A SIMPLE METHOD FOR THE SELECTION OF SATELLITE PROPULSION SYSTEMS

C.E.R. SALLES

W. GILL

Laboratório de Combustão e Propulsão

Instituto de Pesquisas Espaciais (INPE)

Cachoeira Paulista, SP, Brasil

INTRODUCTION

Since the beginning of man's exploration and utilization of outer space, many types of propulsion systems for space vehicles have been developed. In the past the major controlling factor in the choice of a propulsion system was that of the technical capability on hand for designing and producing the system. Nowadays, however the propulsion engineer has at his disposal such a wide variety of materials and manufacturing processes that the proper choice of a propulsion system for a given mission is not entirely clear. Here we present a simple method for the rapid determination of the best system given a minimum knowledge of the mission requirements and the materials on hand.

THE METHOD

Propulsion systems are studied by defining various parameters that relate certain masses of the system. We assume that the total mass of a space vehicle is composed of

$$M_T = M_P + M_S + M_{PL} \qquad (1)$$

where M_P is the propellant mass carried for use during the life of the vehicle, M_S is the mass of the structure associated with the propulsion system and M_{PL} is the rest of the mass of the vehicle. We define

$$\epsilon = \frac{M_S}{M_P + M_S}\text{ , a structure coefficient}$$

$$\eta = \frac{M_{PL}}{M_T}\text{ , a mass efficiency}$$

The ϵ parameter can be found in any text book of rocketry, but mass efficiency, η, is new. We believe it to be specifically applicable space vehicles which must be launched and therefore subject to a more o rigid total mass constraint, i.e., M_T is fixed.

The equation of motion for a vehicle in orbit subject only to propulsion system thrust force can be re-written as

$$\eta = \frac{\epsilon - e^{\frac{-\Delta V}{g_o Isp}}}{\epsilon - 1}$$

where ΔV is the total velocity increment required during the vehicle's life, Isp is the specific impulse and g_o the gravitational constant.

If it is assumed that the propulsion system structure is domin the propellant tanks and, further, the tanks are spherical, it can be show

$$\epsilon = \frac{(S_F + (OF)\,S_O)\,\rho_s}{(S_F + (OF)\,S_O)\,\rho_s + \rho_F + (OF)\,\rho_o}$$

where

$$S_F = (1 + \frac{P_F}{2\sigma_s})^3 - 1$$

$$S_O = (1 + \frac{P_o}{2\sigma_s})^3 - 1$$

and OF is the oxidant/fuel mixture ratio by volume, ρ is the density, P tank pressure, and σ is the tank material maximum permitted tensile str subscripts F, o, and s refer to fuel, oxidant and structural material, respectively.

In Table 1, estimates of these parameters are presented for va propellants. The compressed cold gases are considered to be at 300K and while the condensed cold gases are at the vapor pressure corresponding

347

temperature. The monopropellant hydrazine is assumed to be stored at 20atm and the bipropellants are stored at 200atm with chemical reaction taking place in the combustion chamber at 67atm.

PROPELLANT	Isp (sec)	OF	ρ_0 (g/cm^3)	ρ_f (g/cm^3)	TYPE
H_2	301	–	0.0016	–	COLD GAS
He	179	–	0.0033	–	
N_2	80	–	0.0227	–	
C_4H_{10}	91	–	0.577	–	
NH_3	146	–	0.660	–	
N_2H_4	199	–	1.000	–	MONOPROP
H_2O_2/N_2H_4	177	1.31	1.000	1.446	BIPROP
N_2O_4/N_2H_4	283	0.74	1.000	1.434	
$IRFNA/N_2H_4$	277	0.79	1.008	1.551	
ClF_3/N_2H_4	278	1.10	1.000	1.818	

Table 1. Propellant parameters for some different propulsion systems.

Figure 1 compares the mass efficiency for the various systems as a function of the ΔV mission requirement. It can be seen that at low ΔV there is not much difference in mass efficiency between the systems. This is because the propulsion system is not a major component in the total mass of the vehicle and for such missions the propulsion unit should be selected on the basis of some criteria other than mass efficiency.

However, as the ΔV requirement increases, the propulsion system mass begins to dominate, and differences in mass efficiency between available systems becomes extremely important and should be the determining factor in system selection.

