fied that chamber conditions different from equilibrium prior to expansion could change significantly the equilibrium, kinetic, and frozen nozzle performance calculations from equilibrium-combustion performance for the propellant systems under study. Incomplete combustion of H_2 and F_2 to HF was particularly important in influencing H_2/F_2 performance. Greater than equilibrium concentrations of ClF in the ClF_5/N_2H_4 system also were found to alter performance from the equilibrium-combustion values. Increasing equivalence ratio above 1.0 was found to decrease slightly the effects of the departure from equilibrium. Attempts to refine propellant performance predictions as by kinetic nozzle calculations also should consider nonequilibrium combustion since this effect was shown to be of comparable importance to uncertainties in rate data.[8] It also was found that far down the nozzle, concentration differences from equilibrium which were introduced in the chamber began to approach the equilibrium values. Exhaust samples would appear to have limited value in gauging the effects considered here. What is needed to increase the value of this approach to propellant performance studies is more extensive measurement of actual chamber conditions.

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System Requirements for Application of a Pulsed MPD to Electrical Propulsion

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THE concept of a pulsed MPD accelerator is simply quasi-steady operation at repetitively pulsed power levels two to three orders of magnitude higher than, but at average power levels comparable to those of steady-state MPD accelerators. Potential advantages arise because the efficiency of an MPD accelerator increases as the power input increases; indeed efficiencies as high as 80% might not be an unreasonable expectation for MPD operation at multimegawatt power levels. In comparison, efficiencies generally are not higher than 30% for steady-state MPD accelerators operated at powers of the order of 10 kw. A pulsed MPD accelerator is simpler because no externally applied magnetic field is necessary because the high currents involved (10,000–100,000 amp) provide a sufficiently strong self-magnetic field. Versatility results, in that a variable duty cycle is possible. The accelerator power input, and thus the efficiency, becomes virtually independent of the power delivered by the power supply, an important advantage for solar-powered spacecraft.

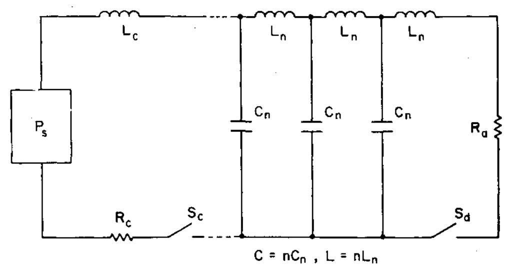

Fig. 1 Simplified network of pulsed MPD accelerator. R_a, thruster; C_nL_n, section of pulse forming network for discharge; S_d, S_c, switches; L_c, R_c, inductance and resistance in the charging loop; P_s, power supply.

However, the potential advantages of pulsed operation may not be realized when the complete propulsion system is considered. Whereas a steady MPD accelerator can be coupled to a solar power supply with very little or virtually no power conditioning, a pulsed one requires at least two additional components: a bank (most likely a capacitor bank) for energy storage between pulses, and a power conditioning unit for charging efficiently the bank from a solar power supply. As depicted in Fig. 1, the capacitor bank is structured, as a pulse-forming network, by nC_nL_n sections, and the power conditioner for charging C is represented symbolically by R_c and L_c. In practice, this conditioner must be substantially more sophisticated, especially if top utilization of the power supply and a high efficiency are desired for the energy transfer. These components required between the accelerator and the solar power supply are not 100% efficient; moreover, they have quite substantial masses, and they offset the supposed simplicity of a pulsed MPD thrustor.

This Note compares quasi-steady pulsed MPD systems with steady MPD systems. The physical phenomena imposing constraints are examined, and the acceptable ranges of the important parameters are determined. Finally, numerical results are produced for the comparison.

Parameters of a Pulsed MPD System

For quasi-steady MPD operation at very high currents (J), no external magnetic field appears to be necessary; under such conditions, the thrust is

$$F = bJ^2, b = 10^{-7}(\tfrac{3}{4} + \ln[r_a/r_c]) \quad (1)$$

where F and J are in N and amp, and r_a and r_c are the terminal radii of the current distribution at the anode and cathode, respectively. For simplicity it is assumed that the total power loss P_e in the accelerator may be represented by

$$P_e = JV_e \quad (2)$$

This assumption is realistic for the electrode losses, which represent a substantial fraction of the total losses. The use of Eq. (2) to express the electrical power not converted into thrust power, is a rough approximation, justified only by

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† The accelerator impedance R_a is obtained when Eq. (4) is divided through by J^2.

simplicity. Accordingly, the over-all thrustor efficiency (thrust power over losses plus thrust power) may be written

$$e = bJI_{sp}/(2V_e + bJI_{sp}) \tag{3}$$

Where V_e is the voltage representing total losses and I_{sp} is the specific impulse. Moreover, the power input, P_a, of the accelerator is given by

$$P_a = JV = JV_e + bJ^2I_{sp}/2 \tag{4}$$

The relations discussed so far refer to the thruster only and the accelerator current appears to be the independent variable. The I_{sp} is a parameter and may have any desirable value; however, the most desirable value is obtained from the well-known optimization condition, $\partial M/\partial I_{sp} = 0$, which will yield the I_{sp} for which the total mass M of the propulsion system is minimized. It is, therefore, important to obtain an expression of M in terms of I_{sp} and other system parameters.

