NASA
Technical
Paper
2602

June 1986

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Summary

An analytical study was conducted to determine the specific-impulse advantages of adding metals to conventional liquid-bipropellant systems. Thermochemical calculations were performed on the tripropellants beryllium/hydrogen/oxygen ($Be/H_2/O_2$), beryllium/hydrazine/nitrogen tetroxide ($Be/N_2H_4/N_2O_4$), beryllium/RP-1/oxygen ($Be/RP\text{-}1/O_2$), lithium/hydrogen/fluorine ($Li/H_2/F_2$), aluminum/hydrogen/oxygen ($Al/H_2/O_2$), aluminum/hydrazine/nitrogen tetroxide ($Al/N_2H_4/N_2O_4$), and aluminum/RP-1/oxygen ($Al/RP\text{-}1/O_2$) for sea-level expansion from 6.895-MN/m^2 (1000-psia) chamber pressure. Three-dimensional plots characterize the effects on specific impulse of mixture ratio and metal loading in the fuel for these tripropellants.

Based on theoretical specific impulse, beryllium is the most attractive metal additive in tripropellant systems. Comparing the specific impulse of the bipropellant at its optimum ratio of oxidizer to total fuel *O/F* with that of the tripropellant at its optimum *O/F*, we find that increments of 69.2, 34.4, and 13.5 sec are theoretically achievable when beryllium is added to H_2/O_2, N_2H_4/N_2O_4, and $RP\text{-}1/O_2$, respectively. Beryllium addition can also increase the density of the bipropellant systems. However, because of its toxicity, there is opposition to the use of beryllium as a rocket fuel. The addition of lithium to H_2/F_2 theoretically results in a 25.9-sec specific-impulse increment, but the low density of lithium can offset this increment by decreasing propellant density. The addition of aluminum to H_2/O_2, N_2H_4/N_2O_4, and $RP\text{-}1/O_2$ theoretically results in specific-impulse increments of only 6.1, 9.6, and 0 sec, respectively. However, the addition of aluminum, with its high density, can substantially increase propellant density.

Several key technologies need to be explored to realistically evaluate the advantages of metallized propellant systems. These technologies include metal ignition and combustion, two-phase flow, cooling requirements, and the storage, transport, and injection of the metal. Also, mission analyses that consider both propellant density and specific impulse must be conducted to determine the true benefits of adding metals to conventional liquid-propellant systems.

Introduction

The need for high-performance propulsion systems to transfer payloads into high-energy trajectories has renewed interest in the addition of metals to traditional liquid propellants. These tripropellants offer the opportunity to advance chemical rocket propulsion performance beyond that of any bipropellant system. The focus of past efforts with tripropellants was the maximization of specific impulse to achieve payload advantages. As a result high-energy, low-molecular-weight metals such as beryllium and lithium were of primary concern. However, the importance of mass fraction in achieving payload gains has placed new emphasis on the potential of high-density metals as additives to liquid propellants. The intent of this report is to review the tripropellant concept in terms of the performance of selected tripropellant systems and to address issues pertinent to a current evaluation of the tripropellant concept.

Tripropellant propulsion systems consist of a liquid oxidizer, a liquid fuel, and a solid metal fuel. Combustion of tripropellants can be conceptually described to occur in discrete steps. All of the oxidizer burns with the metallic fuel for maximum energy release, which, in turn, heats the liquid fuel as a working fluid. Consumption of the oxidizer by the lower energy liquid fuel reduces the specific impulse of the system. This conceptual combustion model illustrates how high-energy metals can increase the specific impulse of liquid-bipropellant systems. Ideal combustion, which consists of a series of complex, simultaneous chemical reactions, is required to physically achieve the theoretical, shifting-equilibrium, specific-impulse values presented in this report. It must be realized, however, that ideal combustion is difficult to achieve with tripropellants because three phases are present in the combustion process. Owing to combustion inefficiencies, two-phase flow losses, and other factors discussed in the Technology Issues section of this report, the specific impulse physically achievable with the use of tripropellants will likely be less than that which is theoretically possible.

The literature was reviewed to determine the status of tripropellant technology and to select promising tripropellant candidates for use in this analytical study. The concept of metallized tripropellants is not new to rocket propulsion. Early analytical work in 1962 (ref. 1) stirred excitement about the use of high-energy metals, such as beryllium and lithium, in tripropellants; experimental demonstrations closely followed. However, the toxicity of beryllium caused strong opposition to its use, and the use of lithium was rejected after the adverse effect of propellant mass fraction was recognized. Subsequently NASA began to focus attention on advanced hydrogen/oxygen bipropellant systems, and budgets for the higher risk, high-payoff propulsion technology began to diminish. Eventually the concept of using tripropellants in liquid propulsion systems was abandoned.

The beryllium/hydrogen/oxygen tripropellant became a primary interest in the 1960's because of its large specific-impulse advantage over hydrogen/oxygen. The U.S. Air Force, hoping to use tripropellants in their propulsion systems, conducted successful hot firings using beryllium in a tribrid configuration (ref. 2). Beryllizine, which results from gelling beryllium in hydrazine, was also developed for propulsion systems application (ref. 3). However, combustion inefficiencies severely limited the performance of beryllium-fueled systems, and the toxicity of beryllium and its derivatives seemed to be an excessive risk. Lithium/hydrogen/fluorine, although not as high in specific impulse as the beryllium system, was thought to be a promising option because lithium was not toxic and, if heated, could be delivered as a liquid to the combustion chamber. A program resulted which achieved combustion efficiencies capable of over 500-sec specific impulse (at 60:1 area ratio) (ref. 4). Unfortunately subsequent studies (ref. 5) showed that the lithium/hydrogen/fluorine tripropellant does not increase payload capability when integrated into an advanced, upper-stage vehicle. The low density of lithium and the inert weight penalties inherent at the low mixture ratio offset the high specific impulse; as a result, there was no payload advantage.

Reconsideration of these experiences using today's improved computational capabilities shows that a wider range of metal loadings and direct vehicle payload analysis should be included to get a true picture of the potential of the concept. In other words in order to maximize payload, propellant densities and vehicle mass fractions with heavy metal loadings must be analyzed as well as specific impulse. When this is done, aluminum and other selected heavy metals look promising for use in tripropellants. In this study, therefore, several tripropellants were selected to reevaluate the potential of metallized tripropellant systems.

The candidates selected for analysis were beryllium/hydrogen/oxygen ($Be/H_2/O_2$), beryllium/hydrazine/nitrogen tetroxide ($Be/N_2H_4/N_2O_4$), beryllium/RP-1/oxygen ($Be/RP\text{-}1/O_2$), lithium/hydrogen/fluorine ($Li/H_2/F_2$), aluminum/hydrogen/oxygen ($Al/H_2/O_2$), aluminum/hydrazine/nitrogen tetroxide ($Al/N_2H_4/N_2O_4$), and aluminum/RP-1/oxygen ($Al/RP\text{-}1/O_2$). Since the $Be/H_2/O_2$ tripropellant can deliver more specific impulse than any other chemical propellant, it was an integral part of the analysis. The $Li/H_2/F_2$ was included because it has the performance closest to that of $Be/H_2/O_2$. The $Al/H_2/O_2$ tripropellant is a nontoxic alternative to $Be/H_2/O_2$, but it offers lower specific impulse. Finally, $Be/N_2H_4/N_2O_4$ and $Al/N_2H_4/N_2O_4$ were included to determine the specific impulse of tripropellants in storable systems, and $Be/RP\text{-}1/O_2$ and $Al/RP\text{-}1/O_2$ were included as representative tripropellants for hydrocarbon systems.

For this analytical study, Gordon and McBride's Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations (CEC computer program) (ref. 6) was used to generate specific-impulse values for the candidate tripropellants over a wide range of mixture ratios and propellant compositions. The program generated these theoretical rocket parameters by assuming equilibrium composition during sea-level expansion for a 6.895-MN/m^2 (1000-psia) chamber pressure. (A chamber pressure of 6.895 MN/m^2 (1000 psia) and a nozzle exit pressure of 0.1014 MN/m^2 (14.7 psia) are generally used today as standards for comparing specific-impulse values.)

For each tripropellant, three-dimensional plots were drawn to show theoretical specific impulse as a function of mixture ratio and metal loading in the fuel. These plots were produced by using the high-speed digital computing system at the NASA Lewis Research Center. This method of data presentation differs from that of past literature (ref. 1), which presents two-dimensional plots of theoretical specific impulse as a function of metal loading in the total propellant and excludes the effect of mixture ratio. The data presented here clarify the effect on specific impulse of both metal loading and mixture ratio and, consequently, eliminate the confusion that has arisen in the past as to how much liquid fuel is required in tripropellant systems.

Symbols

g_0	gravitational constant, 9.80665 m/sec^2
H	enthalpy, J/Kg
I_{sp}	specific impulse, sec
J	mechanical equivalent of heat, 0.102 kg m/J
M	molecular weight, kg/kg mol
M_d	vehicle dry mass, kg
M_f	final vehicle mass, kg
M_p	propellant mass, kg
M_{pl}	payload mass, kg
M_0	initial vehicle launch mass, kg
T	temperature, K
ΔV	velocity change for mission, m/sec
v_p	total propellant volume, m^3
ρ_p	bulk propellant density, kg/m^3

Subscripts:

c	chamber
e	nozzle exit

Background

A tripropellant consists of a liquid oxidizer, a liquid fuel, and a pure, solid metal such as beryllium, lithium, boron, or aluminum. Ideally the metal is delivered to the combustion chamber in pure, particulate form and can be suspended in the fuel, in the oxidizer, or in a separate carrier gas. Conceptually, combustion of tripropellants first burns all the oxidizer with the metal fuel, since this reaction is more energetic than that between the oxidizer and the liquid fuel. However, it is normally assumed that the energy evolved from combustion of some of the liquid fuel with the oxidizer is required to initiate burning of the metal. The energy released from combustion of the metallic fuel with the remainder of the liquid oxidizer then heats the bulk of the liquid fuel, which acts as a working fluid. Since rocket engine thrust results from the conversion of thermal energy generated by combustion to kinetic energy in the nozzle, it can be seen how high-energy metals can increase the specific impulse of conventional liquid bipropellant systems.

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

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

All terms other than enthalpy are constant; so,

$$I_{sp} \alpha \sqrt{\Delta H}$$

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

$$I_{sp} \alpha \sqrt{\frac{T_c}{M_c}}$$

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 (temperature) of the system and reducing the molecular weight of the combustion products. Tripropellant systems 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. Based on

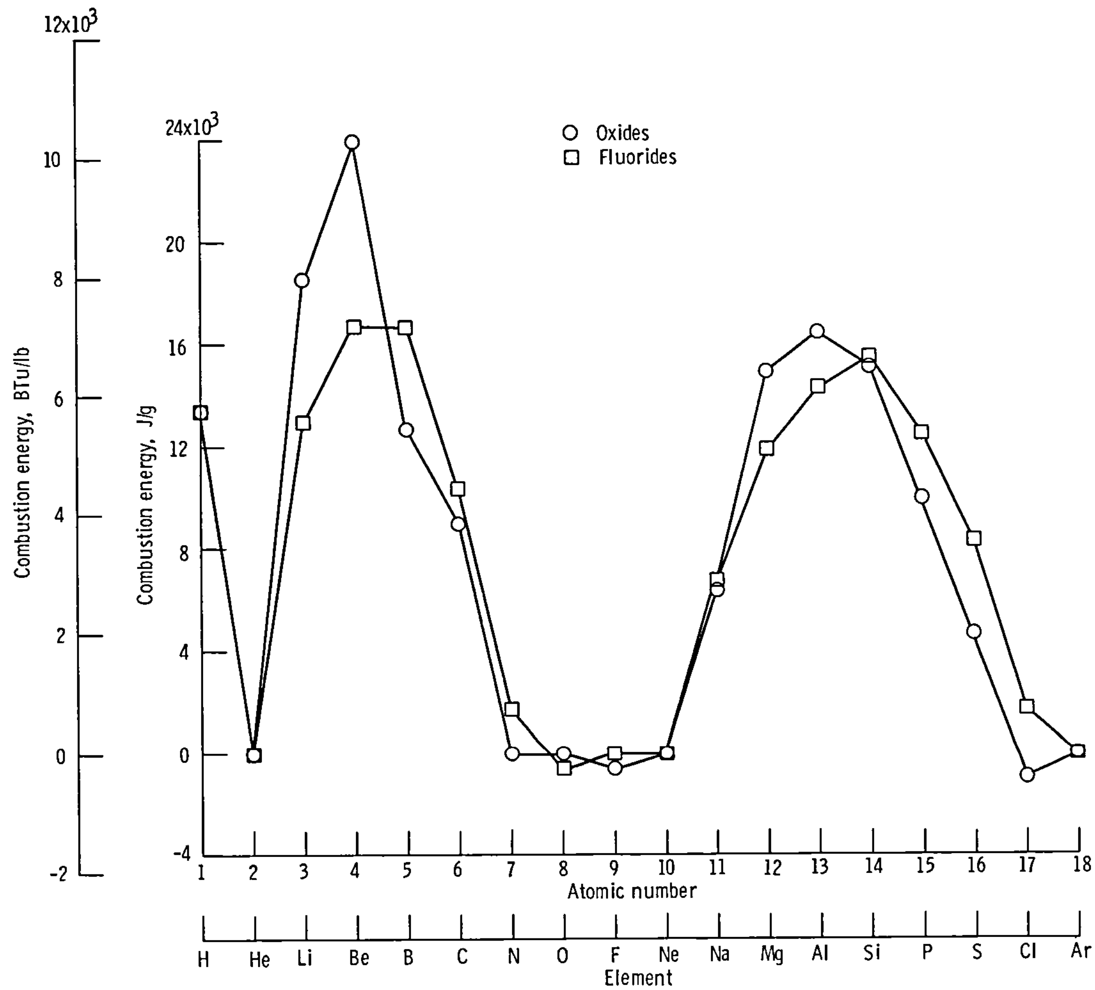


Figure 1.—Combustion energy of elements (from ref. 7).

combustion energy, the elements that appear most attractive for use in tripropellants include lithium, beryllium, boron, magnesium, aluminum, and silicon. When added to oxygen, beryllium has the highest combustion energy of any element. In fact, the $Be/H_2/O_2$ tripropellant can deliver the highest specific impulse of any chemical propellant. Beryllium supplies tremendous energy to the system with its high combustion energy, yet still has a low molecular weight; hydrogen supplies the low-molecular-weight working fluid needed to convert the high heat of metal combustion to thrust.

