NASA Technical Memorandum 100104
AIAA-87-1773

An Evaluation of Metallized Propellants Based on Vehicle Performance

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(NASA-TM-100104) AN EVALUATION OF METALLIZED PROPELLANTS BASED ON VEHICLE PERFORMANCE (NASA) 27 p Avail: NTIS HC A03/MF A01 CSCL 21H

N87-22806

Unclas
G3/20 0077499

Prepared for the
23rd Joint Propulsion Conference
cosponsored by the AIAA, SAE, ASME, and ASEE
San Diego, California, June 29—July 2, 1987

NASA

AN EVALUATION OF METALLIZED PROPELLANTS BASED ON VEHICLE PERFORMANCE

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SUMMARY

An analytical study was conducted to determine the improvements in vehicle performance possible by burning metals with conventional liquid bipropellants. These metallized propellants theoretically offer higher specific impulse, increased propellant density and improved vehicle performance compared with conventional liquid bipropellants. Metals considered were beryllium, lithium, aluminum and iron. Liquid bipropellants were H_2/O_2, N_2H_4/N_2O_4, RP-1/O_2 and H_2/F_2. A mission with ΔV = 4267.2 m/sec (14 000 ft/sec) and vehicle with propellant volume fixed at 56.63 m^3 (2000 ft^3) and dry mass fixed at 2761.6 kg (6000 lb) was used, roughly representing the transfer of a chemically propelled, upper-stage vehicle from a low Earth orbit to a geosynchronous orbit. The results of thermochemical calculations and mission analysis calculations for liquid bipropellants metallized with beryllium, lithium, aluminum and iron are presented. Technology issues pertinent to metallized propellants are discussed.

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INTRODUCTION

The selection of rocket propellants for a particular application depends on many factors including performance, cost, and safety. A number of steps are involved in analytically evaluating the potential of a rocket propellant combination. The first step is to determine rocket engine performance based on specific impulse. Thermochemical calculations are conducted to identify peak specific impulse for the engine configuration to be used in the application. Peak values can be compared for various propellant combinations to determine which yields the optimal propulsion system performance. However, propulsion system performance alone is insufficient to make a propellant selection. Vehicle performance parameters such as the velocity change of the vehicle or the quantity of payload that can be delivered in a mission must next be calculated. Flight relation equations are used in which both the density and specific impulse of the propellant combination become important. In this process, physical constraints resulting from the requirements of the application must be considered. Finally, in evaluating rocket propellants for a particular application, the potential benefits in vehicle performance must be weighed against safety, cost, and technical considerations. The potential benefits derived from an advanced rocket propellant are inconsequential if safety requirements for the application cannot be satisfied, cost for development or operation are unrealistically large, or if the required technology cannot be developed.

This report presents the results of an evaluation of metallized propellants. Propulsion system performance (specific impulse) and vehicle performance (delivered payload mass) are emphasized in the evaluation, although safety and technology issues are also discussed. Thermochemical calculations were conducted to identify the specific impulse of several metallized propellant combinations over a range of compositions. Propellant density data were then calculated as a function of propellant composition. Finally, a simplified upper-stage mission was chosen, and flight performance parameters were calculated using the propulsion system performance and propellant density data.

Metallized propellant (tripropellant) systems consist of a liquid fuel, a liquid oxidizer, and a metal fuel. The metal is typically suspended in fine particulate form as a slurry or gel in the fuel, oxidizer, or a separate carrier fluid, although any metal management system allowing good combustion efficiency could be considered. These metallized propellants have several potential advantages over conventional liquid bipropellants and offer the opportunity to advance chemical rocket propulsion performance beyond that of any liquid bipropellant. The most important of these advantages is the possibility for improved specific impulse and propellant density compared to conventional bipropellant combinations. Better vehicle performance is the end result of these improvements. Other advantages may stem from the use of metallized propellants depending upon the state of the propellant. For example, gelling the metal in the liquid propellant could lead to better storage and handling properties. Since gels are semisolid in composition, mechanical or hydrostatic propellant delivery systems could be used. The need for baffles in propellant tanks may be eliminated, thus reducing vehicle dry mass. Evaporation of cryogenic propellants may be reduced, thereby simplifying ground processing procedures. Finally, an increased margin of safety may be possible due to the flow resistance of the gelled propellant to leaks in tanks and propellant lines.

Metallized propellants are not new to rocket propulsion. Early analytical work in the 1960's generated interest in low molecular weight, high energy metals such as beryllium and lithium. Aluminum was also investigated because of its good combustion energy and desirable density. Experimental demonstrations followed which were primarily directed toward ballistic applications. However, the concept was eventually abandoned after significant technical efforts as budgets for high-risk, high-payoff propulsion technology began to diminish. The major problems remaining unsolved at that time included; combustion inefficiencies and two-phase flow losses limiting delivered performance, safety problems with propellants like beryllium, and the inability to develop an effective metal storage, transport, and injection system. A more detailed review of the history of metallized propellants is contained in reference 1.

Metallized propellants still offer the potential for state-of-the-art advancements in chemical rocket propulsion performance and are reexamined here with today's improved computational capabilities in light of current applications and technology. Metals considered in the analysis were beryllium (Be), lithium (Li), aluminum (Al) and iron (Fe). Bipropellant systems considered were hydrogen/oxygen (H_2/O_2), hydrogen/fluorine (H_2/F_2), hydrazine/nitrogen tetroxide (N_2H_4/N_2O_4), and RP-1/oxygen (RP-1/O_2). Iron was included because of its good combustion energy and very high density. The other metals, although considered in the past, are reexamined here with a wide variety of liquid bipropellant systems. Whereas past work focused heavily on specific impulse for improvements in vehicle performance, the importance of both specific impulse and propellant density are considered here.

THERMOCHEMICAL CALCULATIONS

Specific impulse advantages of metallized tripropellants over conventional liquid bipropellants result because of the large amount of energy released when the metal component burns. If we assume any condensed phases to be in velocity equilibrium with the gaseous phase, the following equation can be used to calculate specific impulse:

$$I_{sp} = \frac{\sqrt{2g_0 J(H_c - H_e)}}{g_0} \tag{1}$$

Since the enthalpy change is the heat release per unit weight of material,

$$I_{sp} \propto \sqrt{\frac{T_c}{M_c}} \tag{2}$$

Therefore, specific impulse is roughly proportional to the square root of the ratio of chamber temperature to molecular weight. Specific impulse is increased by elevating the energy of the system and reducing the molecular weight of the combustion products. Metallized propellants can supply the optimum combination of a high-energy source and low molecular weight, which accounts for their increased specific impulses.

Figure 1 shows the combustion energies of some of the elements when added to oxygen and fluorine. Notice the decaying sinusoidal nature of the combustion energy with atomic number. This trend continues beyond an atomic number of 18. Based on combustion energy, the elements that appear most attractive for use in metallized propellant combinations include beryllium, lithium, boron, magnesium, and aluminum. Beryllium, lithium, and boron appear particularly attractive for improving specific impulse because of their high combustion energy and low molecular weight. Since aluminum and magnesium have higher molecular weights, the addition of these metals to liquid bipropellants would not be expected to improve specific impulse as much as beryllium, lithium, or boron. Iron is not shown in figure 1 because it has an atomic number of 26. The combustion energy of iron with oxygen is 5320 J/g (2290 Btu/lb). Consideration of propellant density may provide justification for using heavier elements such as iron as metal rocket propellant additives. Table I contains element property data such as specific gravity and molecular weight for selected elements. The high density of aluminum and iron relative to the other elements is evident. Since vehicle performance depends on both specific impulse and propellant density, the high density of aluminum and iron is a desirable characteristic of these metals when they are used as rocket propellants.

In order to assess the potential of these metals as rocket propellants, thermochemical calculations were first conducted to identify specific impulse. Gordon and McBride's Computer Program for Calculation of Complex Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations (CEC computer program) (ref. 2) was used to generate vacuum specific impulse values for the metallized propellant combinations over a wide range of mixture ratios and metal loadings. Mixture ratio is defined for metallized propellant combinations as the ratio of liquid oxidizer mass to the sum of liquid-fuel mass and metal mass. Metal loading is defined as the weight percentage of the total fuel (metal plus liquid fuel) that is metal fuel. The program generated the theoretical rocket parameters by assuming shifting equilibrium, ideal expansion to a vacuum from a 6.895-MN/m^2 (1000 psia) chamber pressure. A rocket nozzle with a 60:1 area ratio (ratio of the nozzle exit area to throat area) was assumed.

The results of the thermochemical calculations are shown in figures 2 to 5 which plot vacuum specific impulse versus metal loading for each of the metals and liquid bipropellants considered in the analysis. Figure 2 shows how beryllium, with is high combustion energy and low molecular weight, can increase the specific impulse of each liquid bipropellant combination. This improvement in rocket performance is most striking with the $Be/H_2/O_2$ tripropellant which offers the highest specific impulse of any chemical propellant combination. The improvements in specific impulse are not as pronounced with the storable and hydrocarbon bipropellants because thermal energy is not as easily converted to kinetic energy with the higher molecular weight exhaust products. Figure 3 shows the rocket performance of each liquid bipropellant with lithium addition. The performance of the H_2/F_2, H_2/O_2 and N_2H_4/N_2O_4 bipropellants benefit from the addition of lithium. Lithium produces thermally stable fluorides which do not dissociate at high combustion temperatures. This accounts for the good specific impulse of $Li/H_2/F_2$. The dissociation of lithium oxide at high temperatures is the source of lithium's moderate performance with the H_2/O_2 system. Figure 4 illustrates how aluminum addition affects the specific impulse of various liquid bipropellants. Slight improvements in theoretical rocket performance are possible by the addition of aluminum to the H_2/O_2 and N_2H_4/N_2O_4 bipropellants. Although aluminum is an energetic metal, it has a high molecular weight which is not conducive to high specific impulse. Finally, the rocket performance of iron is shown in figure 5. Iron addition to liquid bipropellants decreases theoretical specific impulse because of its high molecular weight and low combustion energy relative to the other metals. However, the potential of high density metals like aluminum and iron can only be determined by considering both specific impulse and propellant density in calculating flight performance parameters. This was the subject of further analysis which is presented in the Mission Analysis section of this report.

