Effective Specific Impulse of External Nuclear Pulse Propulsion Systems

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Nomenclature

a_R = Rosseland mean opacity, m^{-1}
C = collimation factor
d = pusher diameter, m
E_p = pulse energy, J (1 ton TNT = 4.18×10^9 J)
f_c = fraction of pulse mass that intercepts pusher
f_m = ablation mass loss factor
f = fraction of total mass in included cone angle
H_a = energy required to ablate pusher material, Joule/kg
$(I_{sp})_{\text{base}}$ = specific impulse, $\bar{v}/g$, sec
$(I_{sp})_{\text{eff}}$ = effective specific impulse, sec
M_a = total mass ablated from pusher per pulse, kg
M_p = propellant mass per pulse, kg
p = pressure, N/m^2
p_m = maximum pressure, N/m^2
r = radius, distance from pulse center, m
$r_{\min}$ = minimum radius, m
T_s = stagnation temperature, K
t = time after pulse initiation, sec
t_r = reference time, $r/\bar{v}$, sec
t_z = reference time, $z/\bar{v}$, sec
v = velocity, m/sec
$\bar{v}$ = mean propellant velocity, m/sec
x = thickness of ablated layer, m
z = distance, pulse center to pusher plane, m
z_m = minimum separation distance from pressure limitation, m
β = angle from centerline
θ = included cone angle
ρ = density, kg/m^3

Theme

THE original concept[1, 2] of using externally exploded nuclear pulse units to propel a space vehicle involved the use of fission energy sources. The minimum size energy package was large (of the order of 4.18×10^{12} joules or 1000-tons TNT equivalent). Renewed interest in this mode of propulsion has been stimulated by the possibility of using small fusion microbombs as the energy source. The fusion reaction might be initiated in small pellets of fusable material by either an intense laser beam[3] or an intense relativistic electron beam.[4] These schemes are of particular interest because of the stated possibility of achieving high thrust-weight ratios at high effective specific impulse values, of the order of 10,000 sec.[3] A pulse unit containing fusionable material plus propellant mass is ejected into position behind the vehicle and the pulse energy triggered. The propellant mass expands. A fraction of the propellant intercepts the pusher plate of the vehicle and transfers momentum and heat to the vehicle. The heat flux causes some ablation of the pusher surface. A succession of such pulses is continued until the desired total impulse for the mission is obtained The effective specific impulse for such a system can be expressed as $(I_{sp})_{\text{eff}} = f_c \cdot f_m \cdot (I_{sp})_{\text{base}}$.

One must evaluate the mean propellant velocity $\bar{v}$ that the system can tolerate $(I_{sp})_{\text{base}}$, the effectiveness with which the mass of the pulse can be collimated so as to intercept the pusher plate of the vehicle (f_c), and the unavoidable mass losses in the system (f_m).

The model used for analysis herein is similar to the previous Orion studies but has been generalized and simplified to permit ready evaluation of the interrelation between pulse size, vehicle size, specific impulse, pulse separation distance, and collimation.

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Contents

The propellant mass expands into the vacuum of space in what is called a "self-similar" manner.[5-8] The characteristic relation of this type of expansion for the case herein is, $v(r, t) = r/t$. Assuming that all the energy absorbed by the propellant appears finally as kinetic energy with a Maxwellian distribution about the mean velocity, $\bar{v}$, then, $E_p = (1/2)M_p\bar{v}^2$.

The density at any location and time is given by[9]

$$\rho(r, t) = (M_p/\pi^{3/2}r^3)(v/\bar{v})^3 e^{-(v/\bar{v})^2}$$

Other flow properties readily follow.

If a pulse unit is designed to direct a disproportionate fraction of the total mass into a given cone angle, the flow is still assumed uniformly distributed within the cone. The parameter C (collimation factor) is the ratio of the enhanced total mass in the cone to the amount in the cone if the distribtuion were isotropic—$c = f/\sin^2(\theta/4)$. The relations developed for the isotropic distribution may be used for collimated flow cases by replacing the propellant mass term M_p with the product CM_p.