The energy released by combustion of the metal must be retained in order to attain high specific impulse. The advantage of the high combustion energy is lost if it is dissipated by dissociation of the resultant combustion products (ref. 7). Although the combustion energy of the lithium/oxygen combination competes with that of the beryllium/oxygen combination, the dissociation of lithium oxide at high temperatures makes this propellant combination undesirable. However, lithium produces thermally stable fluorides; therefore, it is the best fuel in fluorine systems. Boron has a relatively high combustion energy but offers little specific-impulse gain because of its relatively high molecular weight. High-molecular-weight gas products result in lower specific impulses because heavier molecules are less easily accelerated than lighter ones.

When only specific impulse is considered, lighter elements, such as beryllium and lithium, appear most attractive as additives for tripropellants because of their low molecular weight and high combustion energy. However, consideration of propellant density provides justification for using heavier elements such as aluminum. The relative importance of propellant density and specific impulse can be seen in the following rocket equation, which (assuming aerodynamic and drag forces to be negligible) gives the change in velocity and altitude of a rocket-powered vehicle:

$$\Delta V = g_0 I_{sp} \ln \frac{M_0}{M_f} = g_0 I_{sp} \ln \frac{M_p + M_d + M_{pl}}{M_d + M_{pl}}$$

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

$$\Delta V = g_0 I_{sp} \ln \frac{M_0}{M_f} = g_0 I_{sp} \ln \frac{\rho_p \nu_p + M_d + M_{pl}}{M_d + M_{pl}}$$

Rearranging the equation yields

$$M_{pl} = \frac{\rho_p \nu_p}{e^{\left(\frac{\Delta V}{g_0 I_{sp}}\right)} - 1} - M_d$$

This equation shows that payload capability is directly proportional to propellant density. Figures 2 and 3 (which show the effects on payload mass of specific impulse and bulk propellant density, respectively) were plotted from this equation by varying bulk propellant density from 320.4 kg/m^3 (20 lb/ft^3) to 1121.3 kg/m^3 (70 lb/ft^3) and specific impulse from 250 to 400 sec with $\Delta V = 4267.2$ m/sec (14 000 ft/sec), $\nu_p = 56.63$ 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. Figure 2 shows that payload capability increases with specific impulse along lines of constant propellant density. Figure 3 shows that payload capability increases with density along lines of constant specific impulse. However, in reality, payload mass does not directly increase

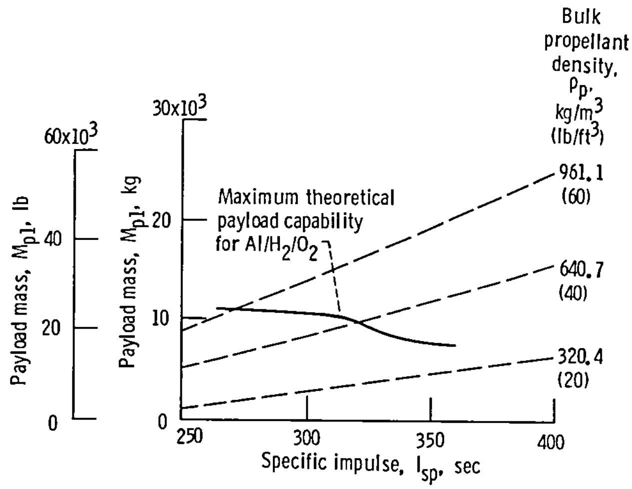


Figure 2.—Payload mass as function of specific impulse. Velocity change ΔV, 4267.2 m/s (14 000 ft/s); total propellant volume ν_p, 56.63 m^3 (2000 ft^3); vehicle dry mass M_d, 2721.6 kg (6000 lb).

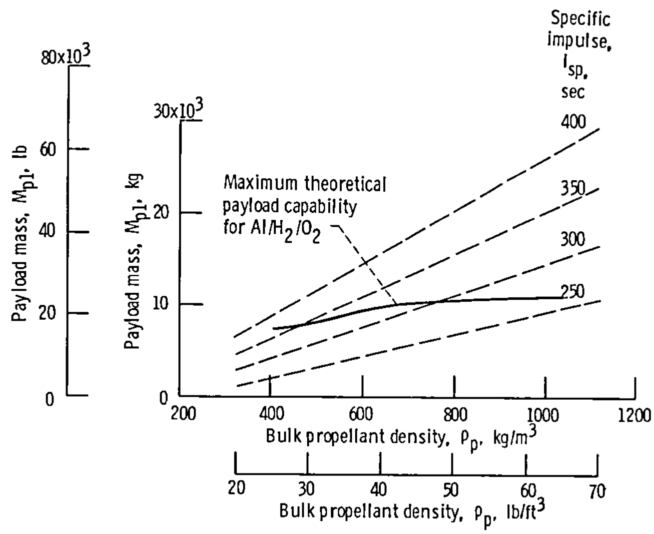


Figure 3.—Payload mass as function of bulk propellant density. Velocity change ΔV, 4267.2 m/s (14 000 ft/s); total propellant volume ν_p, 56.63 m^3 (2000 ft^3); vehicle dry mass M_d, 2721.6 kg (6000 lb).

with either parameter because of the thermochemical relationship between propellant specific impulse and bulk propellant density (i.e., mixture ratio and metal loading). The curves of the maximum, theoretical payload capability for $Al/H_2/O_2$ that are plotted in both figures illustrate this. These curves were calculated from the specific impulse, mixture ratio, and metal loading data. Bulk propellant density was determined from mixture ratio and metal loading as shown in the appendix. The payload capability curve for $Al/H_2/O_2$ (fig. 2) shows that payload mass actually decreases as specific impulse increases because of the resulting low bulk propellant densities. Conversely, figure 3 shows an increase in payload mass 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-molecular-weight metals in tripropellants can lead to payload advantages. It is important to realize that payload advantages can result from the increased performance or from the greater propellant mass fraction of the tripropellant systems.

Thermochemical Calculations

Thermochemical calculations were conducted by using the CEC computer program (ref. 6) to determine the theoretical specific impulse of the $Be/H_2/O_2$, $Be/N_2H_4/N_2O_4$, $Be/RP\text{-}1/O_2$, $Li/H_2/F_2$, $Al/H_2/O_2$, $Al/N_2H_4/N_2O_4$, and $Al/RP\text{-}1/O_2$ tripropellants. This program assumed shifting-equilibrium, ideal expansion to 0.1014 MN/m^2 (14.7 psia) from a chamber pressure of 6.895 MN/m^2 (1000 psia) and used the minimization of the Gibbs free energy of the chemically reacting system as the condition for chemical equilibrium. The results of the thermochemical calculations are summarized in table I, which gives the peak theoretical specific impulse of each tripropellant and its corresponding bipropellant along with optimum mixture ratio and metal loading.

Detailed tables of specific impulse as a function of mixture ratio and metal loading in the fuel are presented for each tripropellant in tables II to VIII. Mixture ratio is defined 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 + liquid fuel) that is metal fuel. The CEC computer program was not able to calculate performance values for some extreme conditions of mixture ratio and metal content in the fuel. These values were interpolated from surrounding data and are indicated by footnotes in tables II to IV and VI to VII. Interpolation was necessary to establish a complete matrix of values so that the data could be plotted three-dimensionally (figs. 8 to 14).

The performance data on tripropellants presented in past literature showed only the effect of metal loading on specific impulse and excluded the effect of mixture ratio. Figures 4 to 7 (ref. 1) show these data. These figures plot shifting-

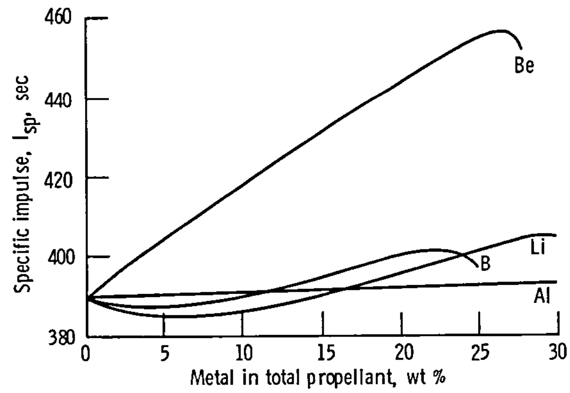


Figure 4.—Theoretical performance of metals in H_2/O_2 (liquids). Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

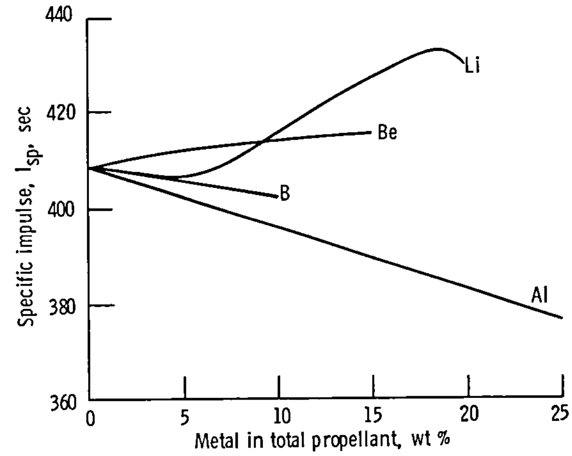


Figure 5.—Theoretical performance of metals in H_2/F_2 (liquids). Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

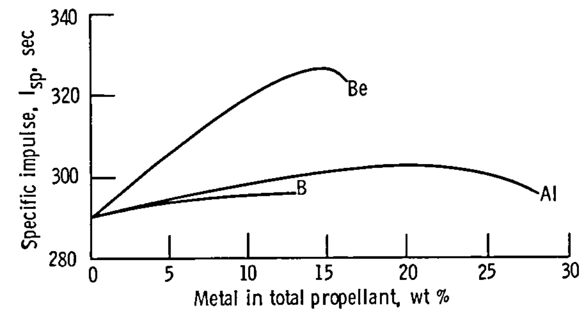


Figure 6.—Theoretical performance of metals in N_2H_4/N_2O_4. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

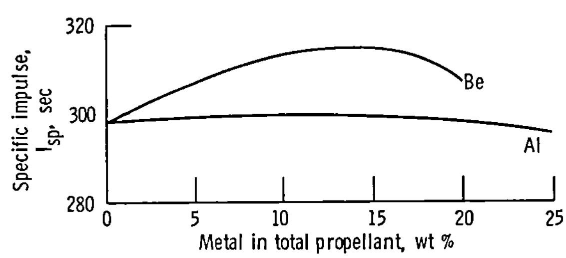


Figure 7.—Theoretical performance of metals in $(\text{-}CH_2\text{-})_x/O_2$ (liquid). Expansion 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

equilibrium specific impulse as a function of weight percent metal in the total propellant (fuel + oxidizer). Mixture ratio varies constantly along the curves of these figures. Data presented by this method exclude the effect of mixture ratio on specific impulse and disguise the liquid-fuel requirements in tripropellant systems. The data presented here in the form of three-dimensional plots clarify the liquid-fuel requirements by presenting the effects on specific impulse of both mixture ratio and metal loading in the total fuel (metal + liquid fuel).

The performance contours from this analysis were created by intersecting curves of constant metal loading with curves of constant mixture ratio for each tripropellant. The three-dimensional surface effect of both metal loading and mixture ratio on specific impulse, the effect of metal loading in the fuel on specific impulse, and the effect of mixture ratio on specific impulse are presented in a set of three plots for each tripropellant (figs. 8 to 14). Since the performance values were calculated and plotted at finite intervals of mixture ratio and metal loading, discontinuities appear in the peak of each contour. In reality the performance of the tripropellants can be represented by a smooth, continuous contour. Additionally, it is difficult to determine performance values from the three-dimensional plots because the plots are in perspective. The three-dimensional plots are included to show the performance contour for each tripropellant as a function of mixture ratio and metal loading in the fuel and are not intended to be used as a data source.

