors such as how much payload can also serve as a crew shield. The diameter of the internal shield is approximately 50 in. and that of the disk shield is 100 in. This means that the internal shield corresponds to 118 g/cm^2 of shielding material between the crew and the reactor core. The 8300 lb disk shield contributes another 75 g/cm^2. Thus the NERVA engine shielding requirements range from 118 up to 193 g/cm^2.

The reference gas-core engine of this study had a power level of 22,000 MW. It would require approximately 62 g/cm^2 additional shielding to account for this factor of 14 increase in radiation source strength. Thus a gas-core engine might require shielding ranging from 180 to 255 g/cm^2. The moderator and pressure shell of the gas-core configuration used in this study provide 178 g/cm^2.

Would this be enough? If a value of 210 g/cm^2 were required in the crew direction, an additional 4000 lbs of lead distributed over 1/16 of the pressure vessel surface would provide it. Of course, in an actual engine, the shielding, criticality, and pressure vessel requirements would all be considered together in an integrated design. In this regard, it is worthwhile to note the 178 g/cm^2 of moderator and pressure shell completely surrounds the reactor cavity, except for the nozzle. The point here is not to design a gas-core shield, but simply to show that incorporation of shielding requirements into an engine design is not likely to significantly change the weight estimates of this study.

III. Discussion of Results

Reference Engine

The reference engine was selected to have the following characteristics:

Thrust	400,000 lbs
Specific impulse	1800 sec
Hydrogen-to-uranium flow ratio	100
Critical mass	50 kg

The moderator weight for this engine is 120,000 lbs, as it is for all the cases of this study since the cavity and moderator dimensions were held constant. Equation (3) gives a reactor pressure of 1000 atmospheres required for the 50 kg critical mass.

The weight breakdown of the reference engine is given in Table 2. The total engine weight is 281,000 lbs. This gives a thrust-to-engine-weight ratio of 1.4. The moderator and pressure shell comprise over 90 percent of the total engine weight. They are about equal contributors.

There is a trade-off available between the moderator weight and the pressure shell weight. The moderator weight could be reduced by decreasing the moderator thickness. This would cause an increase in the critical mass, which would require a higher engine pressure. This would cause an increase in the pressure shell weight. Thus there is some optimum moderator thickness that would minimize the total engine weight. The reactor cavity diameter would add another dimension to this engine weight optimization. The effects of varying moderator thickness and cavity diameter were not included in the present study.

The engine weight is also affected by specific impulse, engine thrust level, and the hydrogen-to-uranium flow rate ratio. These effects will be discussed in the following subsections.

Specific Impulse

For the specific impulse variation, the engine thrust and hydrogen-to-uranium flow rate ratio were held at their reference engine values of 400,000 lbs and 100, respectively. Engine weights for specific impulses in the 1000 to 2000 sec range are shown in Figure 5. Curves are shown for critical masses of 25, 50, and 100 kg.

There is little effect of specific impulse. Engine weight does increase with increasing specific impulse, but the relationship is a weak one. The reason for this is as follows.

An increase in specific impulse at constant thrust is achieved by increasing the reactor power and decreasing the hydrogen flow rate. In order to radiate this higher power, the fuel temperature increases. Then, in order to maintain a constant, critical mass of uranium in the engine, the reactor pressure must be increased. The increase in reactor pressure results in a heavier pressure shell. The combined effect of higher pressure but lower hydrogen flow rate results in a lighter turbopump. The nozzle weight decreases slightly. The overall effect on engine weight of increasing specific impulse is that shown in Figure 5.

Figure 5 shows that there is no significant engine weight penalty caused by operating at a higher specific impulse. There is of course a considerable advantage of higher specific impulse because that would mean either less hydrogen propellant would be required on a given mission, or that the trip time could be reduced. Therefore, one would tend to operate at the highest possible specific impulse. Figure 5 simply says that the upper limit on specific impulse would not be placed by engine weight considerations. It would be placed by something else, such as nozzle heat transfer limitations, for example.