Peak theoretical vacuum specific impulse, mixture ratio and metal loading for each of the metallized propellants are presented in table II. Peak rocket performance is also presented graphically in figure 6. Certain metals, when added to a particular bipropellant, do not increase specific impulse. Zero percent metal addition is indicated in figure 6 for these cases. It must also be noted that the specific impulse physically achievable from metallized propellant combinations will be less than theoretical after taking into account realistic losses due to combustion inefficiencies, chemical kinetic effects, two-phase flow, nozzle divergence, wall friction, and nozzle back-pressure. An analytical prediction of these losses was beyond the scope of this analysis.

Based on theoretical rocket performance (specific impulse), beryllium and lithium appear very promising as rocket propellants while aluminum and iron do not. However, the ultimate criteria of the performance of a rocket propellant are flight parameters (such as payload mass or ΔV) which reflect the effects of both specific impulse and propellant density. Therefore, mission analysis must be conducted to determine the true potential of high density, low energy metals such as aluminum and iron or low density, high energy metals such as beryllium and lithium. In addition, safety, cost and technology issues must be considered. The potential of a rocket propellant cannot be judged solely on specific impulse.

MISSION ANALYSIS

The relative importance of specific impulse and propellant density can be seen in the following rocket equation, which (assuming aerodynamic and drag forces to be negligible) gives the change in velocity of a rocket powered vehicle:

$$\Delta V = g_o I_{sp} \ln \frac{M_o}{M_f} = g_o I_{sp} \ln \frac{M_p + M_d + M_{pl}}{M_d + M_{pl}} \tag{3}$$

Since propellant mass is the product of bulk propellant density ρ_p and total tankage volume for all propellant V_p, the rocket equation becomes

$$\Delta V = g_o I_{sp} \ln \frac{M_o}{M_f} = g_o I_{sp} \ln \frac{\rho_p V_p + M_d + M_{pl}}{M_d + M_{pl}} \tag{4}$$

Rearranging the equation yields

$$M_{pl} = \frac{\rho_p V_p}{e^{(\Delta V / g_o I_{sp})} - 1} - M_d \tag{5}$$

This equation shows that payload capability is directly proportional to propellant density. Figure 7 shows the effect of bulk propellant density on payload mass. This figure was plotted from equation (5) by varying bulk propellant density from 200.0 kg/m^3 (12.49 lb/ft^3) to 1600.0 kg/m^3 (99.88 lb/ft^3) and specific impulse from 250 to 450 sec with ΔV = 4267.2 m/sec (14,000 ft/sec), Vp = 56.63 m^3 (2000 ft^3), and M_d = 2721.6 kg (6000 lb). This roughly represents the transfer of a chemically propelled, upper-stage vehicle from a low Earth orbit to a geosynchronous orbit. The figure shows that payload capability increases with density along lines of constant specific impulse. However, in reality, payload mass does not directly increase with either parameter because of the thermochemical relationship between propellant specific impulse and bulk propellant density (i.e., mixture ratio and metal loading). The curve for $Al/H_2/O_2$ payload capability illustrates this. This curve was calculated from specific impulse, mixture ratio, and metal loading data. The bulk density of the propellant combination is a value of a hypothetical mixture of liquid oxidizer, liquid fuel, and metal fuel and gives an indication of the compactness of the propellant combination. Bulk propellant density was calculated from the following equation which is derived in reference 1.

$$\rho_p = \frac{(1 + MR)}{\frac{MR}{\rho_{ox}} + \frac{(1 - ML)}{\rho_f} + \frac{ML}{\rho_m}} \tag{6}$$

The payload capability curve for $Al/H_2/O_2$ (fig. 7) shows that payload mass increases with bulk propellant density, in spite of the decrease in specific impulse. Therefore, for a given mission and vehicle (i.e., fixed dry mass, propellant volume, and velocity change), increasing bulk propellant density with high-density metals can lead to payload advantages. Conversely, the addition of low density metals to liquid bipropellants could conceivably reduce payload capability while improving rocket performance (specific impulse). It is important to realize that the potential of a rocket propellant is ultimately judged on vehicle performance which is a function of both specific impulse and propellant density. A number of references are available which discuss the relative importance of specific impulse and propellant density for rocket-powered vehicles (refs. 3 and 4).

In order to assess the potential of metallized propellant combinations, mission analyses considering the combined impact of specific impulse and propellant density were conducted. Since the objective of the analysis was to compare the performance of one metallized propellant combination to another and to the unmetallized liquid bipropellants, a simplified mission was assumed. A mission with ΔV = 4276.2 m/sec (14 000 ft/sec) and vehicle with propellant volume fixed at 56.63 m^3 (2000 ft^3) and dry mass fixed at 2761.6 kg (6000 lb) was selected. This roughly represents the transfer of a chemically propelled, upper-stage vehicle from a low Earth orbit to a geosynchronous orbit. The vehicle is propelled by a rocket operating at 6.895-MN/m^2 (1000 psia) chamber pressure with a 60:1 area ratio nozzle.

The assumptions of fixed propellant volume, constant dry mass and mission ΔV are permissible for the purpose of comparing propellant performance in certain applications. A fixed envelope volume is often a requirement of an application. For example, an upper-stage vehicle could be volume constrained by the payload bay of the space shuttle. The replacement of final destination by ΔV is a permissible simplification if velocity losses such as drag are negligible or independant of the propellants used. For missions where large drag losses are inherent, significant ΔV changes may occur due to vehicle drag area changes resulting from variations in propellant density. This is not the case for upper-stage missions. Finally, vehicle dry mass (tank masses, miscellaneous hardware, engine mass, etc.) can be considered constant if optimum propulsion system operating conditions (chamber pressure, tank pressure, etc.) are not a strong function of propellant density (ref. 3).

Several flight performance parameters such as delivered payload mass, minimum weight, occupancy of minimum volume for a given mission, or the velocity change for a given vehicle can be used to quantify vehicle performance. Delivered payload mass was taken as a measure of performance for this analysis. Payload mass was calculated from equation (5) using the theoretical vacuum specific impulse data. Bulk propellant density was calculated for each mixture ratio and metal loading using equation (6).

The results of the mission analysis are shown in figures 8 to 14 which plot delivered payload mass versus metal loading for each of the metals and liquid bipropellant systems considered in the analysis. Figure 8 shows the payload capability of beryllium with H_2/O_2, RP-1/O_2, and N_2H_4/N_2O_4. Beryllium addition improves the performance of all three bipropellants, with the more dense liquid bipropellant systems delivering higher absolute payload masses in the fixed-volume application. The improvement in vehicle performance by beryllium addition is most pronounced with the N_2H_4/N_2O_4 system. Beryllium has high combustion energy, low molecular weight, and high density which ultimately leads to these improvements in flight performance. Figure 9 shows the payload capability of lithium with the liquid bipropellants. Lithium addition results in improved vehicle performance only with H_2/F_2 and H_2/O_2 bipropellants because of the low density of lithium and because specific impulse improvements are appreciable only with these bipropellants. However, the improvements in vehicle performance are slight. The improvements in payload capability theoretically possible by the addition of aluminum to the liquid bipropellants are shown in figure 10. Increased performance in the N_2H_4/N_2O_4 system is due to a combination of improved specific impulse and increased propellant density. In the RP-1/O_2 and H_2/O_2 systems, increased payload mass is attributed almost entirely to increased propellant density by addition of aluminum. As shown in figure 11, the addition of iron to conventional liquid bipropellants shows no potential for increasing performance with the assumed mission model. Although iron has a very high density, the degradation in specific impulse by iron addition to the liquid bipropellants is too severe.

Figures 12 to 14 compare the vehicle performance of the metals with each liquid bipropellant combination. Aluminum and beryllium are the only metals which show real promise for improving performance of the H_2/O_2, N_2H_4/N_2O_4, and RP-1/O_2 bipropellants. Lithium has a high combustion energy but low density. Iron has high density but low combustion energy. Aluminum and beryllium posses the proper balance of combustion energy and density to deliver improved theoretical flight performance.

Peak vehicle performance for all propellant combinations analyzed are presented in table III with the corresponding rocket performance (vacuum specific impulse, mixture ratio and metal loading) and propellant density. Detailed tables of theoretical flight performance (delivered payload mass) as a function of rocket performance and propellant density are presented for each metallized propellant combination in tables IV to XVI. Peak vehicle performance is also presented graphically in figure 15. Certain metals, when added to a particular bipropellant, do not enhance performance. Zero percent metal addition is depicted in figure 15 for these cases. An alternate method for comparing the performance of propellant systems is presented in appendix B. The performance of the metallized propellant and bipropellant combinations is compared in figure 16 using the parameter presented in appendix B.

TECHNICAL DISCUSSION

After a propellant combination has been evaluated based on rocket and flight performance parameters, safety and technical issues associated with the use of the propellant combination must be considered. Theoretical analysis of rocket and flight parameters indicates that metallized propellants potentially offer significant performance advantages over their corresponding bipropellants. However, because of the energetic nature of the propellants and the presence of the solid metal in the system, an advanced technology is required to develop a reliable, high-energy propulsion system using metallized propellants. Safety concerns also arise with the use of some metallized propellant combinations. This discussion is concerned with some major technical and safety issues associated with metallized propellants. More detailed discussion is contained in reference 1.

