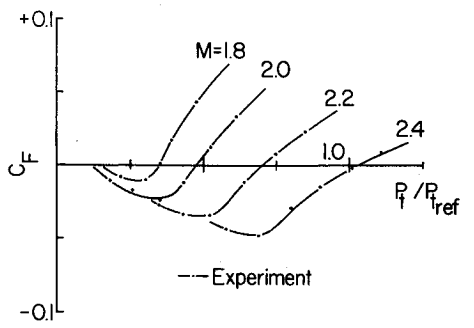

Fig. 5 Side-force coefficient vs stagnation pressure for various Mach numbers for the data from Fig. 2. Reference area and pressure are the lateral projected area of the asymmetry and the exit dynamic pressure.

separate and the entire flow degrades, although the Reynolds number dependence of the effect in this configuration remains to be quantified. On the basis of these data, it is concluded that control of the thruster plenum pressure and exit plane obliquity (including the aforementioned axisymmetric case wherein the sideforce vector may be oriented azimuthally) provides the ability to quickly orient the thrust vector of nongimballed jets.

Acknowledgments

The data in Ref. 2 were acquired while the author was on the faculty of the Department of Aeronautics at the U.S. Naval Postgraduate School. Preparation of this paper was supported by the Aerospace Sciences Directorate of AFOSR and the Office of Basic Energy Sciences, Department of Energy.

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$\vec{V}\times\vec{B}$ and Density Gradient Electric Fields Measured from Spacecraft

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Nomenclature

e	= electron charge
ℓ	= distance
$\vec{v}$	= velocity of satellite
$\vec{B}$	= magnetic field
$\vec{E}$	= electric field
L	= approximate radius of spacecraft
$\vec{F}_L$	= Lorentz force
n_i, n_e	= ion, electron density
n_1, n_2	= local ion densities in spacecraft wake
n_0	= undisturbed electron density
ϕ	= local potential
θ_e	= electron temperature, V

THE electric fields observed on satellites can be due to a number of environmental influences. Density gradients and $\vec{v}\times\vec{B}$ are two causes of electric fields measured in low earth orbit. The electric fields due to density gradients mainly affect the smaller satellites, while voltages generated by moving through magnetic fields are dominant on larger objects. For spacecraft the size of the Space Shuttle Orbiter (10-30 m), the two effects are of the same order of magnitude. Measurements made during flights of the orbiter support this observation.

When a good conductor moves magnetic field lines, it develops a tangential electric field to cancel the Lorentz force on its conduction electrons. The tangential electric field can be found in the plasma's frame of reference by solving

$$\vec{F}_L = e(\vec{E} + \vec{v}\times\vec{B}) = 0$$

to find

$$\vec{E} = -\vec{v}\times\vec{B} \tag{1}$$

An electric field is also generated by the density gradient found in the wake of a fast-moving spacecraft through a dense plasma. By fast, we mean that the spacecraft is supersonic with respect to the dominant ion species, and by dense, we mean that spacecraft dimensions are large compared with the unperturbed ionospheric plasma Debye length. The Shuttle Orbiter satisfies both these conditions. The potential in the wake can be estimated using quasineutrality and the Boltzmann relation for electrons.

$$n_i \approx n_e$$

$$n_e = n_0 e^{(\phi/\theta_e)}$$

Solving for ϕ

$$\phi = \theta_e \ell n(n_e/n_0)$$

the electric field resulting from density gradients can be approximated by the change in the local potential over a length roughly the size of the cross-section of spacecraft with respect to the ram direction. Or

$$\vec{E} \approx -(\Delta\phi/L) \approx -(\phi/L)[\ell n(n_2/n_0) - \ell n(n_1/n_0)] \tag{2}$$

The magnitude of electric fields due to the two effects can be approximated using Eqs. (1) and (2). Assuming a 10^{11} m^{-3} plasma with a magnetic field of 0.4 G and a density gradient of four orders of magnitude in the wake (as observed on the Shuttle Orbiter) at low altitudes and higher latitudes, we can estimate the magnitude of the electric fields caused by both processes. Using an orbital velocity of 7.7 km/s, the $\vec{v}\times\vec{B}$ field would be 0.31 V/m and independent of vehicle dimensions. Table 1 is for density gradient fields and, as can be seen from Eq. (2), depends inversely on the size of the orbiting spacecraft.