Figure 5 also shows that critical mass is more important in determining engine weight than is specific impulse. For example, if the critical mass of the reference engine could be reduced by a factor of 2, the engine weight could be reduced by about 90,000 lbs. If the specific impulse is reduced by nearly a factor of 2 (1800 to 1000 sec), the engine weight would be reduced by about 15,000 lbs.

The reference engine condition is shown in Figure 5. The reference engine pressure is 1000 atmospheres. A higher pressure is required if either specific impulse or critical mass values exceed those of the reference engine. The curves on Figure 5 are shown as solid lines for pressures less than 1000 atmospheres and as dashed lines for pressures greater than 1000 atmospheres. There is no particular significance to the choice of 1000 atmospheres as the change-over value. The curves are shown this way in Figure 5, and in succeeding figures as a reminder that engine pressure is varying from point to point along the curves. For the entire range of all the calculations of this study, engine pressure varied from 190 to 3700 atmospheres.

Engine Thrust Level

Engine thrust was varied over the range from 100,000 to 1,000,000 lbs. Specific impulse and hydrogen-to-uranium flow rate ratio were held constant at their reference engine values of 1800 sec and 100, respectively. The results are shown in Figure 6.

An increase in thrust causes an increase in the required engine weight. The effect of thrust is a little stronger than that of specific impulse. The reason is that an increase in thrust at constant specific impulse requires an increase in both the reactor power and the hydrogen flow rate. The higher reactor power results in a higher uranium temperature. The reactor pressure must then be increased to maintain a constant, critical mass in the engine. The increase in both reactor pressure and hydrogen flow rate causes weight increases in the pressure shell, turbopump and nozzle. The overall effect of thrust level on engine weight is shown in Figure 6.

The engine weight does not increase as rapidly as the thrust does. The reference engine, at a thrust level of 400,000 lbs, has a thrust-to-engine-weight ratio of 1.4. If the thrust is increased to 1,000,000 lbs, the thrust-to-engine-weight ratio increases to about 2.5. Figure 6 also shows the importance of critical mass, at all thrust levels. For example, a decrease in critical mass from 50 to 25 kg would allow an increase in thrust by about a factor of 4, at constant engine weight. Conversely, an increase of critical mass from 50 to 100 kg would require a decrease of thrust by about a factor of 7 at constant engine weight. The actual numbers here are not as important as the point they illustrate. There are more potential performance gains available from improvements in reactor design than from varying engine operating characteristics like specific impulse and engine thrust level.

Uranium Loss Rate

Uranium loss rate is obviously an undesirable engine characteristic. It can be reduced, but not without changing some other engine characteristic. For example, if the uranium loss rate is reduced while holding thrust and specific impulse constant, then the engine pressure and weight increases. This effect is shown in Figure 7.

The physical reasons underlying the exchange between uranium loss rate and engine weight can be explained by the following sequence of events. As a starting point, consider an engine of fixed physical design. It is initially operating with fixed values of hydrogen flow rate, reactor power, specific impulse, reactor pressure, critical mass of uranium, and uranium flow rate. Throughout the following sequence of changes, the hydrogen flow rate, reactor power, and specific impulse do not change.

At this initial steady-state operating point, the uranium flow rate into the engine is the same as the flow rate out of the engine. At time zero, the uranium flow rate into the engine is decreased to some new, lower value. The following events and conditions then transpire:

1. Since the hydrogen flow rate is still the same, the uranium flow rate out of the engine does not change, and is therefore now greater than the uranium flow rate into the engine.

2. This then causes the fuel volume inside the engine to begin to shrink down toward some new smaller steady-state size.

3. However, this would tend to decrease the total mass of uranium inside the engine below the constant, required critical mass.

4. Therefore, the fuel density would have to be increased in proportion to the decreasing fuel volume in order to maintain a constant, critical mass in the engine.

5. This would be accomplished by increasing the engine pressure.

6. Thus, at the final, new steady-state operating condition, the fuel volume is smaller, the reactor pressure is higher, the engine contains the same mass of uranium in it, and the uranium flow rate into and out of the engine is lower.