Safety is a primary consideration when selecting a rocket propellant for any application. Several of the metallized propellant combinations discussed here do present safety problems. Beryllium shows good potential for increasing the performance of certain liquid bipropellants. However, the toxicity of beryllium and its derivatives remains an important aspect to consider. The toxicity of beryllium metal has prevented its past use with solid and liquid propellant rocket systems and is a deterrent to its future use as a rocket propellant. Propellant combinations using fluorine as the oxidizer also present unique safety hazards. The unusually high density of fluorine, coupled with the favorable propellant mixture ratios inherent in the stoichiometry of its combustion, make fluorine a high-performing oxidizer. However, the potential problems in handling fluorine tend to discourage its consideration for rocket propulsion systems (ref. 5). Potential safety hazards do exist with some of the other propellants discussed here such as hydrazine, nitrogen tetroxide, and liquid hydrogen, but these hazards can be controlled so that such propellants are routinely used in current rocket propulsion applications.

Several technology areas are of major importance in evaluating the potential of metallized propellants. These technologies include metal ignition and combustion, performance losses, thrust chamber cooling, advanced materials, and the storage, transport, and injection of the metal. A metallized propellant propulsion system must be designed for high performance. Rocket performance losses due to inefficient combustion and two-phase flow could negate the flight performance advantages theoretically possible with metallized propellant combinations. Efficient combustion of the metal in metallized propellants requires small, solid particles, large residence times for the reactants in the thrust chamber, and a core temperature in the thrust chamber high enough to initiate and maintain combustion of the metal. The development of an effective metal management system and an effective thrust chamber configuration is the first step toward ensuring good combustion efficiency with metallized propellants.

The combustion of metals in metallized propellant combinations results in the formation of small metal-oxide particles whose thermal energy must be converted to kinetic energy by heat and momentum exchange with the surrounding gas in the nozzle. A decreased nozzle efficiency results if the solid fails to maintain thermal and velocity equilibrium with the gas. To prevent such two-phase flow losses, the solid particles must be kept very small so that they will have the same velocity as the gas and be in thermal equilibrium with the gas. Heat transfer will also be greater in metallized propellant thrust chambers than in chambers using conventional propellants because of the presence of the particulate matter in the combustion gases. Advanced cooling techniques would be required to adjust for the increased heat transfer in these rockets. In addition the impingement of solid metal particles on the thrust chamber wall could create durability problems in reusable propulsion systems necessitating development of advanced thrust chamber materials.

Finally, an effective metal management system must be developed for the storage, transport, and injection of the metal. Several types of systems have been explored in the past. The most popular technique has been to suspend the metal in fine particulate form in the liquid fuel as a slurry or gel. In this way the metal could be transported and injected along with the liquid fuel. However, many technical challenges are associated with developing a reliable gelled, metallized fuel combination. Potential problems exist in areas including storage stability, abrasion and clogging of propulsion system components, and propellant waste due to residual deposits in tanks and propellant lines. The concept of metallizing liquid bipropellants is a novel approach for improving performance, but an advanced technology is required to make it practical and safe.

CONCLUDING REMARKS

State-of-the-art advancements in chemical rocket propulsion have historically been driven by the energetics of the propellant. Metallized propellants offer the opportunity to advance the state-of-the-art in chemical rocket performance because they are more energetic than conventional propellants. The addition of metals to conventional liquid bipropellants shows promise for increasing specific impulse or propellant density or both depending on the type and amount of metal added.

It is important to consider propulsion system performance, flight performance, and safety and technology issues when evaluating the potential of a propellant combination for a particular application. Thermochemical calculations were conducted to determine the specific impulse advantages of metallized propellant combinations compared to unmetallized liquid bipropellants. The addition of low molecular weight, high-energy metals like beryllium and lithium to liquid bipropellants can significantly increase rocket performance. High density metals like aluminum and iron with lower combustion energies yield little or no specific impulse improvements. However, the ultimate criteria of the performance of a rocket propellant are flight parameters which reflect the effects of both specific impulse and propellant density. Simplified upper-stage mission analyses were conducted to assess the potential of metallized propellant systems based on flight performance. Iron shows no potential for increasing performance when added to liquid bipropellants. Aluminum and beryllium both appear attractive for improving flight performance when added to liquid bipropellants because of increased specific impulse and propellant density.

Safety and technology issues were reviewed as a final step in evaluating the potential of metallized propellant combinations since benefits in performance are inconsequential if safety requirements for the application cannot be satisfied or if the required technology cannot be developed. Safety (toxicity) problems discourage the use of beryllium as a rocket propellant. Lithium shows potential for increasing the performance of the H_2/F_2 bipropellant, but fluorine exhibits unique safety hazards. Aluminum is the only metal examined in this analysis that shows potential for improving rocket and flight performance and also presents no unique safety problems. Future work on metallized propellant systems should focus on technologies associated with the addition of aluminum to liquid bipropellant systems.

Metallized rocket propellants show promise based on the theoretical analysis of this report, but future experimental efforts are needed to further explore these propellants and realistically evaluate their advantages. Technologies which need to be immediately addressed include physical and chemical properties of metallized propellants, metal ignition and combustion phenomena, performance losses due to two-phase flow and combustion inefficiencies, cooling requirements, advanced thrust chamber materials, and the storage, transport, and injection of the metal. The concept of metallizing liquid bipropellant systems shows promise for increasing rocket propellant performance, but an advanced technology is required to make the concept feasible.

APPENDIX A

SYMBOLS

a constant

b constant

g_o gravitational constant, 9.80665 m/sec^2

H enthalpy, J/kg

I_{sp} vacuum specific impulse, sec

J conversion factor, 0.102 kg m/J

M molecular weight, kg/kg mol

ML metal loading, wt %

MR mixture ratio

M_d vehicle dry mass, kg

M_f final vehicle mass, kg

M_p propellant mass, kg

M_{pl} payload mass, kg

M_o initial vehicle launch mass, kg

n exponent for $\rho_p I_{sp}^n$ parameter

T temperature, K

ΔV velocity change for mission, m/sec

V_p total propellant volume, m^3

ε ratio of rocket nozzle exit area to throat area

ρ_f liquid-fuel dinsity, kg/m^3

ρ_m metal density, kg/m^3

ρ_{ox} liquid oxidizer density, kg/m^3

ρ_p bulk propellant density, kg/m^3

Subscripts

c chamber

e nozzle exit

APPENDIX B

EFFECT OF PROPELLANT DENSITY AND SPECIFIC IMPULSE ON FLIGHT PERFORMANCE

As illustrated by the analysis of this report, the determination of propellant performance is a time consuming and complicated process which must be repeated for each application and propellant combination. A convenient method of determining the potential of rocket propellant combinations without performing this lengthy process is therefore desirable. Since both specific impulse and propellant density are significant in the evaluation of rocket propellant performance, a parameter including both variables could be used as a preliminary criterion for the evaluation of the performance of rocket propellant combinations. Such a parameter can be derived from the rocket equation (eq. (5)). By expanding the exponential term in the rocket equation using an infinite series expansion, the following linear relationship between delivered payload mass and $\rho_p I_{sp}^n$ can be shown where a and b are constants, and the exponent n depends on the vehicle and mission.

$$M_{pl} = \frac{\rho_p V_p}{e^{(\Delta V/g_o I_{sp})} - 1} - M_{dry} \propto a \left(\rho_p I_{sp}^n\right) + b$$

n correlates well with the mission ΔV. For the upper-stage vehicle and mission considered in this analysis, n is approximately 2. Therefore, the highest performing propellant combination for this application yields the greatest value of $\rho_p I_{sp}^2$. The relative performance of the propellant combinations considered in this analysis can be seen in figure 16 which plots delivered payload mass versus $\rho_p I_{sp}^2$. The linear relationship between delivered payload mass and $\rho_p I_{sp}^2$ is evident.

REFERENCES

1. Zurawski, R.L., "Current Evaluation of the Tripropellant Concept," NASA TP-2602, 1986.

2. Gordon, S. and McBride, B.J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouquet Detonation," NASA SP-273, 1971.

3. Jortner, J., "Comparative Applicability of Storable Propellants: Effects of Specific Impulse and Density," Liquid Rockets and Propellants, L.E. Bollinger, M. Goldsmith, and A.W. Lemmon, eds., Academic Press, New York, 1960, pp. 471-493.

4. Mellish, J.A. and Gibb, J.A., "Liquid Propellant Comparison Based on Vehicle Performance," Liquid Rockets and Propellants, L.E. Bollinger, M. Goldsmith, and A.W. Lemmon, eds., Academic Press, New York, 1960, pp. 447-470.

5. Schmidt, H.W. and Harper, J.T., "Handling and Use of Fluorine and Fluorine Oxygen Mixtures in Rocket Systems," NASA SP-3037, 1967.

6. Sarner, S.F., Propellant Chemistry, Reinhold, New York, 1966.

TABLE I. - PROPERTY DATA FOR SELECTED ELEMENTS

Name	Symbol	Atomic number	Molecular weight	Melting point, °C	Boiling point, °C	Specific gravity (20 °C)
Aluminum	Al	13	26.98	660.4	2467	2.70
Beryllium	Be	4	9.01	1278.0	2970	1.85
Boron	B	5	10.81	2300.0	2550	2.34
Carbon	C	6	12.01	3550.0	4827	2.26
Iron	Fe	26	55.85	1535.0	2750	7.87
Lithium	Li	3	6.94	180.5	1342	0.53
Magnesium	Mg	12	24.31	648.8	1090	1.74

TABLE II. - METALLIZED PROPELLANT PEAK THEORETICAL VACUUM SPECIFIC IMPULSE

[Ideal expansion; P_c = 6.895 MN/m^2 (1000 psia); ϵ = 60:1.]