Let us first identify and define the efficiencies involved in the chain from the solar power supply to thrust power. If each power pulse has a duration t_d, which is much shorter than the interval, t_c, between pulses, then the duty cycle is defined by $a = (t_d/t_c)$. The over-all efficiency is defined by

$$e_o = e_c e_d e \tag{5}$$

where e_c is the charging efficiency for energy transfer from the power supply to the capacitor bank, $e_c = W_c/(P_s t_c)$, (W_c is the energy stored in the C bank for each pulse), e_d is the discharge efficiency, for energy transfer from the C bank to the thrustor, $e_d = (P_a t_d)/W_c$, and e is the thrustor efficiency given by (3). Here, it may be written simply, $e = P_t/P_a$.

The total mass M of the pulsed MPD propulsion system may now be obtained as the sum of the main components, namely the masses of the 1) propellant plus power supply, 2) plus C bank, and 3) plus conditioner for charging the C bank. The reasonable assumption is made that the thruster hardware, propellant tankage and other minor structures have relatively negligible masses. The resulting expression for M may be written

$$M = (G/I_{sp}) + (GI_{sp}/2t_t e_o)fm_s \tag{6}$$

where G and t_t are, respectively, the total impulse and total duration required for the electric propulsion mission, whereas m_s is the specific mass of the power supply. The first term in the right-hand side of (6) is simply the propellant mass. The second term, as expanded by (7),

$$f = 1 + (e_c e_d m_c/m_s) + (e_c m_{pc}/m_s) \tag{7}$$

is the sum of the power supply, C bank and power conditioner masses. In (7), m_c and m_{pc} are, respectively, the specific masses of the C bank and power conditioner. The mass of a steady MPD system is given by the special case, $f = 1$. This simply means that m_c and m_{pc} in Eq. (7) are equal to zero, since a steady MPD system requires neither a C bank nor a power conditioner for charging it.

Table 1 Assumptions used for pulsed MPD system

Coefficient b, Eq. (1)	3×10^{-7} N-amp^{-2}
Voltage V_e, Eq. (2)	20 v
Total impulse, G	2.2×10^6 lb-sec
Total duration, t_t	230 days
Power supply to C bank, charging efficiency, e_c	80%
C bank to accelerator, discharge efficiency, e_d	90%
Specific mass of C bank, m_c	50 lb/kw
Specific mass of power conditioner, m_{pc}	10 lb/kw
Specific mass of power supply, m_s	44 lb/kw

When the optimization condition, $\partial M/I_{sp} = 0$, is imposed on (6) the optimum specific impulse is obtained

$$I_{sp}^* = g(e)^{1/2},\ g = (2e_c e_d t_t/fm_s)^{1/2} \tag{8}$$

When (8) is used in (6), the resulting minimum total mass of the pulsed system is

$$M_o = 2G(fm_s/2e_o t_t)^{1/2} \tag{9}$$

Two additional system parameters must be considered, N and r, namely the total number of pulses and the repetition rate. Then, the following relations are evident: $rt_t = N$, $rt_d = a$, and $aFt_t = G$. Furthermore, if top utilization and efficiency are desired in the energy transfer from the C bank to the accelerator, then the accelerator impedance† must be matched by the C bank impedance, namely, $R_a = (L/C)^{1/2}$. Moreover, $t_d = 2(LC)^{1/2}$. In summary, the system parameters must satisfy the five relations just mentioned. However, the ranges of the parameters under consideration are not unlimited. Limitations are imposed by several constraints, two of which are important in setting upper and lower limits for t_d. The upper limit of t_d depends on J and is set by thermal problems; the cathode tip of the accelerator, where the pulsed heat flux is the highest, will reach the melting point unless the product J^2t_d is kept smaller than a limiting value. Numerically

$$J^2t_d < 10^7 \text{ amp}^2\text{-sec} \tag{10}$$

(for tungsten-tipped cathodes).[1] If this relation is multiplied by b of Eq. (1), an upper limit is established for the impulse bit resulting from a single pulse. Furthermore, if the total impulse and the total mission duration are specified by mission requirements, then it is easily seen that lower limits for N and r may be determined.