$Be/H_2/O_2$ Tripropellant

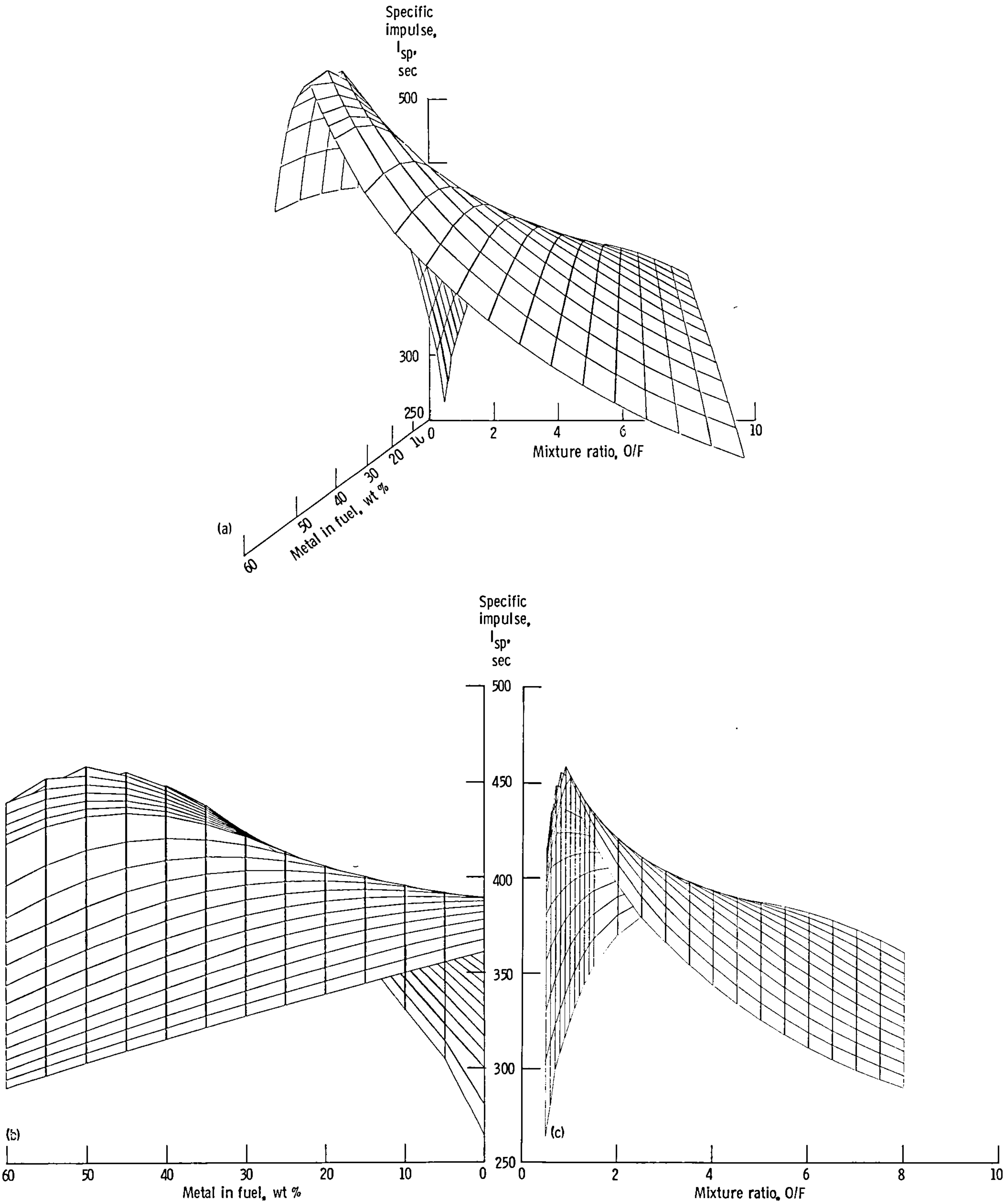
The $Be/H_2/O_2$ tripropellant offers the highest specific impulse of any chemical propellant combination and, as such, acts as a standard by which the performance of other chemical propellants can be compared. Therefore, this propellant combination was an integral part of the study even though it was recognized that in the past the toxicity of beryllium had been a deterrent to using it in a propellant combination as a rocket fuel. Figure 8(a) presents the three-dimensional performance contour for $Be/H_2/O_2$ and shows the effect of both mixture ratio and metal loading on maximum, theoretical specific impulse for sea-level expansion from 6.895-MN/m^2 (1000-psia) chamber pressure. Figure 8(b) is the left view of the contour plot for $Be/H_2/O_2$ and shows the two-dimensional effect of metal loading in the fuel on specific impulse. The upper limit of this plot represents the peak theoretical specific impulse as a function of metal content in the fuel. Figure 8(c) is the right view of the contour plot and shows the two-dimensional effect of mixture ratio on specific impulse. The upper limit of this plot is the peak theoretical specific impulse as a function of mixture ratio. It is evident that peak specific impulse is extremely sensitive to mixture ratio and occurs at a very low mixture ratio. These figures show that the $Be/H_2/O_2$ tripropellant can achieve 458.5 sec of theoretical specific impulse at 50 wt % beryllium in hydrogen and 0.9 oxidizer to total fuel ratio *O/F*. This is 69.2 sec more of specific impulse than is produced by H_2/O_2, whose maximum performance is 389.3 sec at 4.0 *O/F*. However, it must be realized that the specific impulse achievable by using the tripropellant combinations analyzed here will likely be less than the theoretical values shown because of combustion inefficiencies and two-phase flow losses resulting from the presence of the metal component in the system.

In addition to its high combustion energy and low molecular weight, beryllium also has a relatively high density (1850.1 kg/m^3 (115.5 lb/ft^3)), which makes it desirable as a rocket fuel from the standpoint of vehicle mass fraction. However, low mixture ratios are required with $Be/H_2/O_2$ for increased specific impulse. These can be detrimental to payload capability because they require additional hydrogen in the system to act as a working fluid. The addition of hydrogen, with its low density, decreases bulk propellant density and payload capability. Therefore, the high specific impulse offered by the $Be/H_2/O_2$ tripropellant is offset by the low mixture ratio required to achieve this performance. Both specific impulse and bulk propellant density must be considered for this, or any other, tripropellant system in order to accurately assess the true potential (which is ultimately measured by delivered payload).

$Be/N_2H_4/N_2O_4$ Tripropellant

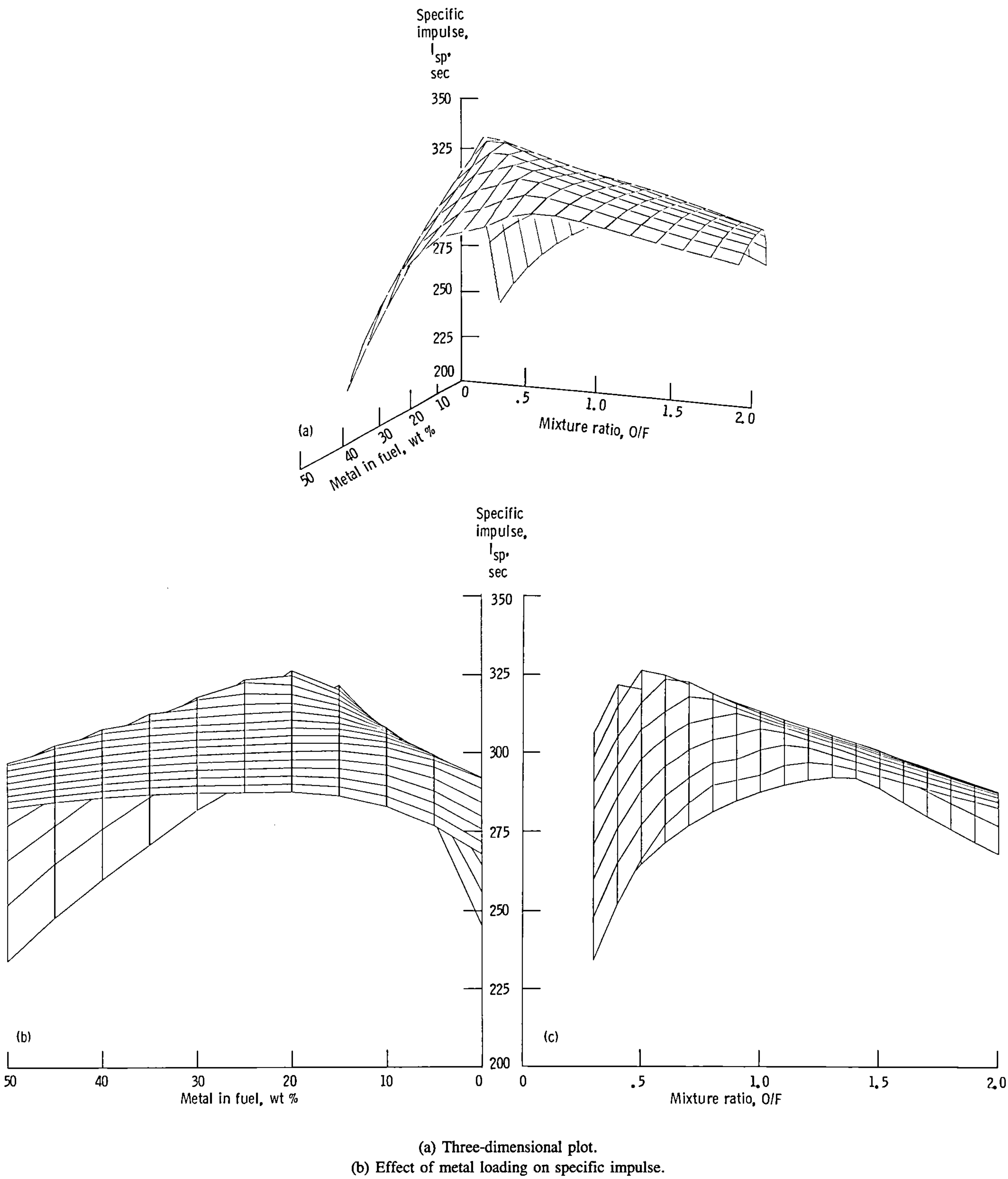
The $Be/N_2H_4/N_2O_4$ system was selected as the candidate for a storable propellant system. The theoretical specific impulse of the $Be/N_2H_4/N_2O_4$ tripropellant is shown in figure 9. Figure 9(a) shows the performance contour for $Be/N_2H_4/N_2O_4$. Figure 9(b) shows the effect of metal loading on specific impulse. Compared with other tripropellants considered in this analysis, much lower metal loadings are required to attain peak specific impulse in the $Be/N_2H_4/N_2O_4$ system. Figure 9(c), which shows the effect of mixture ratio on specific impulse, illustrates that in the $Be/N_2H_4/N_2O_4$ system peak specific impulse is relatively insensitive to mixture ratio compared with the $Be/H_2/O_2$ system. For sea-level expansion from 6.89-MN/m^2 (1000-psia) chamber pressure with $Be/N_2H_4/N_2O_4$, peak specific impulse is 326.4 sec at 20 wt % beryllium in hydrazine and 0.5 *O/F*. This represents a 34.4-sec performance increment over N_2H_4/N_2O_4 which offers 292.0-sec specific impulse at 1.3 *O/F*.

Beryllium metal shows great potential for increasing the performance of storable rocket fuels. The low mixture ratio required for optimum specific impulse does not significantly affect payload capability in this case because the densities of N_2H_4 and N_2O_4 do not differ greatly. As a result, the addition of beryllium to the N_2H_4/N_2O_4 propellant combination will always increase bulk propellant density, vehicle mass fraction, and payload capability. In addition, unlike the other tripropellants analyzed in this study, significant specific-impulse advantages can be derived from the $Be/N_2H_4/N_2O_4$ tripropellant with only small additions of metal (fig. 9). At low metal loadings the metal component is more easily handled; combustion efficiencies are higher; and two-phase flow losses, which detract from performance, are lower.



(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 8.—Theoretical performance for $Be/H_2/O_2$. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).



(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 9.—Theoretical performance for $Be/N_2H_4/N_2O_4$. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

$Be/RP\text{-}1/O_2$ Tripropellant

The $RP\text{-}1/O_2$ propellant system was selected for analysis to determine the specific-impulse increment resulting from the addition of a metal to a hydrocarbon system. Generally the specific impulse of hydrocarbon-fueled systems is not markedly increased by addition of metals because the hydrocarbon fuel does not produce sufficient low-molecular-weight, gaseous combustion products to use the heat of combustion of the metal (ref. 1). This is illustrated by the performance of the $Be/RP\text{-}1/O_2$ tripropellant (fig. 10). At 1.3 *O/F* and 25 wt % beryllium in the fuel, 313.7-sec of specific impulse is theoretically achievable. The peak specific impulse of the $RP\text{-}1/O_2$ propellant is 300.2 sec at 2.5 *O/F*. Therefore, only a 13.5-sec specific-impulse increment is achievable by adding beryllium to $RP\text{-}1/O_2$. However, the increase in propellant density could provide justification for using beryllium in the $RP\text{-}1/O_2$ system.

Beryllium shows great potential for increasing the performance of certain bipropellant systems. However, the toxicity of beryllium and its derivative, beryllium oxide, remains an important issue which has prevented its use in the past and could prevent its use in the future. Toxicity is a problem in the experimental testing and atmospheric use of beryllium-fueled engines. Depending on the concentration and ingestion time inhalation of beryllium or its compounds can cause either acute or chronic berylliosis, a fatal lung disorder. Modes of injestion other than inhalation are considerably less serious. The threshold limit value of beryllium (the average airborne concentration to which humans may be repeatedly exposed without adverse effect) is 2 $\mu g/m^3$, and exposure to concentrations over 25 $\mu g/m^3$ can cause acute berylliosis. Adverse effects at such low concentrations indicate that beryllium is extremely toxic. The toxicity problem may not be as severe as these numbers imply, though, because beryllium oxide (the primary product from combustion of beryllium with oxygen) has been shown to be less toxic than beryllium itself (ref. 8). However, strict safety standards would certainly be required in experimental testing, and all testing would require a scrubber, because open-air test firings of beryllium-fueled propulsion systems are prohibited by government regulation (ref. 9). Although the toxicity of beryllium could certainly be a deterrent to its use as a rocket fuel, in certain propulsion system applications where the severity of the toxicity issue diminishes beryllium could safely be used as a propellant. A complete review of the chemical and physical properties, toxicity, and environmental impacts of beryllium is contained in the literature (ref. 10). References 11 and 12 also contain safety rules for handling beryllium during testing and a test plan for firing a beryllium-fueled propulsion system.