Propellant combination	Oxidizer to total fuel ratio, O/F	Metal in fuel, wt %	Vacuum specific impulse, sec
H_2/O_2	5.0	0	462.0
$Be/H_2/O_2$	0.9	50	548.0
$Al/H_2/O_2$	0.7	65	469.5
$Li/H_2/O_2$	0.7	55	490.2
$Fe/H_2/O_2$	5.0	0	462.0
H_2/F_2	12.0	0	486.4
$Li/H_2/F_2$	1.1	40	528.0
N_2H_4/N_2O_4	1.4	0	349.2
$Be/N_2H_4/N_2O_4$	0.7	25	399.6
$Al/N_2H_4/N_2O_4$	0.5	35	367.7
$Li/N_2H_4/N_2O_4$	0.4	25	358.1
$Fe/N_2H_4/N_2O_4$	1.4	0	349.2
$RP\text{-}1/O_2$	2.8	0	365.8
$Be/RP\text{-}1/O_2$	1.4	35	389.0
$Al/RP\text{-}1/O_2$	2.5	10	365.9
$Li/RP\text{-}1/O_2$	2.8	0	365.8
$Fe/RP\text{-}1/O_2$	2.8	0	365.8

TABLE III. - PEAK VEHICLE PERFORMANCE OF METALLIZED PROPELLANT SYSTEMS

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3)]

Propellant combination	Oxidizer to total fuel ratio, O/F	Vacuum specific impulse, sec	Metal in fuel, wt %	Bulk propellant density, ρ_p		Peak delivered payload mass, Mpl	
				kg/m^3	lb/ft^3	kg	lb
H_2/O_2	8.5	433.8	0	441.31	27.55	11 751.7	25 908.0
$Be/H_2/O_2$	5.5	394.9	60	603.42	37.67	14 279.5	31 480.9
$Al/H_2/O_2$	1.4	273.0	100	1504.45	93.92	18 998.5	41 884.6
$Li/H_2/O_2$	2.5	391.1	80	538.22	33.60	12 202.0	26 900.0
$Fe/H_2/O_2$	1.5	334.8	85	707.38	44.16	12 292.4	27 100.1
H_2/F_2	19.0	481.4	0	749.82	46.81	26 180.6	57 718.4
$Li/H_2/F_2$	11.0	477.3	50	786.03	49.07	27 185.7	59 934.3
N_2H_4/N_2O_4	1.4	349.2	0	1215.32	75.87	25 067.8	55 265.0
$Be/N_2H_4/N_2O_4$	0.8	396.6	30	1268.66	79.20	33 282.7	73 375.9
$Al/N_2H_4/N_2O_4$	0.7	359.0	50	1449.83	90.51	32 063.8	70 688.6
$Li/N_2H_4/N_2O_4$	1.4	349.2	0	1215.32	75.87	25 067.8	55 265.0
$Fe/N_2H_4/N_2O_4$	1.3	337.1	15	1296.05	80.91	25 127.2	55 396.0
RP-1/O_2	2.9	365.6	0	1017.97	63.55	22 478.5	49 556.7
Be/RP-1/O_2	1.4	385.9	40	1082.37	67.57	26 632.1	58 713.8
Al/RP-1/O_2	1.0	348.6	65	1275.07	79.60	26 348.4	58 088.2
Li/RP-1/O_2	2.9	365.6	0	1017.97	63.55	22 478.5	49 556.7
Fe/RP-1/O_2	2.9	365.6	0	1017.97	63.55	22 478.5	49 556.7

TABLE IV. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Be/H_2/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$ kg·s^2/m^3	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3		kg	lb
0	8.5	433.8	441.31	27.55	83.046x10^6	11 757.7	25 908.0
5	8.5	427.4	455.56	28.44	83.218	11 873.2	26 175.9
10	8.0	429.8	456.04	28.47	84.244	12 017.0	26 493.0
15	8.0	423.3	472.22	29.48	84.614	12 174.4	26 840.0
20	7.5	425.5	473.67	29.57	85.757	12 345.5	27 217.1
25	7.5	418.7	492.25	30.73	86.296	12 537.7	27 640.8
30	7.0	420.5	495.29	30.92	87.578	12 737.7	28 081.9
35	7.0	413.0	517.08	32.28	88.197	12 953.5	28 557.5
40	6.5	414.1	522.36	32.61	89.574	13 183.2	29 064.0
45	6.5	405.7	548.15	34.22	90.222	13 424.8	29 596.7
50	6.0	405.8	557.12	34.78	91.743	13 692.2	30 186.2
55	5.5	405.3	567.69	35.44	93.254	13 970.4	30 799.4
60	5.5	394.9	603.42	37.67	94.100	14 279.5	31 480.9

TABLE V. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Be/N_2H_4/N_2O_4$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb);
V_p = 56.63 m^3 (2000 ft^3).]

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	kg·s^2/m^3	kg	lb
0	1.4	349.2	1215.32	75.87	148.197x10^6	25 067.8	55 265.0
5	1.4	360.0	1229.42	76.75	159.332	26 919.0	59 346.2
10	1.4	368.1	1243.99	77.66	168.558	28 435.1	62 688.7
15	1.1	378.8	1237.59	77.26	177.581	29 816.3	65 733.6
20	0.6	396.4	1207.95	75.41	189.809	31 529.2	69 510.1
25	0.7	399.6	1239.35	77.37	197.899	32 888.3	72 506.4
30	0.8	396.6	1268.66	79.20	199.550	33 282.7	73 375.9
35	0.9	390.0	1296.21	80.92	197.154	33 055.6	72 875.2
40	1.0	382.1	1322.00	82.53	193.013	32 542.5	71 743.9
45	1.1	374.7	1346.19	84.04	189.005	32 025.4	70 604.0
50	1.2	368.1	1368.94	85.46	185.438	31 563.3	69 585.2

TABLE VI. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Be/RP\text{-}1/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb);
V_p = 56.63 m^3 (2000 ft^3).]

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	kg·s^2/m^3	kg	lb
0	3.0	364.7	1020.70	63.72	135.759x10^6	22 441.3	49 474.5
5	2.75	367.7	1023.90	63.92	138.435	22 876.1	50 433.2
10	2.5	371.2	1027.58	64.15	141.590	23 385.7	51 556.7
15	2.25	374.8	1031.91	64.42	144.958	23 926.7	52 749.3
20	2.0	378.6	1036.88	64.73	148.624	24 516.4	54 049.3
25	1.6	384.1	1037.68	64.78	153.091	25 204.3	55 565.9
30	1.4	388.9	1046.81	65.35	158.322	26 036.0	57 399.6
35	1.4	389.0	1064.27	66.44	161.046	26 528.8	58 486.0
40	1.4	385.9	1082.37	67.57	161.185	26 632.1	58 713.8
45	1.4	381.1	1100.95	68.73	159.899	26 520.7	58 468.2
50	1.5	376.3	1121.29	70.00	158.777	26 430.1	58 268.5

TABLE VII. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Li/H_2/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Lithium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	kg·s^2/m^3	kg	lb
0	8.5	433.8	441.31	27.55	83.046x10^6	11 751.7	25 908.0
5	8.0	435.1	439.39	27.43	83.181	11 760.3	25 927.0
10	8.0	427.1	453.00	28.28	82.634	11 772.0	25 952.9
15	7.5	428.2	451.56	28.19	82.796	11 788.7	25 989.7
20	7.0	429.4	450.12	28.10	82.995	11 805.4	26 026.4
25	6.5	430.7	448.52	28.00	83.201	11 821.0	26 060.8
30	6.5	421.1	465.50	29.06	82.544	11 838.9	26 100.3
35	6.0	422.0	464.70	29.01	82.755	11 863.8	26 155.2
40	5.5	423.0	463.73	28.95	82.976	11 890.4	26 213.8
45	5.0	424.0	462.61	28.88	83.167	11 912.1	26 261.6
50	5.0	411.7	485.52	30.31	82.294	11 924.9	26 289.9
55	4.5	412.1	486.32	30.36	82.590	11 972.2	26 394.2
60	4.0	412.4	487.28	30.42	82.874	12 018.8	26 497.0
65	3.5	412.2	488.56	30.50	83.011	12 043.1	26 550.6
70	3.5	395.5	523.16	32.66	81.833	12 058.7	26 584.9
75	3.0	393.9	529.57	33.06	82.167	12 140.6	26 765.5
80	2.5	391.1	538.22	33.60	82.326	12 202.0	26 900.9
85	2.5	367.6	593.96	37.08	80.262	12 119.6	26 719.2
90	2.0	359.5	619.27	38.66	80.035	12 172.5	26 835.7
95	1.4	347.3	647.15	40.40	78.057	11 936.5	26 315.4
100	1.0	310.7	727.88	45.44	70.265	10 763.6	23 729.6