7. The final, higher reactor pressure results in a heavier pressure shell and a heavier turbopump.

Figure 7 illustrates two points. First, if the uranium loss rate is decreased by a factor of 8, the engine weight increases by a factor of 2 or less, depending on critical mass. Second, the amount of uranium required in the engine more strongly influences the engine weight than does the uranium flow rate through the engine. These results indicate that the amount of uranium to be lost on a given space mission could be varied by a factor of 2 to 4 without significantly changing the engine weight. The results also indicate that it is more important to know the critical mass pretty accurately, and to know what factors influence its value, than it is to set a goal or a "desired" value for the ratio of hydrogen-to-uranium flow rate.

IV. Conclusions

An analysis was carried out to estimate the engine weight and uranium loss rate of an open-cycle gas-core nuclear rocket engine. Results were obtained for engine thrusts ranging from 100,000 to 1,000,000 lbs and specific impulses ranging from 1000 to 1800 sec. All calculations are based on a reactor cavity diameter of 12 ft, surrounded by 120,000 lbs of moderator-reflector. Critical mass is treated as a parameter in the calculations. Values of 25, 50, which is the current estimate for this configuration, and 100 kg are used.

The results of this study indicate the following conclusions for the thrust and specific impulse ranges given above.

1. An open-cycle, gas-core nuclear rocket engine will weigh between 250,000 and 500,000 lbs for a thrust range of 100,000 to 1,000,000 lbs.

2. The moderator and the pressure shell account for most of the engine weight.

3. Engine weight is insensitive to the uranium loss rate. Therefore, the uranium loss rate for a given mission would be determined on some other basis.

4. Engine weight is more strongly influenced by the critical mass requirement than by specific impulse, thrust level, or the hydrogen-to-uranium flow rate ratio.

5. A reference engine with a thrust of 400,000 lbs, a specific impulse of 1800 sec, a hydrogen-to-uranium flow rate ratio of 100, and a critical mass of 50 kg is estimated to weigh 281,000 lbs.

V. References

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TABLE 1 SCHEDULE OF CALCULATIONS

Parameter	Units	Values used
F, thrust	lb	100,000 400,000* 1,000,000
I_{sp}, specific impulse	sec	1000 1400 1800*
$\dot{w}_{H_2}/\dot{w}_f$, hydrogen-to-uranium flow rate ratio	---	25 50 100* 200
M_c, critical mass	kg	25 50* 100

*22,000 MW reference engine.

TABLE 2 REFERENCE ENGINE WEIGHT BREAKDOWN

F = 400,000 lb

I_{sp} = 1800 sec

Critical mass = 50 kg

$$\frac{\dot{w}_{H_2}}{\dot{w}_f} = 100$$

Component	Weight, lb
Moderator	120,000
Pressure shell	140,000
Turbopump	19,000
Nozzle	2000
Engine	281,000

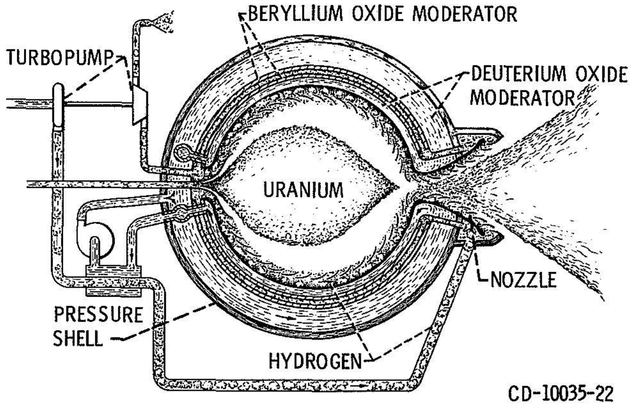

Figure 1. - Conceptual gas-core nuclear rocket engine.