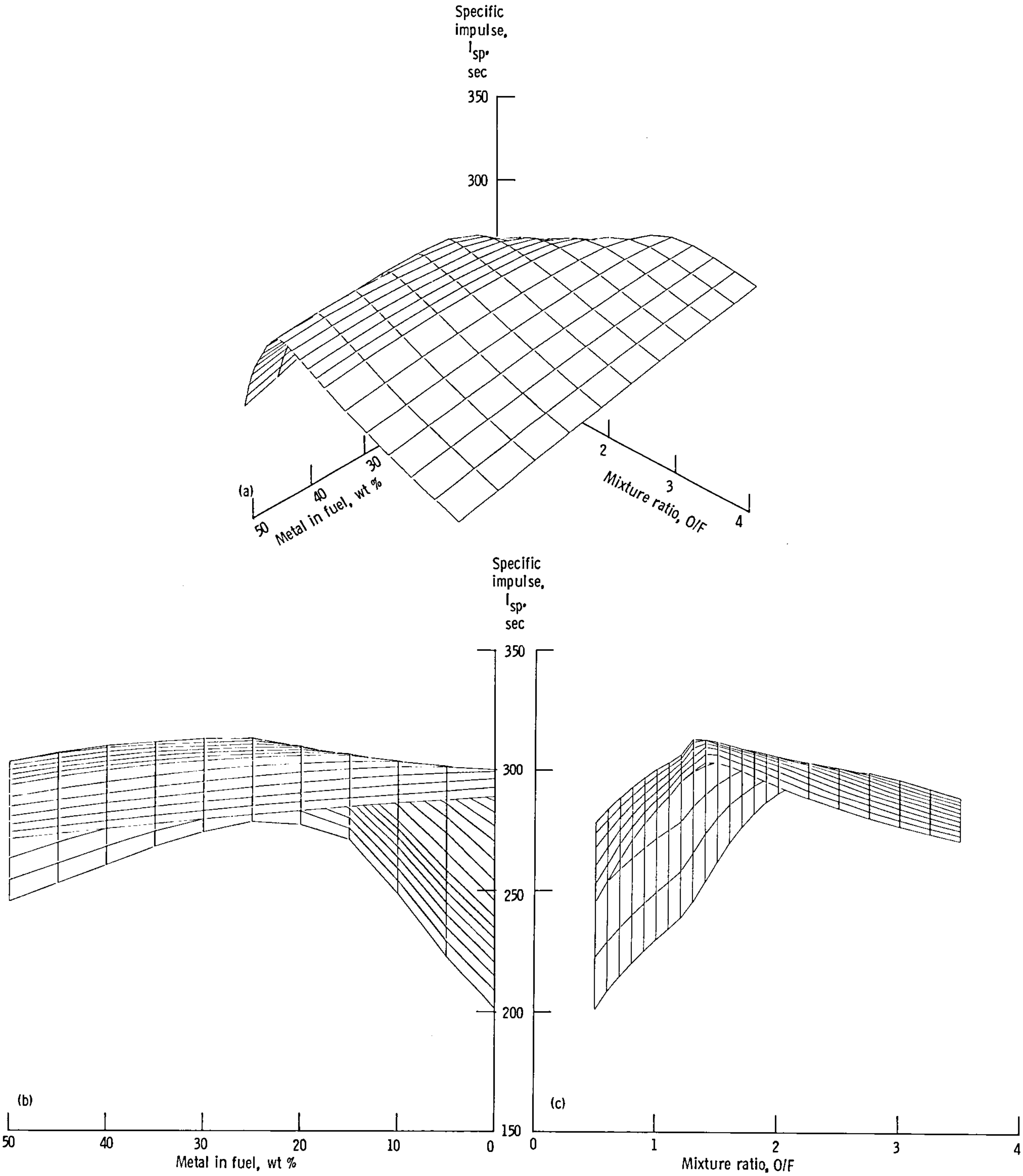
$Li/H_2/F_2$ Tripropellant

$Li/H_2/F_2$ is the tripropellant with the performance closest to that of $Be/H_2/O_2$. Figure 11 presents the theoretical performance for this propellant combination. Figures 11(a) and 11(b) show that metal loadings above 25 wt % in the fuel and mixture ratios around 1.0 *O/F* are required to derive specific-impulse advantage from the $Li/H_2/F_2$ tripropellant. At peak performance this propellant combination can supply 437.7-sec specific impulse at 1.1 *O/F* and 40 wt % lithium in the hydrogen. Comparing this with a peak specific impulse of 411.8 sec at 8.0 *O/F* for H_2/F_2 demonstrates that a 25.9-sec impulse advantage can theoretically be realized by adding lithium to H_2/F_2.

The main advantage of $Li/H_2/F_2$ over other tripropellants is that lithium has a melting point low enough for it to be liquefied. Lithium has a melting point of 180.5 °C (357.0 °F), whereas the melting points of aluminum and beryllium are 660.4 °C (1211 °F) and 1278 °C (2332 °F), respectively. Liquefaction of the metal eliminates the problems associated with the injection of solids. However, liquid lithium is difficult to handle. Propellant lines must be heated to keep the metal a liquid. In addition, lithium, an alkali metal, presents a dangerous fire hazard since it burns spontaneously from contact with the atmosphere. Finally, liquid lithium is highly corrosive to most metals and is incompatible with gasket and sealing materials (ref. 13). The toxic, reactive nature of fluorine adds to these problems. However, the low mixture ratio required to achieve specific-impulse advantages with $Li/H_2/F_2$ is the factor which makes it appear a poor choice for a rocket fuel. Because lithium has a very low density (533.4 kg/m^3 (33.3 lb/ft^3)), its addition tends to decrease bulk propellant density and mass fraction. It was discovered in the 1960's that this decrease can totally offset the specific-impulse advantage of the propellant combination. As a result, there is no increase in payload capability by adding lithium to the H_2/F_2 system.

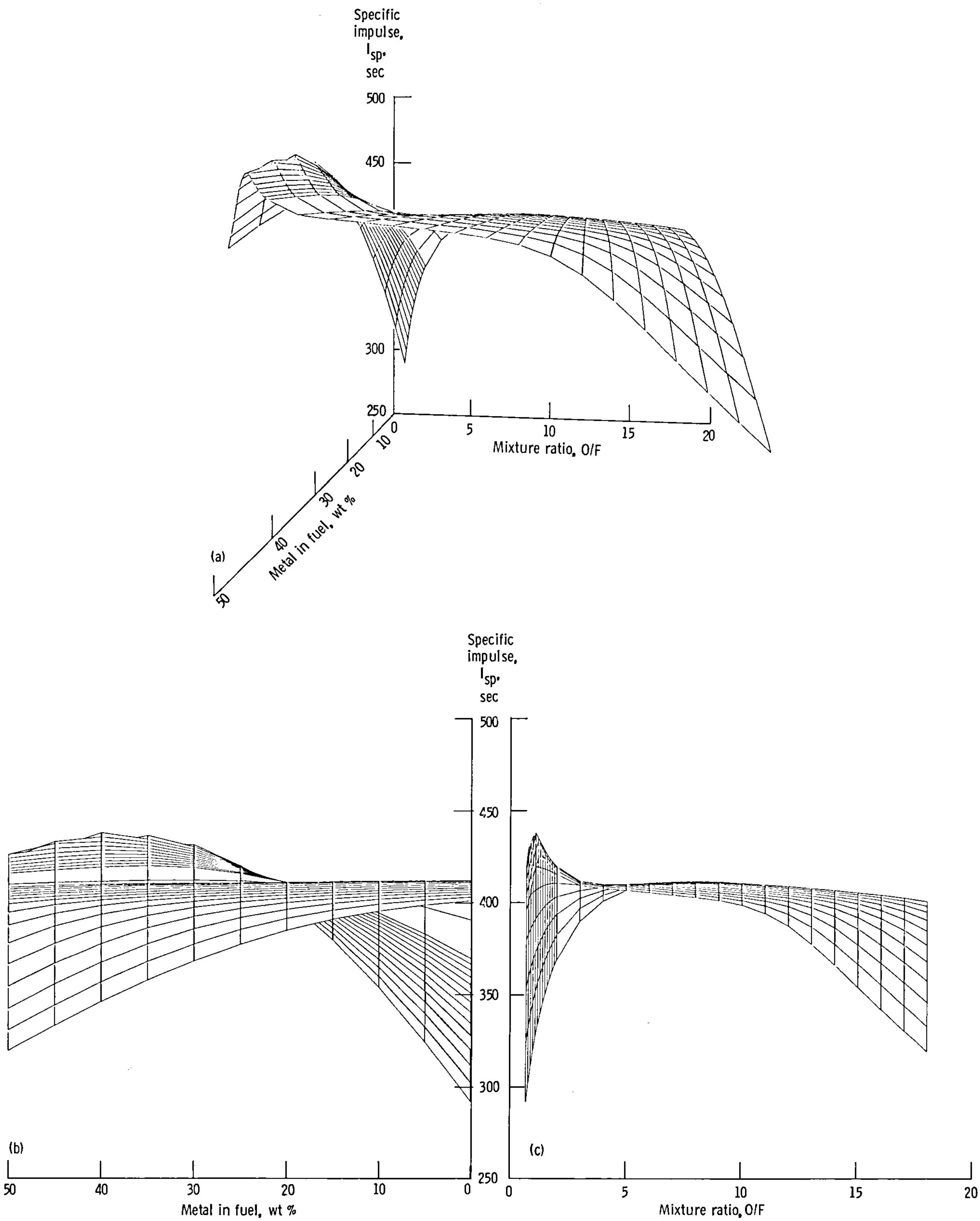
$Al/H_2/O_2$ Tripropellant

The specific impulse of the H_2/O_2 system is only slightly increased by the addition of aluminum. Although aluminum is an energetic metal, it has a high molecular weight, which is not conducive to high specific impulse. However, aluminum is much denser (2700.7 kg/m^3 (168.6 lb/ft^3)) than beryllium or lithium; therefore, because of the increase in propellant density, significant payload benefits can result from adding aluminum to bipropellant systems. An additional advantage of aluminum compared with beryllium is that it is nontoxic. Figure 12 shows the theoretical performance of the $Al/H_2/O_2$ tripropellant for sea-level expansion from 6.895-MN/m^2 (1000-psia) chamber pressure. The $Al/H_2/O_2$ tripropellant can supply 395.4 sec of specific impulse at 0.6 *O/F* and 65 wt % aluminum in hydrogen. This represents an increment of 6.1 sec over the specific impulse of H_2/O_2 at its optimum *O/F*. Figures 12(b) and (c) show that the performance of $Al/H_2/O_2$ is almost constant over a broad range of mixture ratios and metal loadings from 0 to 65 wt % in the fuel. Therefore, since the addition of aluminum to H_2/O_2 results



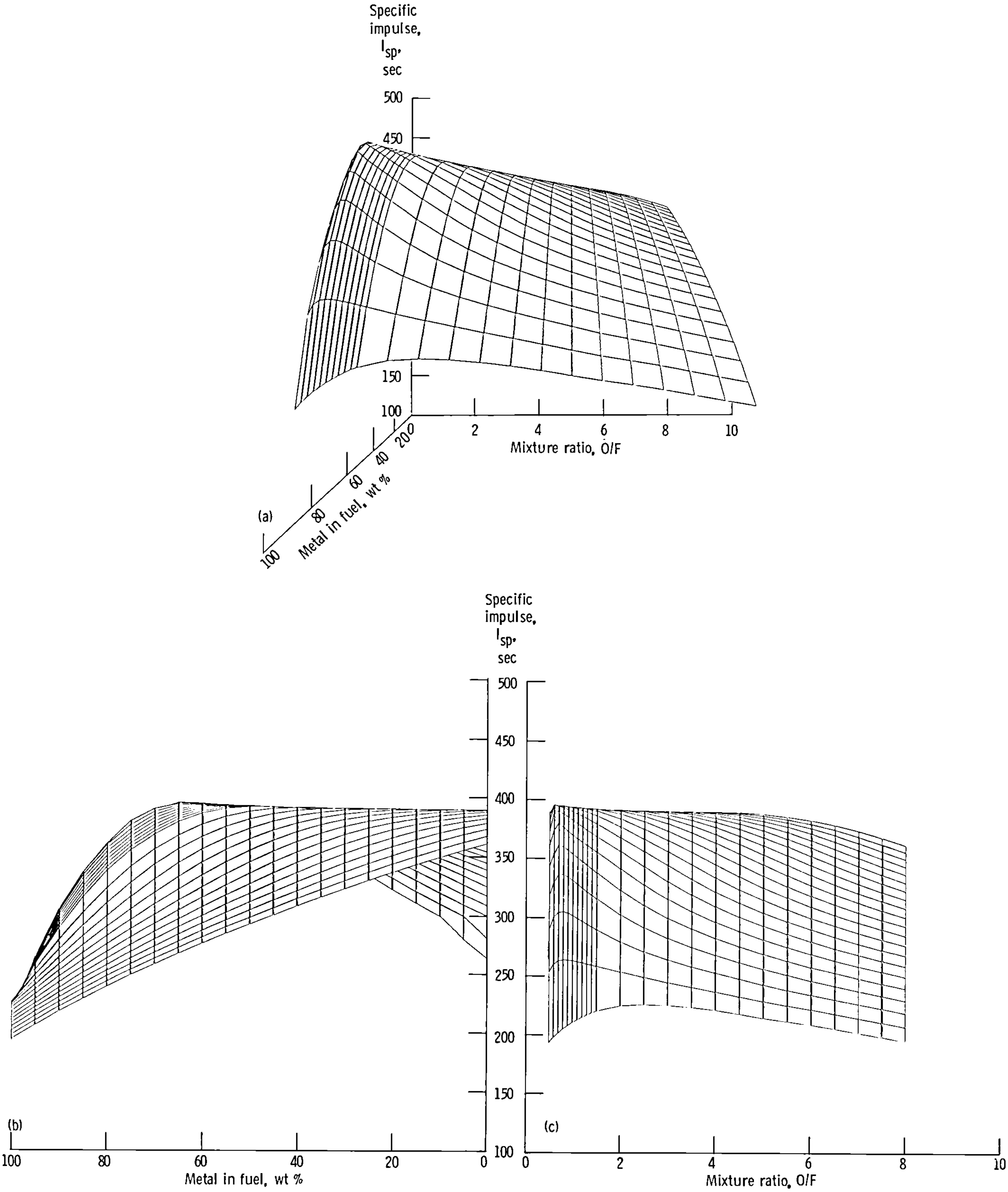
(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 10.—Theoretical performance for $Be/RP\text{-}1/O_2$. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).