The electric field magnitudes lead one to expect small satellites (~1-2 m in diam) to have local fields dominated by density gradient fields and large spacecraft (~50-200 m, i.e.,

Table 1 Electric fields due to density gradients of four orders of magnitude[1]

	$\theta = 0.1$ eV	$\theta = 0.2$ eV
L, m	E, V/m	E, V/m
0.5	1.8	3.7
5.0	0.18	0.37
50.0	0.018	0.037

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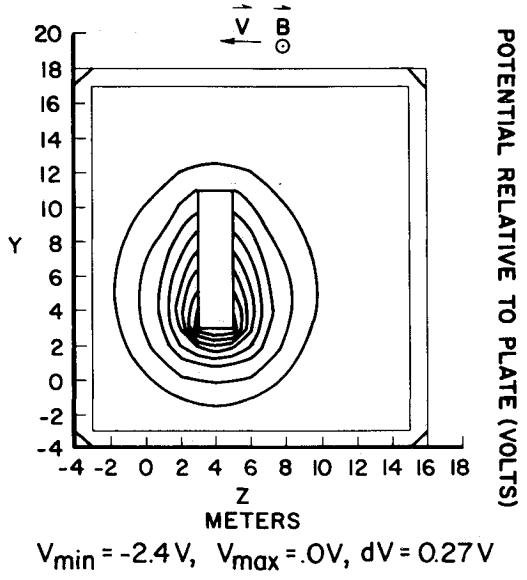

Fig. 1 $8\times8\times2$-m plate in low density (1 m^{-3}) plasma. No density gradient electric fields, viewed in the plasma reference frame.

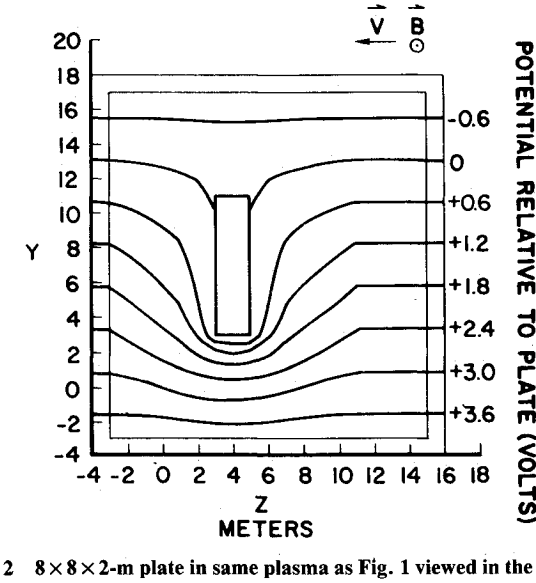

Fig. 2 $8\times8\times2$-m plate in same plasma as Fig. 1 viewed in the plate's reference frame.

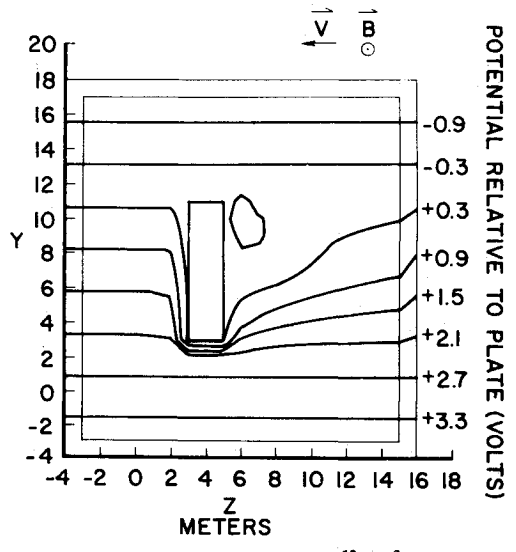

Fig. 3 $8\times8\times2$-m plate in high density (10^{12} m^{-3}) plasma as viewed from the plate's reference frame. Both $\vec{v}\times\vec{B}$ and density gradient fields are present in the wake.

space stations) to have fields mainly dependent on magnetic field effects. Objects the size of the Space Shuttle (~10-30 m) will experience electric field contributions of the same order of magnitude from both the Lorentz force and the density gradient fields.

Small satellites have observed electric fields of the order of 1 V/m. Samir et al.[2] measured these plasma potentials as their probe rotated through the wake of the Atmospheric Explorer-C (AE-C). Measurements made on Orbiter flights have indeed seen electric fields from both influences. Raitt et al.[3] recorded $\vec{v}\times\vec{B}\cdot\vec{\ell}$ on the order of the predicted magnitude, where $\vec{\ell}$ was the distance from the detector to spacecraft ground (the engine nozzle). The potentials they observed correspond to a maximum electric field of roughly 0.4 V/m. Smiddy et al.[4] measured a density gradient electric field of 0.16 V/m while moving with the detector aligned with the velocity vector.

Computer calculations using the POLAR code[5] also show the interaction of the two electric fields. POLAR is a three-dimensional spacecraft/environment interaction computer code designed to model the interaction of large objects in the low earth polar orbit. It includes models of spacecraft wakes, magnetic field effects, plasma sheaths, solar auroral particle descriptions and charged particle/surface interactions.[6]

Solutions of the space potentials were calculated self-consistently along with current balance of the ambient plasma to an $8\times8\times2$-m metal plate. The plate moved with a Mach vector of $-8z$ through a 0.1 eV plasma, typical for non-charging low earth orbit environments. A $-0.4\hat{x}$ G magnetic field was included. To demonstrate the effect of the density gradient electric field, the problem was solved using densities of 1 m^{-3} (vacuum, Figs. 1 and 2) and 10^{12} m^{-3} (low earth orbit environment, Fig. 3).