TABLE VIII. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Li/N_2H_4/N_2O_4$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Lithium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	kg·s^2/m^3	kg	lb
0	1.4	349.2	1215.32	75.87	148.197x10^6	25 067.8	55 265.0
5	1.4	349.3	1188.89	74.22	145.057	24 478.4	53 965.7
10	1.4	348.6	1163.74	72.65	141.420	23 807.5	52 486.5
15	1.4	347.6	1139.39	71.13	137.668	23 125.4	50 982.8
20	1.4	346.4	1116.33	69.69	133.951	22 445.7	49 484.2
25	1.5	343.6	1104.31	68.94	130.376	21 824.6	48 115.0
30	1.5	342.4	1083.49	67.64	127.026	21 210.5	46 761.1
35	1.5	341.2	1063.30	66.38	123.787	20 619.3	45 457.8
40	1.5	339.8	1043.76	65.16	120.517	20 026.2	44 150.2
45	1.5	338.3	1025.02	63.99	117.310	19 442.9	42 864.2
50	1.5	337.0	1006.92	62.86	114.355	18 903.2	41 674.5
55	1.5	335.4	989.46	61.77	111.308	18 348.8	40 452.2
60	1.5	333.4	972.64	60.72	108.114	17 769.4	39 174.9
65	1.5	330.9	956.30	59.70	104.710	17 155.9	37 822.2
70	1.5	328.0	940.60	58.72	101.194	16 520.7	36 421.9
75	1.5	324.6	925.39	57.77	97.504	15 854.9	34 954.1
80	1.5	320.9	910.65	56.85	93.776	15 180.8	33 468.0
85	1.5	316.8	896.23	55.95	89.948	14 489.2	31 943.3
90	1.6	309.9	895.59	55.91	86.011	13 790.1	30 402.0
95	1.7	303.0	894.95	55.87	82.165	13 097.7	28 875.4
100	2.0	292.7	917.38	57.27	78.595	12 460.5	27 470.8

TABLE IX. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Li/RP\text{-}1/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Lithium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	$kg \cdot s^2/m^3$	kg	lb
0	2.9	365.6	1017.97	63.55	136.066x10^6	22 478.5	49 556.7
5	2.8	364.6	1007.24	62.88	133.896	22 096.9	48 715.4
10	2.8	363.1	999.55	62.40	131.783	21 734.6	47 916.7
15	2.7	362.1	988.50	61.71	129.608	21 349.3	47 067.2
20	2.6	361.0	977.13	61.00	127.340	20 946.9	46 180.0
25	2.6	359.0	969.44	60.52	124.942	20 538.7	45 280.1
30	2.5	357.8	957.58	59.78	122.591	20 122.5	44 362.5
35	2.4	356.5	945.41	59.02	120.154	19 689.6	43 408.2
40	2.3	355.0	932.76	58.23	117.550	19 229.6	42 394.0
45	2.3	351.9	925.23	57.76	114.574	18 722.0	41 274.9
50	2.2	349.7	912.25	56.95	111.559	18 189.1	40 100.2
55	2.1	347.0	898.64	56.10	108.204	17 601.9	38 805.5
60	1.9	345.8	877.81	54.80	104.967	17 010.9	37 502.6
65	1.8	343.1	862.91	53.87	101.580	16 408.4	36 174.3
70	1.7	340.1	847.38	52.90	99.751	15 774.7	34 777.2
75	1.6	336.4	831.20	51.89	94.062	15 073.8	33 232.0
80	1.5	332.2	814.54	50.85	89.890	14 328.4	31 588.8
85	1.3	329.6	786.83	49.12	85.478	13 517.2	29 800.4
90	1.2	324.2	768.08	47.95	80.730	12 662.1	27 915.1
95	1.1	318.0	748.38	46.72	75.679	11 749.9	25 904.1
100	1.0	310.7	727.88	45.44	70.265	10 763.6	23 729.6

TABLE X. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Li/H_2/F_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Lithium in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	$kg \cdot s^2/m^3$	kg	lb
0	19.0	481.4	749.82	46.81	173.769x10^6	26 180.6	57 718.4
5	19.0	473.9	767.28	47.90	172.318	26 158.8	57 670.4
10	18.0	475.4	766.48	47.85	173.229	26 263.5	57 901.1
15	17.0	476.9	765.36	47.78	174.069	26 364.0	58 122.8
20	16.0	478.4	764.24	47.71	174.909	26 459.8	58 334.0
25	15.0	479.9	762.96	47.63	175.713	26 549.9	58 532.6
30	14.0	481.1	761.52	47.54	176.259	26 605.4	58 654.9
35	14.0	471.8	785.86	49.06	174.930	26 656.4	58 767.3
40	13.0	473.6	785.86	49.06	176.267	26 829.4	59 148.6
45	12.0	475.4	786.03	49.07	177.646	27 002.6	59 530.5
50	11.0	477.3	786.03	49.07	179.069	27 185.7	59 934.3

TABLE XI. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Al/H_2/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	kg·s^2/m^3	kg	lb
0	8.5	433.8	441.31	27.55	83.046x10^6	11 751.7	25 908.0
5	8.5	426.4	455.72	28.45	82.859	11 824.7	26 069.0
10	8.0	427.6	456.37	28.49	83.443	11 909.7	26 256.5
15	7.5	428.9	457.17	28.54	84.098	12 002.8	26 461.7
20	7.0	430.2	457.81	28.58	84.727	12 099.0	26 673.7
25	7.0	421.5	476.55	29.75	84.665	12 209.7	26 917.8
30	6.5	422.3	478.79	29.89	85.386	12 326.3	27 174.9
35	6.0	423.2	481.52	30.06	86.238	12 460.1	27 469.9
40	6.0	413.0	505.38	31.55	86.203	12 598.6	27 775.2
45	5.5	413.1	510.67	31.88	87.146	12 766.0	28 144.3
50	5.0	413.0	516.92	32.27	88.170	12 952.6	28 555.5
55	4.5	412.5	524.76	32.76	89.292	13 155.3	29 002.5
60	4.0	411.7	534.22	33.35	90.548	13 394.0	29 528.7
65	3.5	410.4	546.39	34.11	92.027	13 677.0	30 152.6
70	3.5	394.2	596.05	37.21	92.622	14 026.2	30 922.6
75	3.0	390.0	622.48	38.86	94.679	14 461.1	31 891.2
80	2.5	383.8	660.12	41.21	97.237	15 019.4	33 112.1
85	1.5	391.0	668.29	41.72	102.169	15 802.7	34 839.1
90	1.1	371.4	776.41	48.47	107.097	17 020.4	37 523.5
95	1.0	327.8	1035.59	64.65	111.278	18 440.5	40 654.3
100	1.4	273.0	1504.45	93.92	112.126	18 998.5	41 884.6

TABLE XII. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Al/N_2H_4/N_2O_4$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	kg·s^2/m^3	kg	lb
0	1.4	349.2	1215.32	75.87	148.197x10^6	25 067.8	55 265.0
5	1.4	352.7	1234.86	77.09	153.614	26 011.1	57 344.7
10	1.4	355.2	1255.05	78.35	158.346	26 842.2	59 176.9
15	1.3	357.8	1269.94	79.28	162.579	27 573.6	60 789.4
20	1.3	359.0	1292.37	80.68	166.562	28 285.3	62 358.4
25	1.1	361.7	1305.50	81.50	170.795	29 006.8	63 949.0
30	0.9	364.0	1321.68	82.51	175.118	29 752.7	65 593.5
35	0.6	367.3	1337.06	83.47	180.382	30 643.2	67 556.6
40	0.6	367.5	1373.10	85.72	185.446	31 571.5	69 603.2
45	0.6	364.7	1410.91	88.08	187.659	32 060.5	70 681.4
50	0.7	359.0	1449.83	90.51	186.856	32 063.8	70 688.6
55	0.7	353.1	1489.56	92.99	185.717	32 006.6	70 562.5
60	0.8	346.5	1525.60	95.24	183.167	31 693.4	69 871.9
65	0.8	338.2	1567.25	97.84	179.260	31 149.1	68 672.0
70	0.9	330.5	1600.56	99.92	174.830	30 473.5	67 182.5
75	0.9	321.3	1643.97	102.63	169.714	29 672.4	65 416.4
80	0.9	311.3	1689.63	105.48	163.738	28 691.6	63 254.1
85	1.0	302.5	1719.58	107.35	157.352	27 577.9	60 798.9
90	1.1	293.2	1747.61	109.10	150.236	26 295.5	57 971.7
95	1.4	287.0	1739.12	108.57	143.250	24 987.5	55 088.1
100	1.4	277.6	1779.49	111.09	137.131	23 838.0	52 553.9

TABLE XIII. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Al/RP\text{-}1/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	$kg \cdot s^2/m^3$	kg	lb
0	2.9	365.6	1017.97	63.55	136.066x10^6	22 478.5	49 556.7
5	2.7	365.7	1024.86	63.98	137.063	22 662.8	49 963.0
10	2.6	365.4	1035.59	64.65	138.270	22 890.5	50 464.9
15	2.4	365.6	1044.40	65.20	139.598	23 135.3	51 004.6
20	2.2	365.7	1054.66	65.84	141.046	23 400.5	51 589.3
25	2.0	365.6	1066.51	66.58	142.553	23 681.0	52 207.8
30	1.8	365.5	1080.44	67.45	144.337	24 011.3	52 935.9
35	1.6	365.1	1096.78	68.47	146.199	24 367.1	53 720.2
40	1.4	364.6	1116.65	69.71	148.439	24 791.7	54 656.3
45	1.2	363.7	1141.00	71.23	150.928	25 273.0	55 717.5
50	1.1	361.9	1170.31	73.06	153.277	25 747.5	56 763.6
55	1.1	359.2	1201.22	74.99	154.988	26 125.1	57 596.0
60	1.0	354.3	1238.71	77.33	155.493	26 327.0	58 041.0
65	1.0	348.6	1275.07	79.60	154.949	26 348.4	58 088.2
70	1.0	340.9	1313.83	82.02	152.684	26 075.2	57 486.1
75	0.9	330.7	1368.30	85.42	149.640	25 686.7	56 629.5
80	0.9	320.2	1415.39	88.36	145.117	24 993.8	55 102.0
85	0.8	306.2	1489.08	92.96	139.614	24 122.9	53 181.9
90	0.7	289.1	1581.18	98.71	132.153	22 830.1	50 331.7
95	0.8	277.4	1612.26	100.65	124.064	21 307.6	46 975.3
100	1.4	273.0	1504.45	93.92	112.126	18 998.5	41 884.6