(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 11.—Theoretical performance for $Li/H_2/F_2$. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).



(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 12.—Theoretical performance for $Al/H_2/O_2$. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

in an increase in propellant density while performance remains essentially constant, significant payload benefits can result. Complete mission studies need to be conducted to discover the true potential of dense metals in tripropellant systems.

$Al/N_2H_4/N_2O_4$ Tripropellant

The addition of aluminum only slightly increases the specific impulse of the N_2H_4/N_2O_4 system. However, as in the $Al/H_2/O_2$ system, the aluminum addition can increase propellant density. The performance of the $Al/N_2H_4/N_2O_4$ propellant combination is shown in figure 13. This propellant combination offers 301.6 sec of theoretical specific impulse at 0.4 O/F and 30 wt % aluminum in hydrazine. The result of adding aluminum to N_2H_4/N_2O_4 is a 9.6-sec specific-impulse increment. Aluminum seems as attractive as beryllium for increasing the payload capability of the N_2H_4/N_2O_4 system; however, the anticipated increase in payload capability with aluminum is attributed almost entirely to the increase in propellant density due to the addition of this metal to the system. The potential of this tripropellant combination was recognized in the past. In fact, technology has already been developed for suspending aluminum powder in hydrazine with a substance called alumizine (ref. 14).

$Al/RP\text{-}1/O_2$ Tripropellant

Figure 14 shows the theoretical specific impulse of the $Al/RP\text{-}1/O_2$ tripropellant for sea-level expansion from 6.895-MN/m^2 (1000-psia) chamber pressure. Figure 14(a) illustrates that based on specific impulse there is no advantage to adding aluminum to $RP\text{-}1/O_2$ because no performance increment results from the addition. The best specific impulse that can be achieved with this metallized system is 300.1 sec at 2.4 O/F and 5 wt % aluminum in the fuel. However, the bipropellant, itself, offers 300.2 sec of specific impulse. Although no specific-impulse advantage is shown with this tripropellant system, mission analyses considering both propellant density and specific impulse should be conducted to determine if there can be a benefit by adding aluminum to the $RP\text{-}1/O_2$ bipropellant. Table I summarizes the peak theoretical specific impulse (optimum mixture ratio and metal loading) of each of the tripropellants discussed.

Technology Issues

Theoretical analysis indicates that tripropellants can offer significant performance advantages over their corresponding bipropellants. However, because of the energetic nature of the propellants and the problems associated with the presence of solid metal in the system, an advanced technology is required to develop a reliable, high-energy tripropellant propulsion system. Research was done with tripropellants in the 1960's by the Air Force and private industry, and much of that technology is still applicable today. The technology issues discussed here were uncovered from a literature survey of this past work. Some critical technology issues important to determining the feasibility of the tripropellant concept are presented.

Ignition and Combustion

Failure to achieve ignition or efficient combustion of the metal could limit delivered performance to levels substantially below those theoretically attainable and thus make the tripropellant concept unattractive. Experiments with the $Be/H_2/O_2$ tripropellant demonstrated that efficient ignition and combustion of beryllium in beryllium-fueled tripropellants are the primary problems to solve for the tripropellant concept to be feasible. The only beryllium-fueled tripropellant systems which demonstrated efficient ignition and combustion in the past were solid propellant motors (ref. 5). Efficient combustion of the metal in tripropellant systems 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 feed system and an effective thrust chamber configuration is the first step toward solving the metal ignition problem and achieving efficient combustion of the metal.

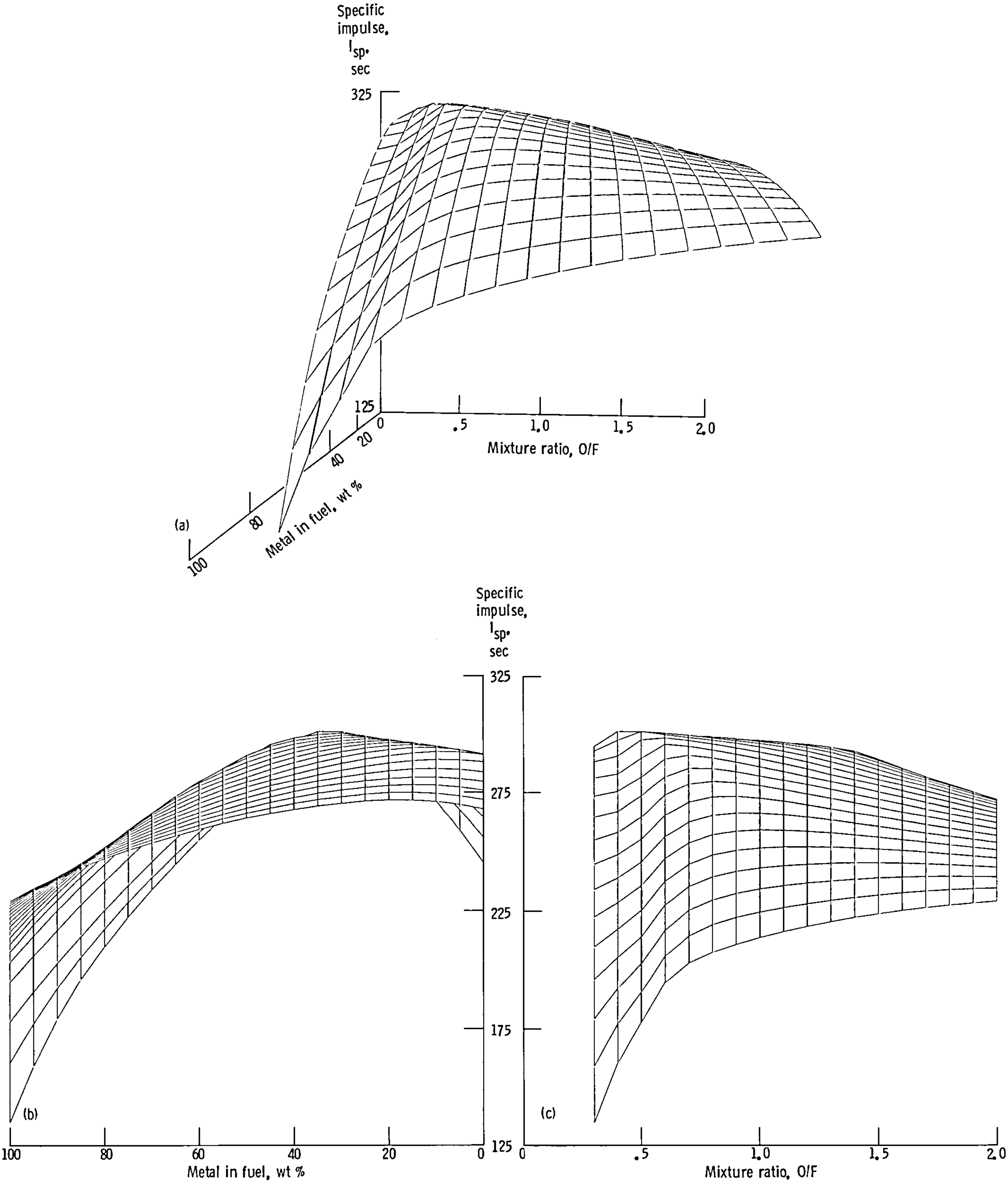
Two-Phase Flow

The combustion of metals in tripropellants 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. If the solid particles are very small, they will have the same velocity as the gas and will be in thermal equilibrium with the nozzle gas flow. Therefore, small, solid particles are required in tripropellant systems to improve combustion efficiency and minimize two-phase flow losses in the nozzle.

Specific-impulse losses due to two-phase nozzle flow in thrust chambers employing metallized propellant systems are potentially quite large, particularly at relatively low thrust levels, because the exhaust products are characterized by high weight fractions of particles and a carrier gas or working fluid having low molecular weight. In addition, two-phase flow effects cause the optimum delivered performance to occur at mixture ratios significantly different from those predicted solely on the basis of thermochemical calculations (ref. 2). Consequently, an assessment of two-phase flow losses and kinetic effects should precede experimentation with a tripropellant system in order to compare actual and theoretical performance and to determine if the concept remains feasible.

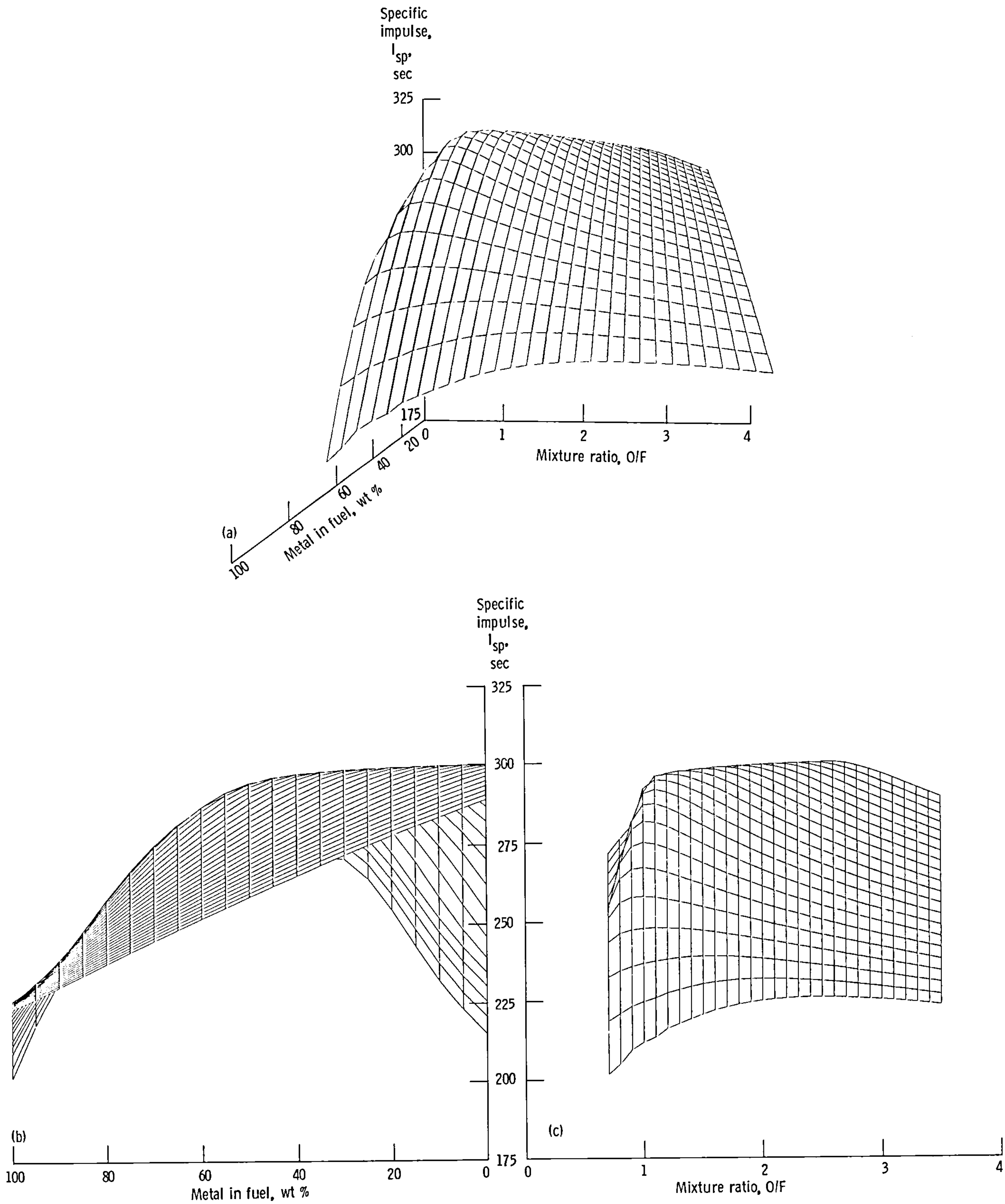
Cooling Requirements

The high thermochemical energy released during the combustion of metals implies the need for advanced cooling



(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 13.—Theoretical performance for $Al/N_2H_4/N_2O_4$. Expansion, 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).



(a) Three-dimensional plot.
(b) Effect of metal loading on specific impulse.
(c) Effect of mixture ratio on specific impulse.