The magnetic field generated an electric field of -0.25 V/m along the y-axis. The density gradient electric field was found by the code.[7] Figure 1 shows the potential around the plate due only to $\vec{v}\times\vec{B}$ field in plasma's reference frame. Figure 2 is the same set of potentials as seen in the spacecraft frame. Figure 3 is the same object in the plate's reference frame, with the plasma and density gradient electric fields included. In Fig. 3, the electric fields interact in the wake in an anticipated manner. Note that the $\vec{v}\times\vec{B}$ field is not perturbed by density gradient fields in the ram direction, since the ion density there is almost undisturbed and thus there is no quasineutral electric field, while behind the plate, the electric fields are roughly equilvalent.

In conclusion, for Shuttle-sized objects, care must be taken when interpreting measurements of plasma electric fields or space potentials. Plasma parameters, geometrical effects, and velocity effects may obscure the source of observed electric fields.

Acknowledgment

This work supported and performed in cooperation with the Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts, under Contract F19628-82-C-0081.

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Comparison of Methane and Propane Rockets

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Introduction

THE potential benefits of hydrocarbon fuels and dual-fuel propulsion for future Earth-to-orbit vehicles have been shown in a number of studies.[1-6] Of the several hydrocarbon fuels considered, methane and propane are the favored candidates. In a previous study,[5] methane and propane were compared for use in a single-stage, Earth-to-orbit vehicle with dual-fuel rocket propulsion. The results indicated a significant advantage for propane, and further optimizations were conducted using this fuel. The purpose of this Note is to show how the comparison changes when both methane and propane vehicles are optimized. The analysis is the same as that described in Ref. 5.

Results

The results are shown in Figs. 1 and 2. In Fig. 1, the dry mass characteristics of vehicles with both fuels are shown. The flagged symbols at a hydrocarbon thrust fraction of 0.8 and a hydrocarbon propellant fraction of 0.79 are the same results shown in preliminary screening.[5] As the vehicles are optimized, the difference is reduced slightly, but the conclusions do not change. Propane is still the preferred hydrocarbon fuel to minimize dry mass. Figure 2 shows the corresponding results for vehicle gross mass. In this figure, the difference between propane and methane decreases noticably when moving from the flagged symbols to the points with minimum gross mass. Propane is the fuel which minimizes gross mass. The results with methane indicate that a vehicle with only hydrogen fuel (a hydrocarbon fuel fraction of 0.0) has a gross mass as low as any dual-fuel vehicle.

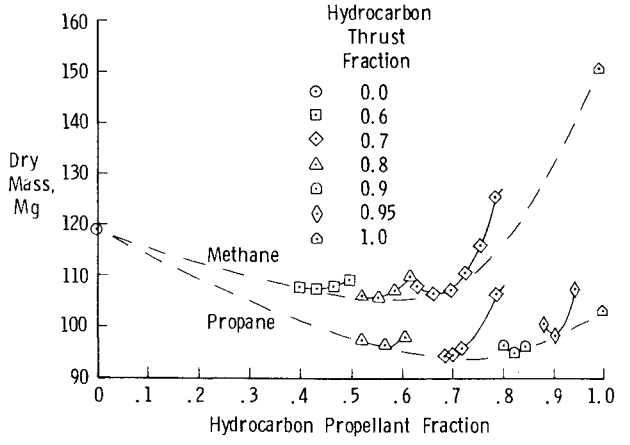

Fig. 1 Effect of fuel on vehicle dry-mass optimization.

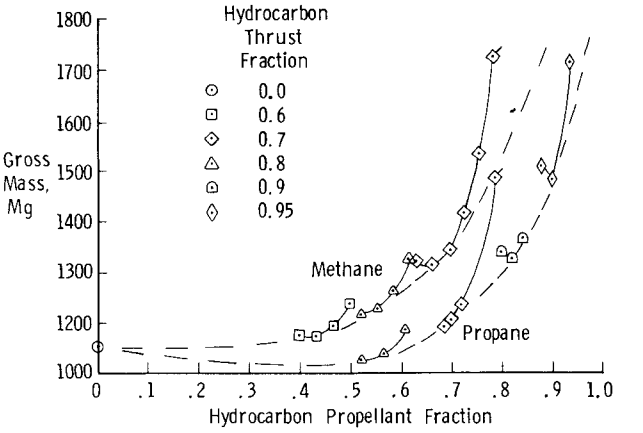

Fig. 2 Effect of fuel on vehicle gross-mass optimization.

Conclusion

When single-stage-to-orbit vehicles with methane and propane fueled rockets are optimized, the preferred fuel for minimum dry or gross mass is propane.

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Second-Order Roll Damping of Rolling Wings at Supersonic Speeds

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Nomenclature

b = wing span
B = $(M^2-1)^{1/2}$

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