TABLE XIV. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Fe/H_2/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Iron in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	$kg \cdot s^2/m^3$	kg	lb
0	8.5	433.8	441.31	27.55	83.046x10^6	11 751.7	25 908.0
5	8.0	433.9	441.31	27.55	83.085	11 758.8	25 923.7
10	7.5	434.0	441.31	27.55	83.123	11 766.2	25 940.0
15	7.5	424.3	457.97	28.59	82.448	11 780.1	25 970.7
20	7.0	424.0	459.09	28.66	82.533	11 800.3	26 015.2
25	6.5	423.6	460.53	28.75	82.636	11 820.0	26 058.6
30	6.0	423.0	461.97	28.84	82.660	11 834.8	26 091.2
35	5.5	422.4	463.73	28.95	82.740	11 857.0	26 140.3
40	5.5	409.7	488.08	30.47	81.927	11 884.3	26 200.5
45	5.0	408.0	492.57	30.75	81.995	11 918.4	26 275.7
50	4.5	405.9	497.85	31.08	82.024	11 954.3	26 354.8
55	4.0	403.3	504.42	31.49	82.045	11 993.8	26 441.8
60	3.5	400.1	512.75	32.01	82.081	12 042.4	26 549.0
65	3.0	395.9	523.64	32.69	82.074	12 093.6	26 661.8
70	3.0	374.0	576.18	35.97	80.594	12 105.7	26 688.6
75	2.5	365.2	602.77	37.63	80.393	12 174.3	26 839.7
80	2.0	353.0	642.34	40.10	80.041	12 247.5	27 001.1
85	1.5	334.8	707.38	44.16	79.290	12 292.4	27.100.1
90	1.1	302.0	844.65	52.73	77.036	12 115.2	26 709.5
95	0.8	245.0	1180.08	73.67	70.834	10 898.7	24 027.5

TABLE XV. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Fe/N_2H_4/N_2O_4$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Iron in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	$kg \cdot s^2/m^3$	kg	lb
0	1.4	349.2	1215.32	75.87	148.197x10^6	25 067.8	55 265.0
5	1.4	345.0	1242.71	77.58	147.914	25 096.2	55 327.7
10	1.3	341.2	1265.14	78.98	147.284	25 051.0	55 228.1
15	1.3	337.1	1296.05	80.91	147.279	25 127.2	55 396.0
20	1.2	332.1	1324.25	82.67	146.052	24 983.9	55 080.1
25	1.2	327.5	1359.97	84.90	145.865	25 022.6	55 165.3
30	1.1	321.6	1395.85	87.14	144.368	24 832.0	54 745.2
35	1.1	316.3	1437.50	89.74	143.815	24 800.6	54 676.0
40	1.0	309.4	1484.11	92.65	142.072	24 557.5	54 140.0
45	1.0	303.0	1533.61	95.74	140.799	24 384.1	53 757.7
50	0.9	294.9	1595.60	99.61	138.763	24 065.8	53 056.0
55	0.9	286.9	1655.99	103.38	136.307	23 644.8	52 127.9
60	0.8	277.1	1740.89	108.68	133.673	23 167.6	51 075.9
65	0.8	267.3	1817.29	113.45	129.844	22 422.2	49 432.6
70	0.7	255.2	1938.07	120.99	126.221	21 659.5	47 751.1
75	0.7	242.4	2038.99	127.29	119.806	20 281.9	44 713.9
80	0.6	226.6	2221.12	138.66	114.049	18 881.1	41 625.8

TABLE XVI. - EFFECT OF METAL LOADING ON VEHICLE PERFORMANCE FOR $Fe/RP\text{-}1/O_2$

[ΔV = 4267.2 m/sec (14 000 ft/sec); M_{dry} = 2761.6 kg (6000 lb); V_p = 56.63 m^3 (2000 ft^3).]

Iron in fuel, wt %	Ratio of oxidizer to total fuel, O/F	Vacuum specific impulse, sec	Bulk propellant density, ρ_p		$\rho_p I_{sp}^2$	Maximum payload mass, M_{pl}	
			kg/m^3	lb/ft^3	$kg \cdot s^2/m^3$	kg	lb
0	2.9	365.6	1017.97	63.55	136.066x10^6	22 478.5	49 556.7
5	2.8	362.2	1031.11	64.37	135.270	22 398.4	49 380.0
10	2.6	359.4	1042.80	65.10	134.697	22 347.6	49 268.1
15	2.5	355.9	1058.66	66.09	134.095	22 299.4	49 161.7
20	2.4	352.1	1075.80	67.16	133.372	22 236.2	49 022.4
25	2.2	348.3	1093.26	68.25	132.626	22 164.2	48 863.8
30	2.1	343.9	1114.56	69.58	131.816	22 090.1	48 700.4
35	2.0	339.0	1138.27	71.06	130.811	21 983.2	48 464.6
40	1.8	333.7	1165.66	72.77	129.803	21 875.1	48 226.4
45	1.7	327.7	1196.74	74.71	128.515	21 719.1	47 882.4
50	1.5	320.4	1235.82	77.15	126.865	21 506.2	47 413.1
55	1.4	313.0	1278.59	79.82	125.262	21 289.3	46 934.9
60	1.3	304.4	1328.41	82.93	123.090	20 963.6	46 216.9
65	1.2	294.3	1387.52	86.62	120.177	20 483.5	45 158.4
70	1.0	281.2	1479.14	92.34	116.961	19 922.6	43 921.9
75	0.9	267.3	1575.10	98.33	112.540	19 071.2	42 044.8

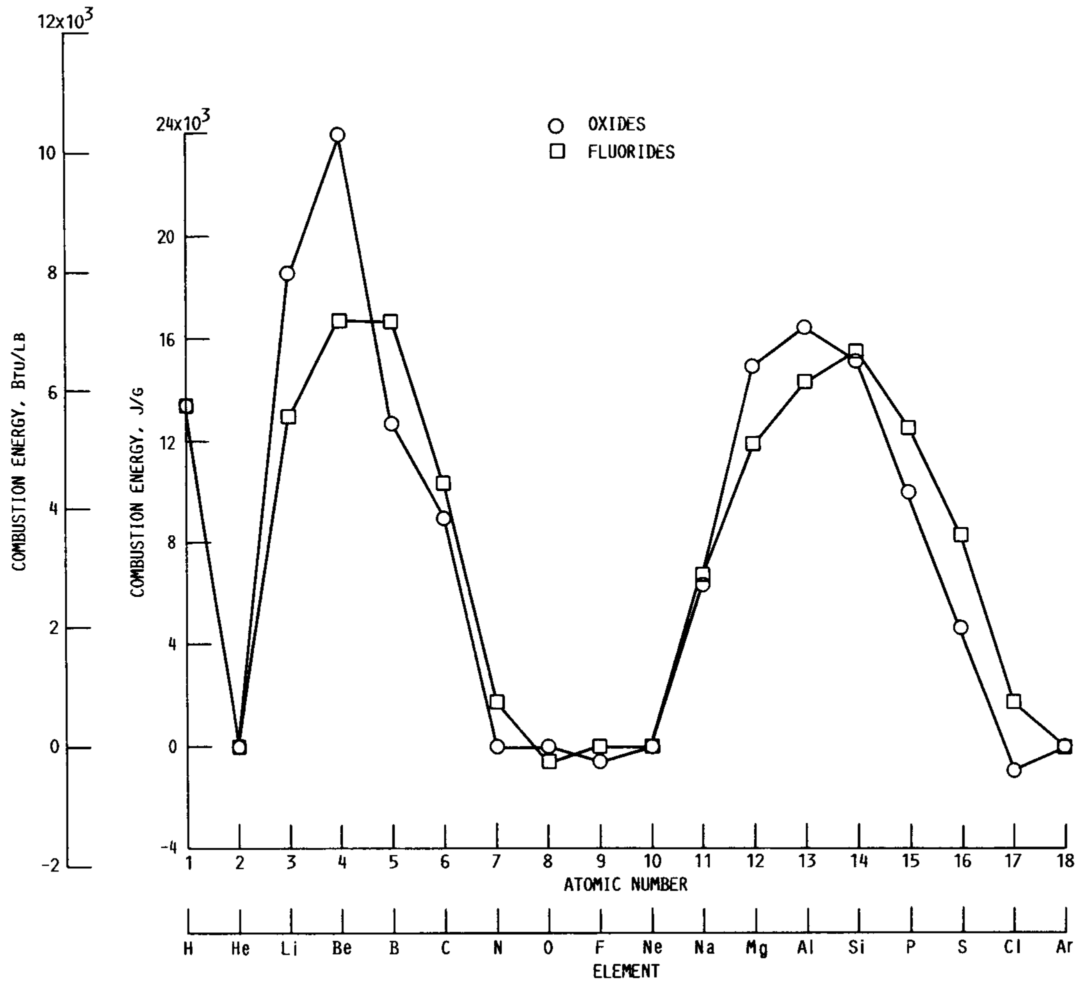

FIGURE 1. - COMBUSTION ENERGY OF ELEMENTS (FROM REF. 6).