Figure 14.—Theoretical performance for Al/RP-1/O_2. Expansion 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).

techniques in thrust chambers employing tripropellants. Radiation heat transfer will be greater than in conventional thrust chambers because of the presence of particulate matter in the combustion gases. Radiation interchange between gaseous combustion products and the thrust chamber wall is normally 5 to 10 percent of the convective heat-transfer rate and is normally neglected. However, the particulate matter introduced by metallized propellants can significantly increase the thermal interchange between the reactants and the thrust chamber wall. In addition, impingement of condensed particles on the converging portion of the thrust chamber wall could present a problem. Reference 15 contains more information on heat-transfer considerations for metallized propellant systems.

Storage, Transport, and Injection of Solid

The development of a reliable means to store, transport, and inject the solid into the thrust chamber must precede the development of a tripropellant propulsion system. A number of metal feed systems were considered in the 1960's. The most popular metal feed technique for tripropellants was to bind the metal into a carbonaceous grain. The grain regressed uniformly by pyrolysis as a result of convective heat transfer from the core flow of hot liquid fuel-oxidizer combustion products. Such a system is called a tribrid system. The tribrid system offers a very convenient way to package the metal component, although it does not satisfy the ideal combustion scheme for tripropellant systems. The addition of a fourth component (the carbonaceous binder) to a tripropellant system results in a decrease in theoretical specific impulse roughly proportional to the amount of material added. Tribrid grains must contain 95 wt % metal to derive performance advantages from this type of system (ref. 2). However, there is a limit to the amount of metal that can be bound in the grain. Therefore, although the metal can be introduced into the thrust chamber effectively and at a controlled rate, an overall performance less than optimum is inherent with the tribrid system.

Other metal feed systems were considered by the Air Force Rocket Propulsion Laboratory in their assessment of cryogenic tripropellant systems in 1965 (ref. 16). It was proposed that metal powder be suspended in hydrazine and then be introduced into the thrust chamber, but loadings of only 62 wt % could be obtained, and the performance degradation introduced by the required quantity of hydrazine precludes further consideration of this technique in cryogenic systems. An all-metal, sintered grain which would be inserted into the combustion chamber was also proposed as a means of introducing the metal into the thrust chamber in pure form, but several tests with sintered aluminum grains indicated that the all-metal grain tended to melt rather than to regress in a uniform manner.

The fluidized bed and the cryogel feed techniques are metal feed systems in which the metal is introduced into the thrust chamber in pure, particulate form with either the fuel or the oxidizer. These feed systems offer the greatest potential for a high-performance tripropellant system, but also require the most technical development. With the fluidized-bed approach, a bed of powdered metal is fluidized by gaseous fuel and is transported into the thrust chamber. Approximately 10 percent of the total fuel flow is required to transport the metal, and a small amount of deflocculating agent is added to assure that the powder will flow freely. The cryogel feed technique uses a cryogenic gel of liquid oxidizer, a metal, and a gelling agent. The particulate gelling agent is required in only minute quantities; so no significant theoretical performance penalty is incurred by its presence. Adiabatic compression tests on a gel sample of O_2/Be at liquid-nitrogen temperatures indicated that the liquid oxidizer/metal gel could be handled as a monopropellant with relative safety. In addition, cryogel injector tests indicated that, even at very low injection velocities, no burn-back problems existed, and no such problems were anticipated. However, the threat of accidental detonation always exists with this technique because the fuel is premixed with oxidizer. A better approach might be to mix the metal with the liquid fuel.

It is evident from past efforts that the development of an effective metal feed system is only one of several key technologies which need to be explored before metallized propellants can be used in rocket propulsion systems. Although much of this technology is new to the liquid-rocket community, metals have been extensively used in solid-rocket propulsion, and that technology can be applied to tripropellants. The issues which need to be addressed initially are the development of a metal management system (i.e., storage, transport, and injection of metal), combustion, metal ignition, cooling, and the overall performance of tripropellant systems.

Concluding Remarks

Historically state-of-the-art advancements in chemical rocket propulsion have been driven by the energetics of the propellant. Tripropellants offer the opportunity to advance the state of the art in chemical rocket performance because they are more energetic than conventional propellants. They could satisfy the need for high-performance propulsion systems to transfer payloads into high-energy trajectories. However, the potential of tripropellants as rocket fuels is ultimately judged by their payload advantage in tripropellant-fueled vehicles. Payload capability depends on both specific impulse and propellant density. The addition of metals to conventional liquid bipropellant systems shows promise for increasing specific impulse or propellant density or both, depending on the type and amount of metal added.

Past tripropellant efforts, which focused on the importance of specific impulse and ignored density considerations for enhancing payload capability, were unsuccessful. High-energy, low-molecular-weight metals like beryllium and lithium were a prime concern. Lithium showed little promise for increasing payload capability because of its low density. Beryllium significantly enhanced the specific impulse of bipropellant systems and has a high density, but it is toxic and has poor combustion efficiency. After significant, unsuccessful efforts in these areas, the tripropellant concept was abandoned.

A new and different look at tripropellants needs to be taken for this concept to gain acceptance. Future efforts on tripropellants should focus on the enhancement of liquid-bipropellant density by metal addition. Aluminum, for example, does not significantly enhance specific impulse when added to liquid bipropellants, but it has a high density that can lead to significant payload advantages. In order to accurately assess the real potential of tripropellants, a wider range of metals and vehicle applications also needs to be considered with focus on dense, energetic metals. Finally, mission analyses that consider the combined impact of both performance and propellant mass fraction on the payload capability of various tripropellants must be conducted. In this process, though, the reality of the technology issues associated with tripropellants cannot be forgotten. Issues such as metal ignition and combustion, cooling, two-phase flow, and metal management are critically important in determining the feasibility of the tripropellant concept. The payoff of tripropellants is potentially large, but, because of the energetic nature of the propellants and the problems associated with the presence of the metal component in the system, an advanced technology will be required to develop a reliable, high-energy tripropellant system.

Summary of Results

Thermochemical calculations were conducted to predict the theoretical specific impulse of the tripropellants beryllium/hydrogen/oxygen ($Be/H_2/O_2$), beryllium/hydrazine/nitrogen tetroxide ($Be/N_2H_4/N_2O_4$), beryllium/RP-1/oxygen ($Be/RP\text{-}1/O_2$), lithium/hydrogen/fluorine ($Li/H_2/F_2$), aluminum/hydrogen/oxygen ($Al/H_2/O_2$), aluminum/hydrazine/nitrogen tetroxide ($Al/N_2H_4/N_2O_4$), and aluminum/RP-1/oxygen ($Al/RP\text{-}1/O_2$). The results of the analytical study were summarized by giving the peak theoretical specific impulse of each tripropellant and its corresponding bipropellant along with optimum mixture ratio and metal loading for sea-level expansion from 6.895-MN/m^2 (1000-psia) chamber pressure. Comparing the specific impulse of the bipropellant at its optimum oxidizer to fuel ratio O/F with that of the tripropellant at its optimum O/F, shows that beryllium theoretically offers 69.2 additional seconds of specific impulse in the H_2/O_2 system, 34.4 sec in the N_2H_4/N_2O_4 system, and 13.5 sec in the $RP\text{-}1/O_2$ system. Lithium can deliver 25.9 extra seconds of specific impulse to the H_2/F_2 system when added at optimum O/F and metal loading. Aluminum offers only 6.1 additional seconds of specific impulse in H_2/O_2, 9.6 sec in N_2H_4/N_2O_4, and no impulse increase when added to $RP\text{-}1/O_2$.

For each tripropellant three plots are presented which illustrate the following: the three-dimensional surface effect of metal loading and mixture ratio on specific impulse, the effect of metal loading in the fuel on specific impulse, and the effect of mixture ratio on specific impulse.

A review of past work on tripropellants indicates that several areas of technology need to be explored to realistically evaluate the potential of a tripropellant propulsion system. The areas which need to be addressed initially are the development of a storage, transport, and injection system for the metal; ignition and combustion of the metal; cooling; and an overall assessment of the performance of tripropellant systems.

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio, March 3, 1986

Appendix—Calculation of Bulk Propellant Density from Mixture Ratio and Metal Loading

The following analysis was used to calculate bulk propellant density from the mixture ratio and metal loading data in Table VI. Mixture ratio MR is defined as

$$MR = \frac{M_{ox}}{M_f + M_m} \tag{1}$$

where

M_{ox} liquid oxidizer mass

M_f liquid fuel mass

M_m metal mass

Metal loading ML is defined as

$$ML = \frac{M_m}{M_f + M_m} \tag{2}$$

The oxidizer mass fraction X_{ox} (the fraction of total propellant mass that is oxidizer) is calculated from equation (1):

$$MR(M_f + M_m) = M_{ox}$$

$$MR(M_f + M_m + M_{ox}) = M_{ox} + MR(M_{ox})$$

$$MR(M_f + M_m + M_{ox}) = (1 + MR)(M_{ox})$$

So,

$$X_{ox} = \frac{M_{ox}}{M_f + M_m + M_{ox}} = \frac{MR}{1 + MR} \tag{3}$$

The metal mass fraction X_m (the fraction of total propellant that is metal) is calculated from equation (2):

$$ML(M_f + M_m) = M_m$$

$$ML(M_f + M_m + M_{ox}) = M_m + ML(M_{ox})$$

From equations (1) and (2)

$$MR(M_m) = ML(M_{ox})$$

So,

$$ML(M_f + M_m + M_{ox}) = M_m + MR(M_m)$$

$$ML(M_f + M_m + M_{ox}) = (1 + MR)M_m$$

Thus,

$$X_m = \frac{M_m}{M_f + M_m + M_{ox}} = \frac{ML}{1 + MR} \tag{4}$$

Since the sum of mass fractions must be unity,

$$X_{ox} + X_f + X_m = 1 \tag{5}$$

Hence, the liquid-fuel mass fraction X_f (the fraction of total propellant that is liquid fuel) can be calculated from equations (3) to (5):

$$X_f = 1 - X_m - X_{ox}$$

$$X_f = 1 - \frac{MR}{1 + MR} - \frac{ML}{1 + MR}$$

$$X_f = \frac{1 + MR - MR - ML}{1 + MR}$$

$$X_f = \frac{1 - ML}{1 + MR} \tag{6}$$

Bulk propellant density ρ_p can be calculated from propellant densities and mass fractions:

$$\frac{1}{\rho_p} = \frac{X_f}{\rho_f} + \frac{X_m}{\rho_m} + \frac{X_{ox}}{\rho_{ox}}$$

where

ρ_f liquid-fuel density

ρ_m metal density

ρ_{ox} liquid-oxidizer density

So,

$$\rho_p = \frac{1}{\dfrac{X_{ox}}{\rho_{ox}} + \dfrac{X_f}{\rho_f} + \dfrac{X_m}{\rho_m}} \tag{7}$$

Using equations (3), (4), and (6) yields

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

Finally,

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

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TABLE I.—TRIPROPELLANT PEAK THEORETICAL SPECIFIC IMPULSE

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Propellant combination	Oxidizer to total fuel ratio, O/F	Metal in fuel, wt %	Specific impulse, sec
H_2/O_2	4.0	0	389.3
$Be/H_2/O_2$	.9	50	458.5
$Al/H_2/O_2$	.6	65	395.4
H_2/F_2	8.0	0	411.8
$Li/H_2/F_2$	1.1	40	437.7
N_2H_4/N_2O_4	1.3	0	292.0
$Be/N_2H_4/N_2O_4$	.5	20	326.4
$Al/N_2H_4/N_2O_4$	.4	30	301.6
RP-1/O_2	2.5	0	300.2
Be/RP-1/O_2	1.3	25	313.7
Al/RP-1/O_2	2.4	5	300.1

TABLE II.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR $Be/H_2/O_2$

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	2.0
	Specific impulse, sec											
0	263.9	280.6	299.9	308.5	316.7	324.5	331.9	338.4	344.2	349.3	353.9	370.4
5	[a]304.6	[a]314.2	322.9	331.1	338.6	345.3	351.1	356.2	360.7	364.7	368.3	380.8
10	330.6	339.1	346.8	353.6	359.3	364.3	368.7	372.5	375.9	378.9	381.4	390.3
15	356.9	363.6	369.2	374.0	378.1	381.7	384.7	387.4	389.7	391.7	393.4	398.7
20	381.4	385.7	389.4	392.5	395.2	397.4	399.3	400.8	402.1	403.2	404.1	406.1
25	403.2	405.6	407.6	409.2	410.5	411.5	412.3	412.8	413.2	413.5	413.5	412.4
30	415.1	423.4	423.8	424.0	424.1	424.0	423.7	423.3	422.9	422.3	421.7	417.2
35	412.7	434.8	438.1	437.0	435.9	434.8	433.5	432.3	431.0	429.7	428.3	420.0
40	409.8	431.3	448.5	448.1	445.9	443.8	441.6	439.5	437.4	435.2	432.8	420.8
45	406.2	427.0	443.6	455.6	453.9	450.7	447.4	444.1	440.7	437.4	434.2	419.1
50	401.7	421.8	437.6	450.0	458.5	453.8	449.2	444.8	440.6	436.5	432.6	414.6
55	396.2	415.3	430.3	441.6	449.0	452.4	446.9	441.7	436.7	431.9	427.3	406.9
60	389.1	407.2	421.1	430.9	[a]436.0	439.4	439.8	433.9	428.3	423.0	417.9	396.0
Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
	Specific impulse, sec											
0	380.1	385.6	388.4	389.3	389.0	387.5	385.1	382.0	378.0	373.1	367.4	360.9
5	387.7	391.0	391.9	391.3	389.6	387.0	383.6	379.4	374.5	368.8	362.3	355.5
10	394.5	395.7	395.0	392.9	389.8	386.0	381.5	376.3	370.4	363.8	356.8	349.9
15	400.4	399.5	397.1	393.5	389.2	384.1	378.5	372.4	365.6	358.4	351.2	344.3
20	405.3	402.2	398.1	393.1	387.5	381.3	374.7	367.6	360.2	352.7	345.5	338.8
25	408.8	403.7	397.8	391.4	384.5	377.3	369.8	362.1	354.3	346.8	339.7	333.2
30	410.7	403.6	396.1	388.3	380.3	372.2	364.0	355.8	348.0	340.6	333.8	327.4
35	411.0	401.9	392.8	383.8	374.8	366.0	357.0	349.1	341.4	334.3	327.7	321.5
40	409.3	398.3	387.8	377.7	368.1	358.9	350.1	342.0	334.5	327.7	321.3	315.5
45	405.3	392.7	381.1	370.3	360.5	351.3	342.6	334.6	327.4	320.9	314.9	309.3
50	398.8	385.0	372.8	362.3	352.4	343.2	334.7	326.9	320.0	313.9	308.2	303.0
55	389.9	375.7	364.2	353.5	343.6	334.6	326.4	319.0	312.5	306.7	301.4	296.5
60	379.2	366.2	354.5	343.8	334.2	325.6	317.9	310.9	304.7	299.2	294.4	289.9

[a]Interpolated.