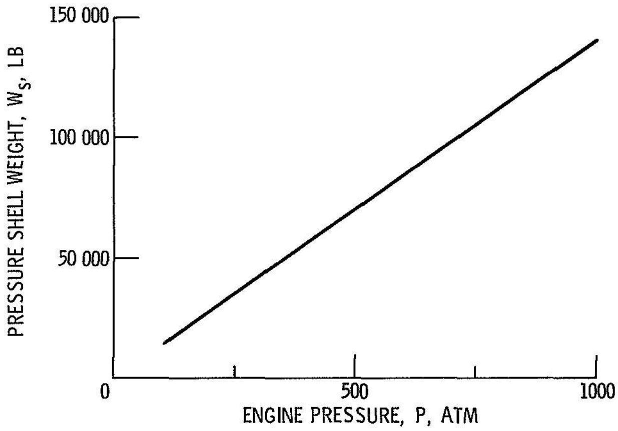

Figure 2. - Pressure shell weight; $t_s = PR_s/2\sigma$; $V_s = 4\pi R_s^2 t_s$; $W_s = \rho_s V_s = 140$ P; $\sigma/\rho_s = 0.69\times10^6$ inch; $R_s = 8.5$ feet.

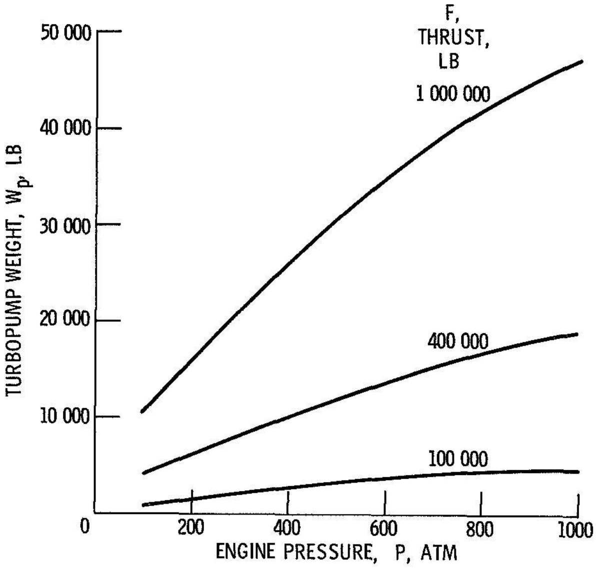

Figure 3. - Hydrogen turbopump weight for I_{sp} = 1800 seconds; $W_p = (3\dot{w}_{H_2}/\rho_{H_2}) P_d^{2/3}$.

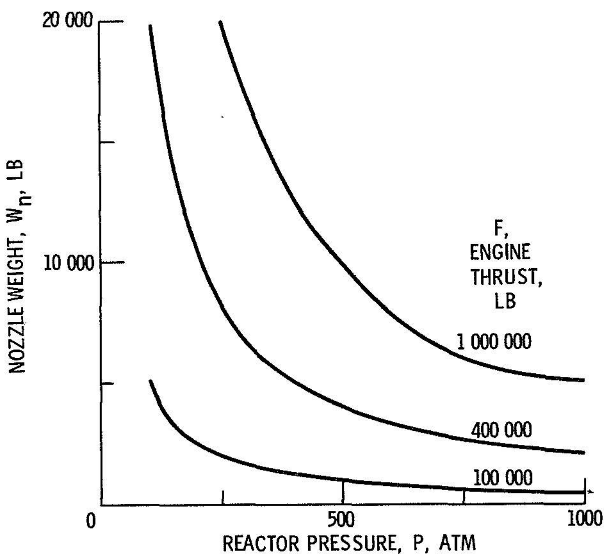

Figure 4. - Nozzle weight; $W_n = 0.25\epsilon F/14.7$ P; $\epsilon = 300$.