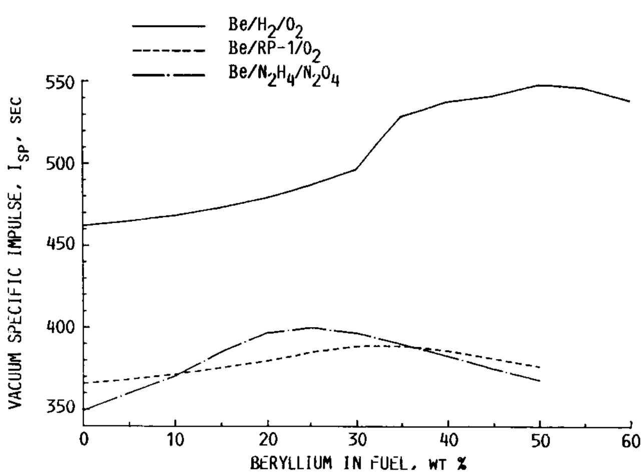

FIGURE 2. - PERFORMANCE OF BERYLLIUM AS A ROCKET PROPELLANT. P_c, 6.895 MN/M^2 (1000 PSIA); ε, 60:1; IDEAL EXPANSION.

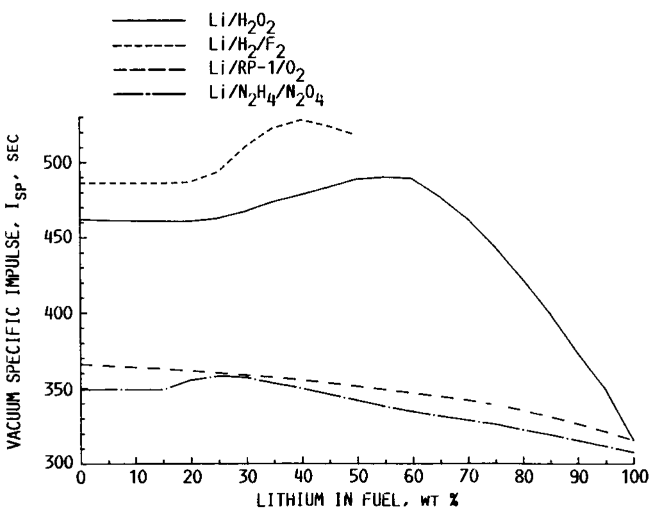

FIGURE 3. - PERFORMANCE OF LITHIUM AS A ROCKET PROPELLANT. P_c, 6.895 MN/M^2 (1000 PSIA); ε, 60:1; IDEAL EXPANSION.

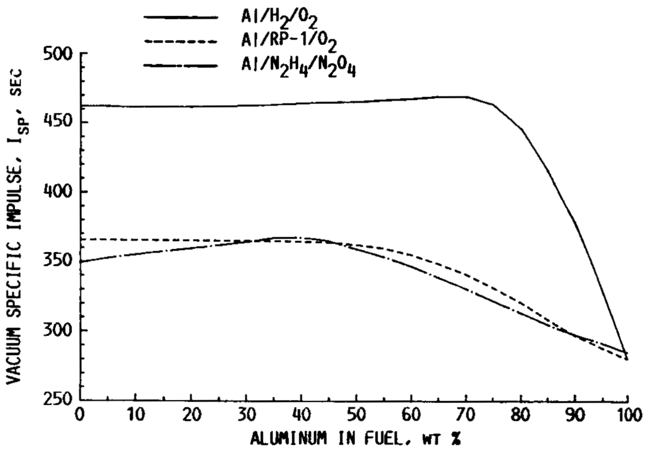

FIGURE 4. - PERFORMANCE OF ALUMINUM AS A ROCKET PROPELLANT. P_C, 6.895 MN/M^2 (1000 PSIA); ϵ, 60:1; IDEAL EXPANSION.

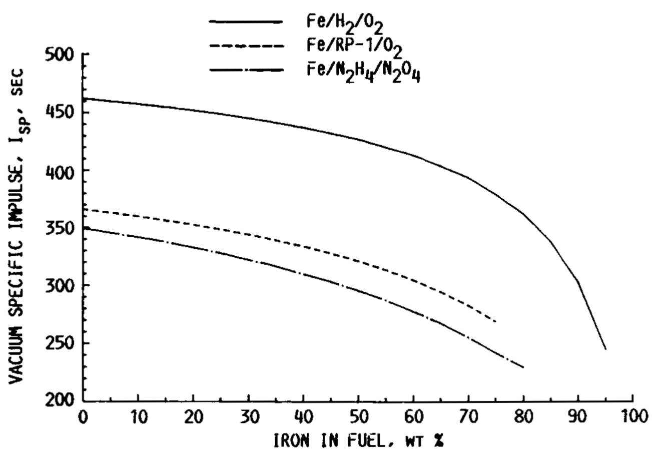

FIGURE 5. - PERFORMANCE OF IRON AS A ROCKET PROPELLANT. P_C, 6.895 MN/M^2 (1000 PSIA); ϵ, 60:1; IDEAL EXPANSION.

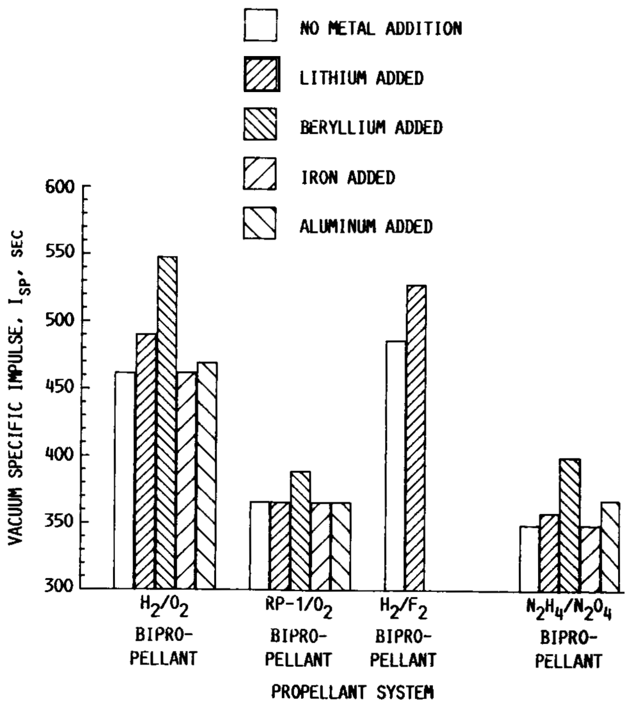

FIGURE 6. - ROCKET PERFORMANCE OF PROPELLANT SYSTEMS. P_C, 6.895 MN/M^2 (1000 PSIA); ϵ, 60:1; IDEAL EXPANSION.

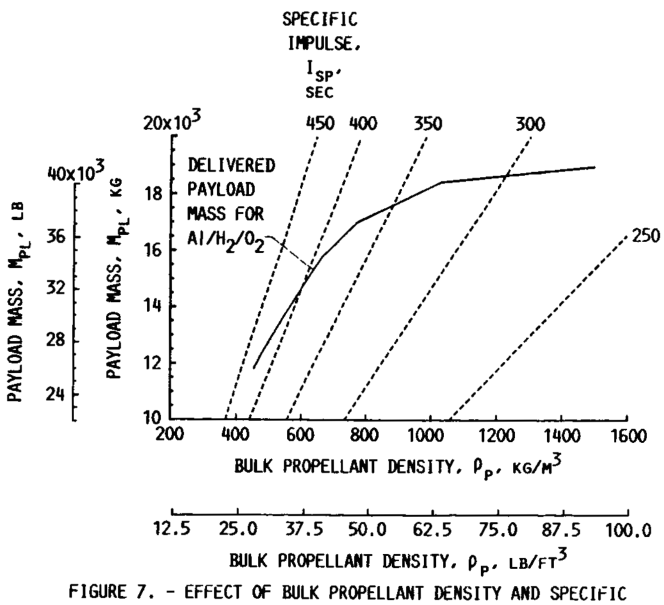

FIGURE 7. - EFFECT OF BULK PROPELLANT DENSITY AND SPECIFIC IMPULSE ON DELIVERED PAYLOAD MASS. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

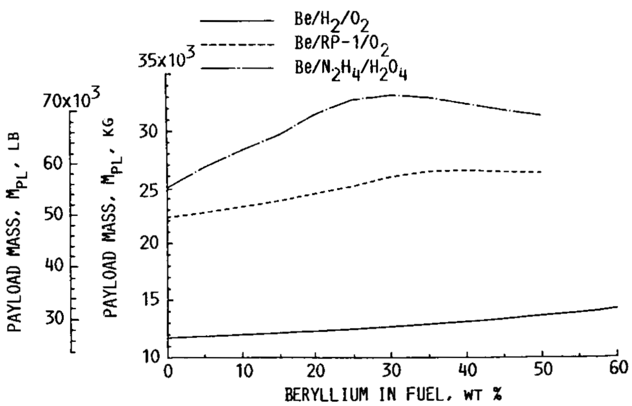

FIGURE 8. - PAYLOAD CAPABILITY OF BERYLLIUM TRIPROPELLANTS. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

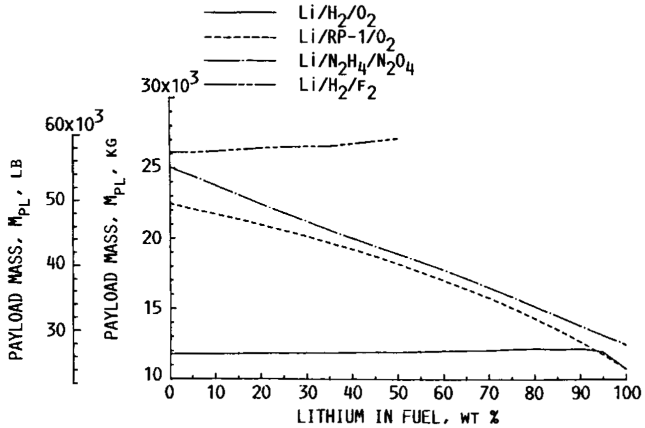

FIGURE 9. - PAYLOAD CAPABILITY OF LITHIUM TRIPROPELLANTS. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

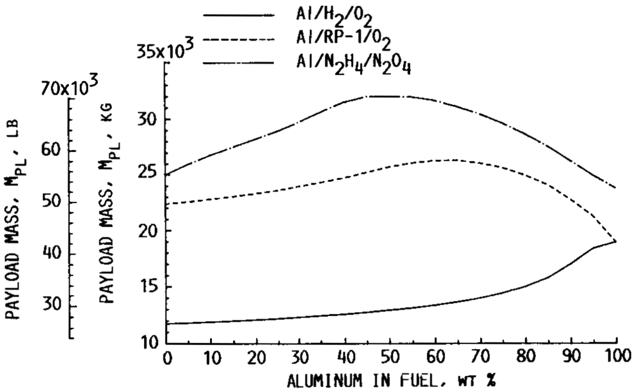

FIGURE 10. - PAYLOAD CAPABILITY OF ALUMINUM TRIPROPELLANTS. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY} = 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