TABLE III.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR $Be/N_2H_4/N_2O_4$

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
	Specific impulse, sec											
0	245.3	256.1	264.6	271.4	276.8	281.2	284.7	287.4	289.6	291.1	292.0	291.8
5	278.3	284.3	288.9	292.4	294.9	296.8	298.0	298.9	299.3	299.3	298.9	297.6
10	304.0	306.3	307.5	308.1	308.3	308.2	307.7	307.0	306.1	304.9	303.4	301.5
15	306.3	321.7	320.3	318.8	317.2	315.4	313.6	311.7	309.8	307.7	305.5	303.1
20	298.6	[a]315.0	326.4	324.8	321.8	318.9	316.1	313.4	310.8	308.2	305.6	303.1
25	290.5	[a]305.0	316.1	323.5	322.6	319.1	315.8	312.7	309.9	307.3	304.8	302.4
30	281.9	[a]296.0	307.5	313.2	318.0	317.2	314.4	311.6	309.1	306.7	304.2	301.8
35	[a]271.0	[a]286.0	[a]298.0	304.5	309.6	311.3	312.7	310.6	308.1	305.6	303.2	300.7
40	[a]260.0	[a]276.0	[a]288.0	295.5	300.7	304.1	305.6	307.7	306.3	304.0	301.6	299.2
45	[a]248.0	[a]265.0	[a]277.0	286.1	291.8	296.6	297.9	300.7	302.3	301.4	299.3	297.1
50	[a]234.0	[a]252.0	[a]266.0	[a]277.0	[a]284.0	[a]289.6	291.1	292.7	295.8	296.8	296.1	294.4

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*					
	1.5	1.6	1.7	1.8	1.9	2.0
	Specific impulse, sec					
0	288.6	284.2	279.9	275.8	271.8	268.0
5	295.3	291.7	287.8	284.1	280.5	276.9
10	299.0	296.0	292.8	289.5	286.2	283.0
15	300.6	297.8	294.9	292.0	289.2	286.4
20	300.4	297.8	295.2	292.6	290.1	287.6
25	299.9	297.4	294.8	292.3	289.8	287.4
30	299.4	296.9	294.5	292.0	289.6	287.3
35	298.3	295.9	293.6	291.3	289.0	286.8
40	296.8	294.5	292.2	290.1	287.9	285.9
45	294.8	292.7	290.5	288.4	286.4	284.5
50	292.4	290.4	288.4	286.4	284.6	282.6

[a]Interpolated.

TABLE IV.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR $Be/RP\text{-}1/O_2$

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, O/F											
	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
	Specific impulse, sec											
0	201.3	208.7	215.0	220.5	225.5	230.2	234.5	239.1	245.8	253.9	262.3	270.1
5	222.9	229.2	234.9	240.2	245.1	249.6	253.8	258.3	265.8	273.7	280.4	285.8
10	248.6	254.1	259.1	263.7	267.9	271.8	275.3	278.8	285.0	290.3	294.4	297.7
15	270.9	275.6	279.9	283.8	287.3	290.3	293.1	295.8	299.5	302.3	304.4	305.8
20	[a]277.2	[a]282.7	[a]287.6	[a]292.0	296.8	299.8	302.5	305.3	309.2	310.0	310.3	310.2
25	278.4	283.9	288.8	293.2	297.1	300.6	303.8	307.3	313.7	313.5	312.5	311.2
30	[a]274.0	279.5	284.9	289.8	294.2	298.1	301.7	305.8	312.6	313.4	311.7	310.2
35	[a]268.0	274.3	280.6	285.9	290.7	295.0	298.9	303.6	310.1	312.0	310.9	309.5
40	[a]260.5	268.0	275.5	281.7	287.0	291.6	295.9	301.2	306.5	310.4	309.6	307.9
45	[a]253.0	261.2	269.6	276.7	282.8	287.9	292.8	298.7	303.1	307.5	307.2	305.3
50	[a]245.5	254.2	263.2	271.1	278.0	283.9	289.5	295.6	299.9	303.8	303.7	302.0

Beryllium in fuel, wt %	Ratio of oxidizer to total fuel, O/F									
	1.7	1.8	1.9	2.0	2.25	2.5	2.75	3.0	3.25	3.5
	Specific impulse, sec									
0	276.7	282.3	287.0	290.9	297.5	300.2	299.4	296.5	292.9	289.1
5	290.2	293.8	296.7	298.9	301.8	301.4	298.7	295.1	291.3	287.5
10	300.3	302.1	303.4	304.2	303.9	301.4	297.7	293.7	289.8	286.1
15	306.7	307.1	307.0	306.5	303.9	300.3	296.3	292.2	288.3	284.5
20	309.7	308.8	307.7	306.4	302.9	298.9	294.6	290.5	286.6	282.9
25	309.7	308.3	306.9	305.6	301.6	297.1	292.8	288.6	284.8	281.2
30	308.9	307.6	306.0	304.3	299.7	295.1	290.7	286.6	282.8	279.4
35	307.9	306.2	304.3	302.4	297.4	292.7	288.4	284.4	280.8	277.4
40	306.0	304.0	301.9	299.8	294.8	290.2	286.0	282.1	278.6	275.4
45	303.3	301.1	299.0	296.9	291.9	287.4	283.3	279.7	276.3	273.2
50	299.9	297.7	295.6	293.5	288.7	284.4	280.5	277.1	273.9	271.0

[a]Interpolated.

TABLE V.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR $Li/H_2/F_2$

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Lithium in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	2.0
	Specific impulse, sec											
0	266.3	280.4	292.0	302.2	311.5	320.0	327.7	334.4	340.5	345.9	350.8	369.5
5	303.7	314.5	324.0	332.4	339.7	346.1	351.8	356.8	361.2	365.3	368.9	382.7
10	339.2	347.1	353.8	359.6	364.6	369.0	372.9	376.4	379.5	382.3	384.8	394.2
15	370.6	375.6	379.5	383.0	386.1	388.9	391.3	393.4	395.4	397.1	398.6	403.6
20	390.1	399.4	401.3	403.0	404.5	405.8	406.9	407.8	408.6	409.3	409.8	410.7
25	393.9	408.7	419.4	419.6	419.6	419.6	419.5	419.3	419.0	418.7	418.3	415.5
30	396.1	409.4	420.2	429.9	431.1	430.0	428.6	427.4	426.1	424.9	423.7	418.7
35	396.4	408.1	417.3	424.7	432.5	436.2	434.2	432.5	430.8	429.1	427.5	419.7
40	394.3	404.3	412.0	417.9	424.2	431.6	437.7	435.4	432.9	430.5	428.2	419.0
45	389.3	397.9	404.6	409.6	415.7	422.6	429.1	432.9	431.8	429.1	426.6	417.4
50	381.6	389.5	395.5	400.4	406.3	413.2	419.6	423.5	425.7	425.7	423.6	415.4

Lithium in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	Specific impulse, sec											
0	390.5	401.3	407.2	410.2	411.5	411.8	411.5	410.8	409.9	409.0	408.0	407.0
5	397.4	404.6	408.5	410.6	411.5	411.5	411.0	410.2	409.2	408.2	407.2	406.1
10	403.0	407.2	409.4	410.8	411.3	411.1	410.4	409.4	408.4	407.4	406.3	405.0
15	407.1	408.8	410.0	410.9	411.0	410.5	409.6	408.6	407.6	406.4	405.2	403.8
20	410.0	409.7	410.3	410.7	410.5	409.8	408.8	407.7	406.6	405.4	404.0	402.2
25	411.5	410.1	410.3	410.4	409.9	409.0	407.9	406.8	405.6	404.2	402.5	400.2
30	411.9	410.2	410.1	409.8	409.1	408.1	406.9	405.7	404.4	402.8	400.5	397.2
35	411.8	410.1	409.7	409.1	408.2	407.0	405.8	404.5	403.0	400.9	397.7	392.9
40	411.2	409.7	409.0	408.2	407.1	405.9	404.6	403.1	401.2	398.2	393.5	386.6
45	410.6	409.0	408.1	407.1	405.9	404.9	403.2	401.4	398.6	394.0	387.1	377.7
50	409.6	408.0	407.0	405.8	404.5	403.2	401.5	399.0	394.6	387.6	377.8	366.4

TABLE VI.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR $Al/H_2/O_2$

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	2.0
	Specific impulse, sec											
0	263.9	280.6	299.9	308.5	316.7	324.5	331.9	338.4	344.2	349.3	353.9	370.4
5	279.8	299.7	309.0	317.7	326.0	333.6	340.3	346.2	351.4	356.0	360.0	374.7
10	299.4	309.6	318.9	327.6	335.5	342.3	348.3	353.5	358.2	362.2	365.8	378.5
15	310.2	320.2	329.5	337.6	344.6	350.6	355.9	360.5	364.5	368.1	371.2	382.1
20	321.8	331.5	339.9	347.0	353.1	358.4	363.0	367.0	370.5	373.5	376.2	385.2
25	333.8	342.4	349.7	355.9	361.2	365.7	369.6	373.0	376.0	378.5	380.7	387.7
30	345.2	352.6	358.8	364.1	368.6	372.4	375.7	378.6	381.0	383.0	384.7	389.6
35	355.9	362.1	367.3	371.7	375.4	378.5	381.2	383.4	385.3	386.8	388.1	390.7
40	365.7	370.8	375.0	378.6	381.5	384.0	386.0	387.6	388.9	389.8	390.4	391.0
45	374.6	378.6	381.9	384.6	386.8	388.5	389.8	390.7	391.3	391.6	391.7	390.1
50	382.4	385.4	387.8	389.6	391.0	391.8	392.2	392.4	392.4	392.2	391.8	387.7
55	389.1	391.1	392.4	393.1	393.4	393.3	393.1	392.6	391.9	391.1	390.1	383.4
60	387.3	394.7	394.7	394.3	393.7	392.9	391.9	390.6	389.3	387.8	386.1	376.6
65	381.7	395.4	394.3	393.0	391.4	389.7	387.7	385.7	383.5	381.3	379.0	367.5
70	373.5	388.5	390.2	387.7	385.0	382.3	379.4	376.5	373.6	371.0	368.5	355.9
75	361.5	373.7	379.8	376.4	372.7	369.6	366.8	363.9	361.1	358.2	355.3	341.1
80	343.2	354.3	360.9	359.9	356.9	353.7	350.4	347.2	344.0	340.9	337.8	323.2
85	318.5	329.9	336.2	336.6	334.3	331.3	328.2	325.0	321.9	318.9	315.9	302.5
90	289.7	300.8	304.7	305.1	303.9	301.8	299.4	296.9	294.4	292.0	289.6	279.4
95	253.5	260.6	263.4	264.1	264.0	263.4	262.6	261.7	260.7	259.7	258.7	253.7
100	193.2	197.8	[a]201.5	[a]205.0	[a]208.0	[a]210.9	[a]213.2	[a]215.3	[a]217.1	219.1	220.5	225.0

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
	Specific impulse, sec											
0	380.1	385.6	388.4	389.3	389.0	387.5	385.1	382.0	378.0	373.1	367.4	360.9
5	382.9	387.3	389.2	389.4	388.3	386.1	383.0	379.1	374.2	368.5	361.9	355.1
10	385.4	388.7	389.6	389.0	387.1	384.1	380.2	375.4	369.7	363.1	356.0	349.0
15	387.5	389.6	389.6	388.0	385.2	381.4	376.7	371.0	364.3	357.0	349.7	342.6
20	389.0	390.0	388.9	386.4	382.7	378.0	372.2	365.5	358.0	350.4	343.0	336.1
25	390.1	389.8	387.6	384.0	379.3	373.5	366.7	359.1	351.1	343.4	336.1	329.3
30	390.4	388.8	385.4	380.7	374.8	368.0	360.2	351.9	343.8	336.1	329.0	322.3
35	390.0	386.9	382.2	376.2	369.2	361.2	352.6	344.1	336.1	328.6	321.6	315.1
40	388.5	383.9	377.7	370.5	362.3	353.4	344.4	335.9	328.0	320.7	314.0	307.7
45	385.7	379.3	371.8	363.4	354.1	344.7	335.7	327.4	319.7	312.7	306.1	300.1
50	381.2	373.1	364.5	354.8	344.8	335.3	326.5	318.5	311.1	304.4	298.1	292.3
55	374.7	365.5	355.4	344.8	334.7	325.4	317.0	309.3	302.3	295.8	289.8	284.3
60	366.5	355.8	344.6	333.8	323.9	315.0	307.0	299.7	293.1	286.9	281.2	276.0
65	356.0	344.0	332.4	321.9	312.6	304.3	296.7	289.9	283.5	277.7	272.4	267.4
70	343.0	330.5	319.3	309.5	300.8	293.0	286.0	279.6	273.6	268.3	263.2	258.4
75	327.6	315.6	305.3	296.3	288.4	281.3	274.9	268.9	263.4	258.5	253.7	249.1
80	310.4	299.6	290.4	282.5	275.5	269.1	263.2	257.7	252.9	248.2	243.7	239.4
85	291.5	282.5	274.8	268.1	262.0	256.3	251.0	246.2	241.8	237.5	233.3	229.1
90	271.1	264.2	258.2	252.8	247.8	242.9	238.2	234.2	230.2	226.2	222.2	218.2
95	249.1	244.8	240.8	236.8	232.8	228.8	224.9	221.5	217.9	214.2	210.4	206.6
100	226.0	225.2	223.4	221.0	217.9	214.5	211.5	208.5	205.1	201.5	197.9	194.3

[a]Interpolated.