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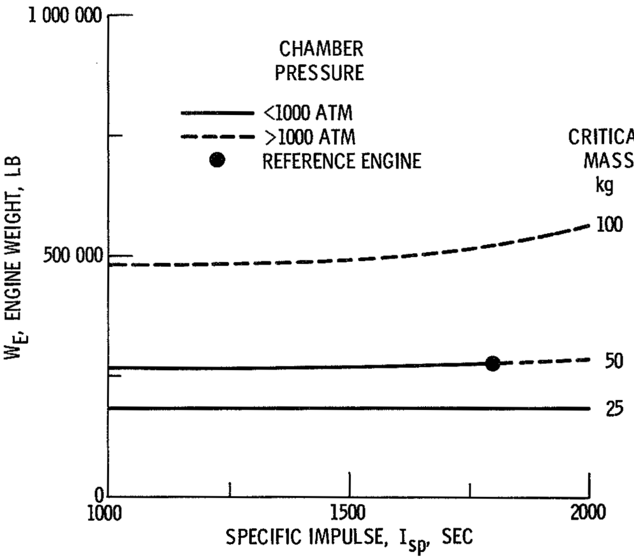

Figure 5. - Effect of specific impulse on engine weight. F = 400 000 pounds; $(\dot{w}_{H_2}/\dot{w}_f) = 100$.

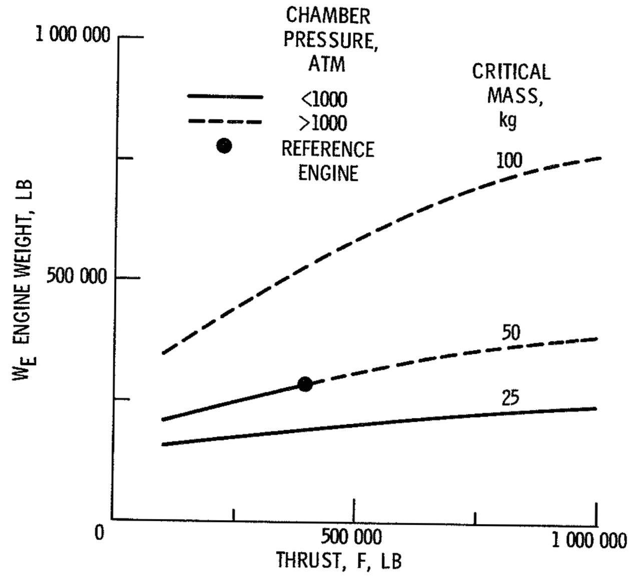

Figure 6. - Effect of thrust level on engine weight; $(\dot{w}_{H_2}/\dot{w}_f) = 100$; $I_{sp} = 1800$ seconds.

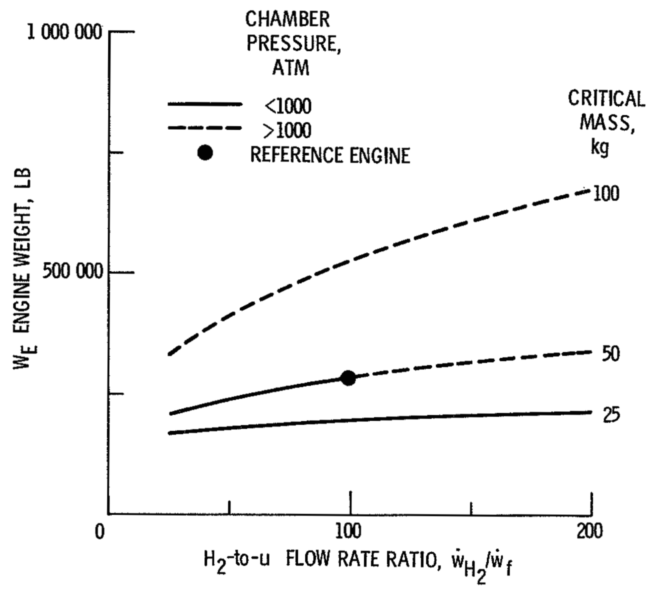

Figure 7. - Effect of uranium loss rate on engine weight; F = 400 000 pounds; $I_{sp} = 1800$ seconds.