SENSITIVITY ANALYSIS

In comparing the results in Figure 1 with the differences in propellant parameters in Table 1, it can be seen that the structure coefficient ε can be more important than the propellant Isp. The sensitivity of the vehicle mass efficiency to these parameters can be studied by taking the mathematical derivative of Eq (2) to obtain

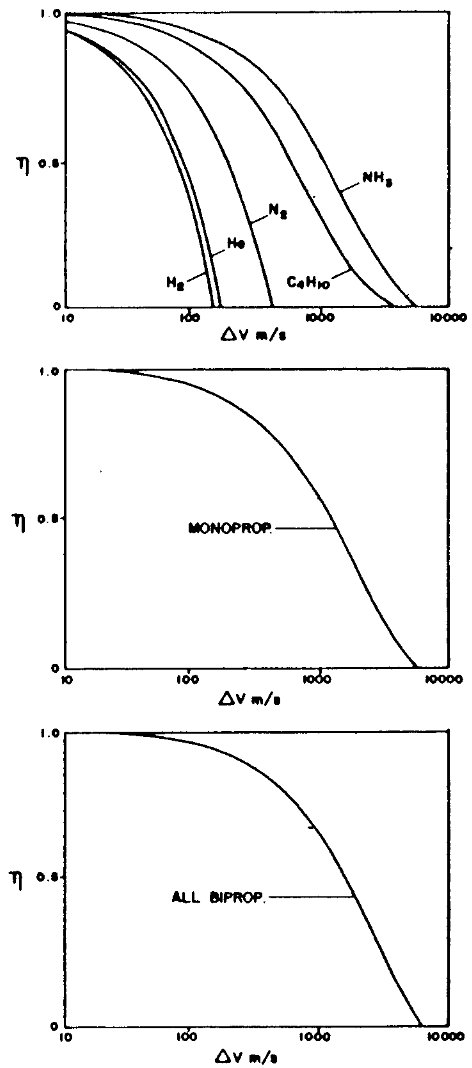

Figure 1. Comparison of the mass efficiency for the different propulsion systems of Table 1.

$$\frac{d\eta}{\eta} = \frac{\epsilon}{\eta}\left(\frac{\partial \eta}{\partial \epsilon}\right)\frac{d\epsilon}{\epsilon} + \frac{Isp}{\eta}\left(\frac{\partial \eta}{\partial Isp}\right)\frac{d\,Isp}{Isp}$$

or

$$\frac{d\eta}{\eta} = x_\epsilon \frac{d\epsilon}{\epsilon} + x_{Isp} \frac{d\ Isp}{Isp} \qquad (6)$$

Eq. (6) shows the sensitivity of the mass efficiency of some given base line design to changes in the parameters. The sensitivity coefficients are easily found to be

$$x_\epsilon = \frac{\epsilon}{\epsilon - 1} \frac{\left(e^{\frac{-\Delta V}{g_o Isp}} - 1\right)}{\left(\epsilon - e^{\frac{-\Delta V}{g_o Isp}}\right)}$$

and

$$x_{Isp} = \frac{-\Delta V}{g_o Isp} \frac{e^{\frac{-\Delta V}{g_o Isp}}}{\left(\epsilon - e^{\frac{-\Delta V}{g_o Isp}}\right)}$$

The ratio of these two coefficients is then

$$\frac{x_\epsilon}{x_{Isp}} = - \frac{g_o Isp}{\Delta V} \left(\frac{\epsilon}{\epsilon - 1}\right)\left(1 - e^{\frac{+\Delta V}{g_o Isp}}\right)$$

which is shown in Figure 2.

It is worth noting that the scale is in Log_{10} and that at small values of $\frac{g_o Isp}{\Delta V}$ the x_ϵ is some 400 orders of magnitude greater than x_{Isp}. As $\frac{g_o Isp}{\Delta V}$ increases the two coefficients rapidly approach a common value, i.e., their ratio becomes 1.

It is easy to see that the idea of sensitivity coefficients can be extended to the parameters that make up ϵ. For example, the sensitivity of a given design to a change in structural material could be studied by forming

$$x_\sigma \equiv \frac{\sigma}{\eta}\frac{\partial\eta}{\partial\sigma} = \frac{\sigma}{\eta}\frac{\partial\eta}{\partial\epsilon}\frac{\partial\epsilon}{\partial\sigma} = \frac{\sigma}{\epsilon} x_\epsilon \left(\frac{\partial\epsilon}{\partial\sigma}\right)$$

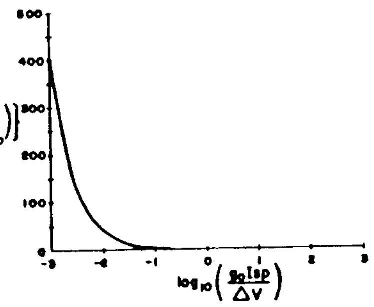

Figure 2. Comparison of the sensitivity coefficients in terms of orders of magnitude.

or for a change in propellant density

$$x_\rho = \frac{\rho}{\epsilon} x_\epsilon \left(\frac{\partial\epsilon}{\partial\rho}\right)$$

and so forth.

CONCLUSION

In closing we point out that the methodology presented here inc all of the pertinent parameters of a propulsion system such as the opera pressure, structural material, and propellant characteristics in one sim expression that can be mathematically manipulated. The formulation can b incremented if desired to include such things as interactions between Is ϵ through the adoption of different nozzles, combustion chambers, inject systems, and the like.