At the center of the pusher the maximum pressure is $p_m = 0.291\ CE_p/r^3$. Where a specific value of maximum pressure is used, the value is $p_m = 6.9 \times 10^8$ newtons per square meter (100,000 psi). Using this value, the minimum separation distance is $r_{\min} = 7.51 \times 10^{-4}\ (CE_p)^{1/3}$. The fraction of mass intercepted by the pusher, f_c, can be expressed

$$f_c = \frac{C}{2\pi^{1/2}}\left[\frac{d^2}{d^2 + 2.26 \times 10^{-6}\ (CE_p)^{2/3}}\right]$$

With the assumption that all the propellant mass has the mean velocity v, the upper limit to f_c is 0.5 in order to satisfy the momentum balance requirement. A typical plot of f_c is shown in Fig. 1.

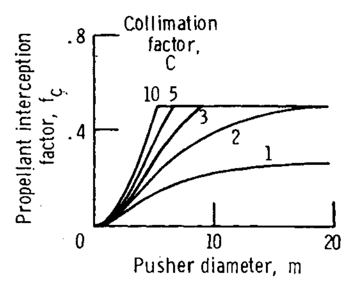

Fig. 1 Propellant interception factor. Pulse energy E_p, 4.18×10^{10} joules (10 tons).

The propellant that arrives is assumed to just lose its kinetic energy and form a hydrodynamic stagnation layer. The temperature of this stagnation layer, calculated by assuming that it reaches equilibrium through blackbody radiation back to the vacuum of space, ranges up to 20 ev.

The formation of this high temperature layer causes the temperature of a pusher surface to rise quickly to the ablation level. The ablated gas then forms a protective layer and slows down subsequent ablation rates. The ablated vapor layer and the high temperature layer from stagnating propellant were assumed to remain unmixed. Assuming that heat transfer to the surface by radiation (though only a small fraction of the total radiant energy is available) is still the major mode of energy transfer, the increment of mass ablated per unit area may be expressed

$$dm_a = [\sigma T_s(t)/H_a] \exp[-a_R X(t)]\, dt$$

The mass loss factor, $f_m = [1 + (M_a/M_p)]^{-1}$, was calculated assuming the only mass loss was that by ablation from the pusher surface.

$$\frac{M_a}{M_p} = \left(\frac{10\pi\bar{v}^2}{E_p}\right)\int_0^{d/2} y \left[\int_0^{\infty} \frac{4.23\times 10^7}{H_a} z_m \left(\frac{t_z}{t}\right)^6 \right. \\ \left. \exp - \left(\frac{t_z}{t\cos\beta}\right)^2 e^{-\alpha_R x} d\left(\frac{t}{t_z}\right)\right] dy$$

Some typical values of f_m calculated via this relation are shown in Fig. 2.

Finally, the two principal factors determining the effective specific impulse, f_c and f_m, are combined to yield the typical values shown in Fig. 3.

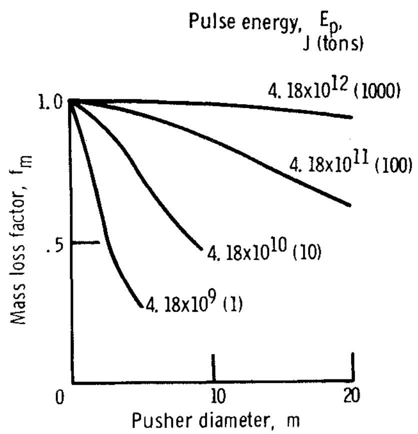

Fig. 2 Mass loss factor. $C = 3$; $\bar{v} = 1.5 \times 10^{10}$ **m/sec;** a_R/ρ 10^2 **m²/kg.**

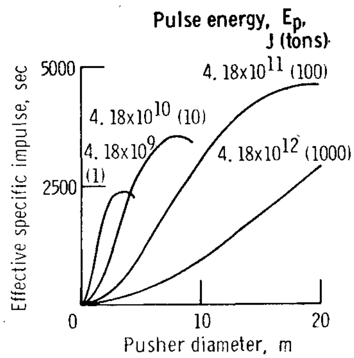

Fig. 3 Effective specific impulse. $(Isp)_{\text{base}}$ **15,000 sec.** $C = 3$; $a_R/\rho = 10^2$ **m²/kg.**

This analytical model of the external nuclear pulse propulsion system shows: a) there is an optimum pulse energy for a given system to yield a maximum specific impulse; b) increased mean propellant velocity does not necessarily result in increased I_{sp}; c) mean opacities of 10^3 m²/kg or above appear necessary to approach maximum specific impulse; and d) increased vehicle size (diameter) leads to higher specific impulse if the pulse energy is kept at the optimum value for the particular size.

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