TABLE VII.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR $Al/N_2H_4/N_2O_4$

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*											
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
	Specific impulse, sec											
0	245.3	256.1	264.6	271.4	276.8	281.2	284.7	287.4	289.6	291.1	292.0	291.8
5	259.0	267.7	274.4	279.7	283.9	287.1	289.7	291.6	293.0	293.7	293.9	292.9
10	271.2	277.8	282.8	286.7	289.7	292.0	293.7	294.8	295.4	295.4	294.8	293.1
15	281.5	286.3	289.8	292.5	294.4	295.7	296.5	296.9	296.7	296.1	294.8	292.4
20	290.0	293.2	295.4	296.9	297.8	298.2	298.2	297.8	296.9	295.6	293.9	291.3
25	295.1	298.4	299.3	299.7	299.7	299.3	298.5	297.4	296.2	294.6	292.6	289.9
30	295.3	301.6	301.5	300.9	300.0	298.9	297.7	296.5	295.0	293.1	290.7	288.0
35	293.3	297.9	301.6	300.3	299.0	297.9	296.6	295.0	293.1	291.0	288.5	285.8
40	288.7	291.2	298.1	298.9	297.8	296.3	294.6	292.8	290.7	288.4	285.9	283.3
45	281.6	283.4	290.2	296.2	295.3	293.7	291.9	289.9	287.7	285.4	282.9	280.5
50	273.4	275.4	282.0	289.9	291.5	290.3	288.5	286.4	284.3	282.0	279.7	277.3
55	264.5	267.0	273.5	282.1	285.8	285.7	284.3	282.4	280.4	278.3	276.1	273.9
60	255.0	258.2	264.6	273.9	278.6	279.9	279.3	277.8	276.0	274.1	272.2	270.3
65	244.8	248.8	255.4	265.4	270.8	273.0	273.2	272.4	271.1	269.5	267.9	266.2
70	234.0	239.0	245.8	256.5	262.5	265.3	266.3	266.2	265.5	264.4	263.2	261.8
75	222.5	228.6	235.7	247.2	253.8	257.2	258.7	259.2	259.0	258.5	257.8	256.9
80	210.0	[a]217.5	225.3	237.6	244.8	248.6	250.5	251.5	251.9	251.9	251.8	251.4
85	[a]196.1	205.4	214.3	227.6	235.3	239.4	241.8	243.2	244.1	244.6	245.0	245.2
90	[a]179.2	192.1	202.8	217.0	225.3	229.7	232.4	234.2	235.6	236.7	237.5	238.2
95	158.8	177.1	190.6	206.0	214.6	219.3	222.3	224.5	226.4	228.0	229.4	230.6
100	[a]134.7	[a]160.2	[a]177.8	194.8	203.1	207.6	211.0	213.9	216.3	218.5	220.4	222.2

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*					
	1.5	1.6	1.7	1.8	1.9	2.0
	Specific impulse, sec					
0	288.6	284.2	279.9	275.8	271.8	268.0
5	289.4	285.3	281.2	277.2	273.4	269.8
10	289.6	285.7	281.9	278.1	274.5	271.0
15	289.1	285.5	281.9	278.4	275.0	271.6
20	288.1	284.7	281.3	278.0	274.9	271.7
25	286.7	283.5	280.3	277.1	274.2	271.3
30	285.0	282.0	279.0	276.0	273.1	270.3
35	283.0	280.2	277.4	274.6	271.9	269.3
40	280.6	278.0	275.4	272.8	270.3	267.9
45	278.0	275.5	273.1	270.7	268.4	266.2
50	275.0	272.8	270.5	268.4	266.3	264.2
55	271.8	269.8	267.7	265.8	263.8	262.0
60	268.4	266.5	264.7	262.9	261.2	259.5
65	264.6	262.9	261.3	259.8	258.2	256.7
70	260.5	259.1	257.7	256.4	255.1	253.8
75	256.0	254.9	253.9	252.8	251.7	250.6
80	250.9	250.3	249.6	248.8	248.0	247.2
85	245.2	245.1	244.8	244.4	243.9	243.4
90	238.8	239.1	239.4	239.5	239.4	239.3
95	231.6	232.5	233.2	233.8	234.2	234.5
100	223.7	225.1	226.3	227.4	228.3	229.1

[a]Interpolated.

TABLE VIII.—EFFECT OF OXIDIZER-FUEL RATIO AND METAL LOADING ON SPECIFIC IMPULSE FOR Al/RP-1/O_2

[Expansion; 6.895 to 0.1014 MN/m^2 (1000 to 14.7 psia).]

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*														
	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
	Specific impulse, sec														
0	215.0	220.5	225.5	230.2	234.5	239.1	245.8	253.9	262.3	270.1	276.7	282.3	287.0	290.9	294.0
5	222.7	228.2	233.3	238.0	242.5	248.1	256.1	264.6	272.3	278.8	284.2	288.7	292.3	295.2	297.4
10	231.9	237.4	242.6	247.4	251.9	258.6	267.0	274.6	280.9	286.1	290.3	293.7	296.2	298.1	299.3
15	242.8	248.3	253.3	257.9	262.0	269.6	277.0	283.1	288.0	291.9	294.9	297.1	298.6	299.4	299.7
20	254.5	259.5	[a]264.0	268.1	272.4	279.5	285.2	289.8	293.3	295.9	297.7	298.8	299.3	299.4	298.9
25	264.3	268.9	273.1	276.8	281.9	287.3	291.4	294.5	296.6	298.0	298.7	299.1	298.8	298.1	296.9
30	270.5	274.9	278.8	282.5	289.2	292.9	295.4	297.0	297.9	298.6	298.6	298.1	297.0	295.7	294.1
35	271.3	276.0	280.1	285.9	293.8	295.9	296.9	297.8	298.1	297.9	297.0	295.8	294.2	292.5	290.7
40	268.5	273.5	278.2	288.2	295.5	296.7	297.4	297.4	296.8	295.7	294.2	292.5	290.7	288.8	287.0
45	265.0	270.4	277.3	290.8	295.9	296.4	296.2	295.3	294.0	292.4	290.6	288.6	286.7	284.8	282.9
50	261.3	267.2	278.8	292.0	294.7	294.4	293.4	291.9	290.2	288.2	286.3	284.3	282.4	280.5	278.7
55	257.3	265.8	281.2	290.4	291.7	290.8	289.3	287.5	285.5	283.5	281.5	279.6	277.7	275.9	274.2
60	253.7	267.6	281.6	286.8	287.1	285.9	284.2	282.2	280.3	278.3	276.4	274.6	272.8	271.1	269.5
65	252.0	269.6	278.8	281.6	281.3	280.0	278.2	276.4	274.5	272.7	271.0	269.3	267.7	266.2	264.7
70	254.0	268.3	273.6	274.9	274.4	273.1	271.6	270.0	268.4	266.8	265.2	263.8	262.4	261.0	259.7
75	254.9	263.5	266.5	267.0	266.5	265.5	264.3	263.0	261.8	260.5	259.2	258.0	256.8	255.6	254.5
80	251.1	256.1	257.7	258.0	257.7	257.1	256.4	255.6	254.7	253.8	252.9	251.9	251.0	250.1	249.1
85	243.4	246.3	247.4	247.9	248.1	248.0	247.9	247.6	247.2	246.7	246.1	245.5	244.9	244.2	243.6
90	232.4	234.4	235.8	236.8	237.5	238.1	238.6	238.9	239.0	239.0	239.0	238.8	238.5	238.2	237.8
95	218.4	220.7	[a]223.1	[a]224.7	[a]225.9	[a]227.5	[a]228.5	229.4	230.2	230.8	231.2	231.6	231.7	231.8	231.8
100	[a]201.7	[a]205.0	[a]209.3	[a]211.7	[a]213.3	[a]216.1	[a]217.6	219.1	220.5	221.8	222.8	223.7	224.4	225.0	225.4

Aluminum in fuel, wt %	Ratio of oxidizer to total fuel, *O/F*													
	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
	Specific impulse, sec													
0	296.5	298.4	299.6	300.2	300.2	299.8	298.9	297.8	296.5	295.1	293.6	292.1	290.6	289.1
5	298.9	299.8	300.1	299.9	299.2	298.2	296.9	295.5	294.0	292.5	291.0	289.4	287.9	286.4
10	299.8	299.9	299.4	298.5	297.3	295.9	294.4	292.9	291.3	289.8	288.2	286.7	285.1	283.6
15	299.5	298.8	297.7	296.3	294.8	293.3	291.6	290.0	288.4	286.9	285.3	283.8	282.3	280.8
20	297.9	296.6	295.2	293.6	291.9	290.3	288.6	287.0	285.4	283.3	282.3	280.8	279.3	277.9
25	295.5	293.9	292.2	290.5	288.8	287.1	285.5	283.8	282.3	280.7	279.2	277.7	276.3	274.9
30	292.4	290.6	288.9	287.2	285.4	283.8	282.1	280.5	279.0	277.5	276.0	274.6	273.2	271.8
35	288.9	287.1	285.3	283.6	281.9	280.3	278.7	277.1	275.6	274.2	272.7	271.3	270.0	268.6
40	285.1	283.3	281.6	279.9	278.3	276.7	275.1	273.6	272.2	270.7	269.4	268.0	266.7	265.4
45	281.1	279.4	277.7	276.0	274.5	272.9	271.5	270.0	268.6	267.3	266.0	264.7	263.4	262.2
50	276.9	275.2	273.6	272.1	270.6	269.1	267.7	266.3	265.0	263.7	262.5	261.2	260.0	258.9
55	272.5	270.9	269.4	267.9	266.5	265.2	263.8	262.5	261.3	260.1	258.9	257.7	256.6	255.5
60	268.0	266.5	265.1	263.7	262.4	261.1	259.9	258.7	257.5	256.4	255.3	254.2	253.1	252.1
65	263.3	261.9	260.6	259.4	258.2	257.0	255.8	254.7	253.7	252.6	251.6	250.6	249.6	248.6
70	258.4	257.2	256.1	254.9	253.8	252.8	251.7	250.7	249.7	248.8	247.8	246.9	246.0	245.0
75	253.4	252.4	251.3	250.4	249.4	248.4	247.5	246.6	245.7	244.8	244.0	243.1	242.3	241.5
80	248.3	247.4	246.5	245.7	244.8	244.0	243.2	242.4	241.7	240.9	240.1	239.3	238.6	237.8
85	242.9	242.2	241.6	240.9	240.2	239.5	238.9	238.2	237.5	236.9	236.2	235.5	234.8	234.1
90	237.4	236.9	236.5	236.0	235.5	235.0	234.4	233.9	233.3	232.8	232.2	231.6	231.1	230.5
95	231.7	231.5	231.3	231.0	230.7	230.4	230.0	229.6	229.2	228.7	228.3	227.8	227.3	226.8
100	225.7	225.9	226.0	226.0	225.9	225.8	225.6	225.4	225.2	224.9	224.6	224.2	223.8	223.4

[a]Interpolated.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-2602		

4. Title and Subtitle	5. Report Date
Current Evaluation of the Tripropellant Concept	June 1986
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Robert L. Zurawski	E-2863
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Paper
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Presented in part at AIAA/SAE/ASME/ASEE Twenty-Second Joint Propulsion Conference, Huntsville, Alabama, June 16-18, 1986.

16. Abstract

An analytical study was conducted to determine the specific-impulse advantages of adding metals to conventional liquid-bipropellant systems. These tripropellant systems theoretically offer higher specific impulse and increased propellant density compared with bipropellant systems. Metals considered were Be, Li, and Al. Bipropellant systems were H_2/O_2, N_2H_4/N_2O_4, RP-1/O_2, and H_2/F_2. Thermochemical calculations were performed for sea-level expansion from 6.895-MN/m^2 (1000-psia) chamber pressure over a wide range of mixture ratios and propellant compositions. Three-dimensional plots characterize the specific impulse of each tripropellant system. Technology issues pertinent to metallized propellant systems are discussed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Tripropellants, Liquid rocket propellants, Metal propellants, High-energy propellants, Specific impulse, Beryllium, Lithium, Aluminum	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	29	A03

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration
Code NIT-4

Washington, D.C.
20546-0001

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