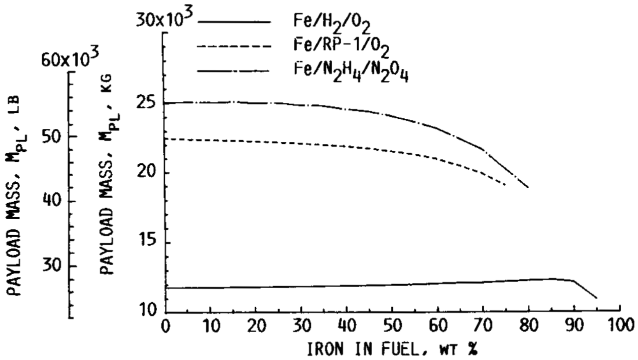

FIGURE 11. - PAYLOAD CAPABILITY OF IRON TRIPROPELLANTS. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

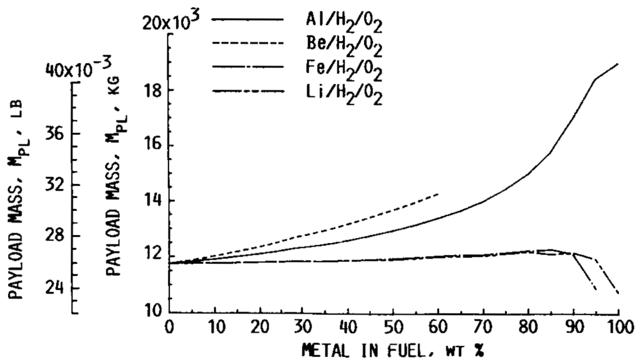

FIGURE 12. - VEHICLE PERFORMANCE OF METALS WITH H_2/O_2. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

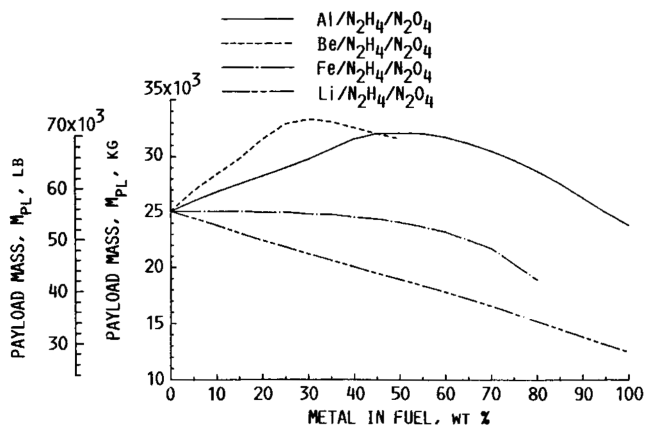

FIGURE 13. - VEHICLE PERFORMANCE OF METALS WITH N_2H_4/N_2O_4. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

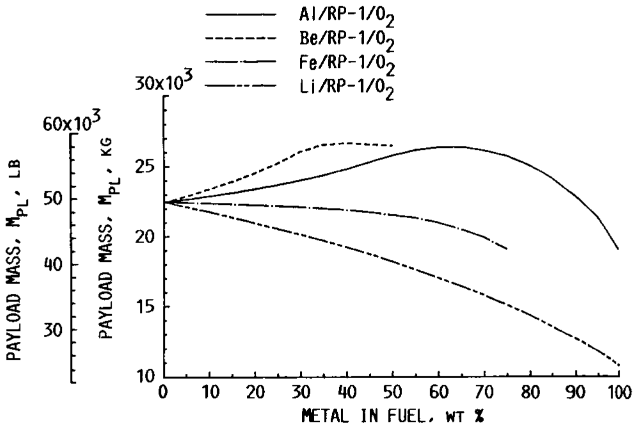

FIGURE 14. - VEHICLE PERFORMANCE OF METALS WITH RP-1/O_2. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

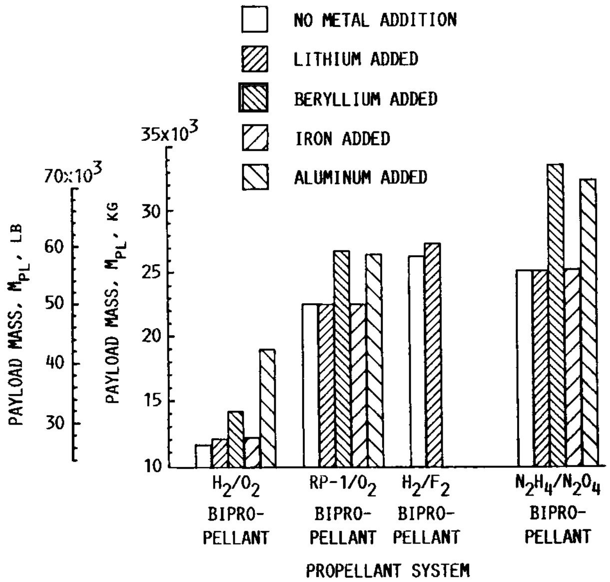

FIGURE 15. - VEHICLE PERFORMANCE OF PROPELLANT SYSTEMS. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

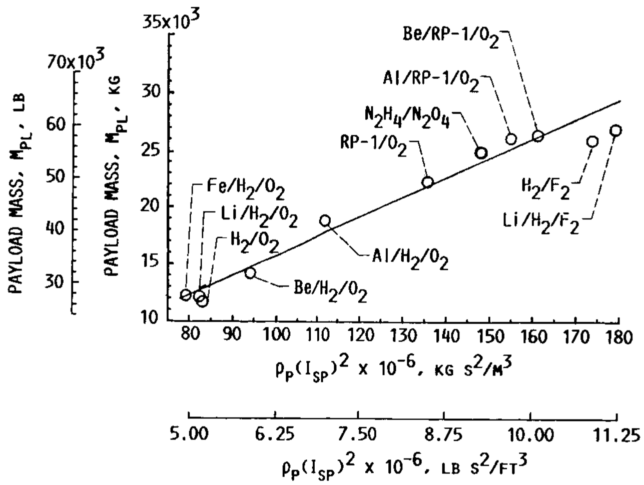

FIGURE 16. - RELATIVE PERFORMANCE OF PROPELLANT SYSTEMS BASED ON $\rho_P(I_{SP})^2$ PARAMETER. ΔV, 4267.2 M/SEC (14 000 FT/SEC); M_{DRY}, 2761.6 KG (6000 LB); V_P, 56.63 M^3 (2000 FT^3).

National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-100104 AIAA-87-1773	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle: An Evaluation of Metallized Propellants Based on Vehicle Performance	5. Report Date
	6. Performing Organization Code: 506-42-11
7. Author(s): Robert L. Zurawski and James M. Green	8. Performing Organization Report No.: E-3639
	10. Work Unit No.
9. Performing Organization Name and Address: National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 23rd Joint Propulsion Conference cosponsored by the AIAA, SAE, ASME, and ASEE, San Diego, California, June 29 - July 2, 1987. Robert L. Zurawski, NASA Lewis Research Center; James M. Green, Sverdrup Technology, Inc., Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

An analytical study was conducted to determine the improvements in vehicle performance possible by burning metals with conventional liquid bipropellants. These metallized propellants theoretically offer higher specific impulse, increased propellant density and improved vehicle performance compared with conventional liquid bipropellants. Metals considered were beryllium, lithium, aluminum and iron. Liquid bipropellants were H_2/O_2, N_2H_4/N_2O_4, RP-1/O_2 and H_2/F_2. A mission with ΔV = 4267.2 m/sec (14 000 ft/sec) and vehicle with propellant volume fixed at 56.63 m^3 (2000 ft^3) and dry mass fixed at 2761.6 kg (6000 lb) was used, roughly representing the transfer of a chemically propelled, upper-stage vehicle from a low Earth orbit to a geosynchronous orbit. The results of thermochemical calculations and mission analysis calculations for liquid bipropellants metallized with beryllium, lithium, aluminum and iron are presented. Technology issues pertinent to metallized propellants are discussed.

17. Key Words (Suggested by Author(s)): Tripropellants; Metal propellants; High-energy propellants; Liquid rocket propellants; Specific impulse; Mission analysis; Propellant density; Beryllium; Lithium; Aluminum; Iron	18. Distribution Statement: Unclassified - unlimited; STAR Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	26	A03

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