Table 2 Characteristics of the pulsed MPD accelerator and certain system parameters corresponding to operation at the optimum specific impulse (minimum total mass of the system)

Accel. current J, kamp	Accel. effic. e, %	Optimum I_{sp}, sec	Pulsed thrust F, kg	Pulsed flow $\dot{m}$, g/sec	Accel. voltage V_a, v	Accel. imped. R_a, mohms	Power input p_a, kw	Duty cycle a, %	Power supply p_s, kw	Over-all effic. e_o, %	Minim. mass M_o, lb
2.8	20	1200	0.23	0.17	25	9.0	70	22	20	14	3700
3.6	30	1500	0.4	0.27	28	7.8	100	12.5	17.5	22	2900
5.3	40	1700	0.8	0.47	34	6.4	180	6.2	15.5	29	2600
7	50	1900	1.5	0.8	40	5.7	280	3.3	12.8	36	2300
10	60	2100	3	1.4	52	5.2	520	1.7	12.5	43	2100
14	70	2250	6	2.7	68	4.9	950	0.83	11.0	50	1950
22	80	2400	15	6.2	103	4.7	2,300	0.33	10.9	58	1850
30	85	2500	27	11	133	4.4	4,000	0.19	10.3	61	1750
50	90	2550	75	29	200	4.0	10,000	0.07	10	65	1700
100	95	3650	300	113	420	4.0	42,000	0.02	10	68	1650

The lower limit of t_d is established by considering the relation $t_d = 2L/R_a$. It is noted that R_a, for conditions of present interest, is approximately constant with a value near 5×10^{-3} ohms. Accordingly, the lower limit of t_d is set virtually by the lower limit of L. For practical reasons, $L \geq 10$ microhenry, which is representative of the residual self-inductance in a network where the different components must be adequately deployed for cooling by radiation. Thus, $t_d \geq 4$ msec, and this lower limit is relatively insensitive to other experimental conditions.

Numerical results may be obtained when appropriate values are assigned to some of the many parameters of the problem. The values in Table 1 appear reasonable.[1] With these assumed values, some characteristics of an optimized pulsed MPD system may be obtained, with J as the independent variable. This is done in Table 2 as follows: $I_{sp}{}^*$, given by (8) is used in (3). This establishes a relation between J and e, and for given values of J, results may be obtained for the first three columns of Table 2. The following columns are obtained by applying previously discussed relations.

The last two columns of Table 2 reveal that a pulsed MPD system improves rapidly as J increases, at small values, but the rate of improvement declines at higher values. Other important system parameters are determined according to previously discussed relations, provided that the associated constraints are not violated. In fact, these constraints limit the performance of the pulsed MPD system to a level not higher than that corresponding to the 30 kamp entry of Table 2. For this entry, N will have the lowest allowed value of 3×10^6, t_d will be about 11 msec, and C and L will be ~1.3 farad and ~24 microhenry, respectively. For higher currents, either the required t_d is unacceptably short, or relation (10) is violated. Note that for this 30 kamp case, the overall efficiency is about 60% and the minimized system mass is 1750 lb.

A comparison of pulsed and steady MPD systems is best made by considering Eq. (9) for the pulsed system, and writing a similar equation with primed symbols for the steady system; then the following result is obtained when the two equations are divided:

$$M_o/M'_o = (fe'_o/e_o)^{1/2} \quad (11)$$

Parameters G, t_t and m_s do not appear because they must be identical in both systems, if the comparison is to be on a common basis. Parameter f, given by (7) is approximately 2 for the pulse system, according to Table 1; the corresponding parameter is equal to unity for the steady MPD system as discussed earlier. Thus, Eq. (11) indicates that in a comparison of pulsed with steady MPD systems, the over-all efficiency of the pulsed system must be reduced by the factor f, which is the penalty that must be paid, because the necessary energy transformations in a pulsed system require components with substantial mass and with efficiencies lower than 100%. Since the highest over-all efficiency that may be expected from a pulsed system is about 60% and $f \simeq 2$, the best expected pulsed MPD will be superior only to steady MPD systems which have over-all efficiencies lower than 30%. Moreover, the superiority of the pulsed MPD would be rather marginal, due to the square root relationship in (11), unless the efficiency of the steady MPD is very much lower than 30%. Since the main contribution to a high value of f is made by the ratio m_c/m_s, (specific masses of the C bank and of the solar power supply), the superiority of the pulsed MPD system will remain at best marginal unless appropriate advances of the state-of-the-art force the ratio m_c/m_s to values substantially lower than the 50/44 assumed herein.

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Particle Cloud Impingement Damage

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SEVERAL studies of target damage induced by impaction of a cloud of micron-sized aluminum-oxide particles have been reported recently.[1–3] The results of these programs have established that, for a wide range of conditions typical of solid-propellant exhaust plumes, a debris layer forms immediately ahead of the exposed target surface, partially shielding it from subsequent impingement by oncoming particles. Furthermore, the test results, which were similar for all target materials including several metals and ablators,‡ indicated that a significant fraction of the incident particle kinetic energy flux can be absorbed by the impact debris with a corresponding large decrease in target damage. This effect, referred to as debris shielding or target shielding, is shown in Fig. 1 where the relative target damage, i.e., the ratio of total target mass loss m_T to total mass of incident

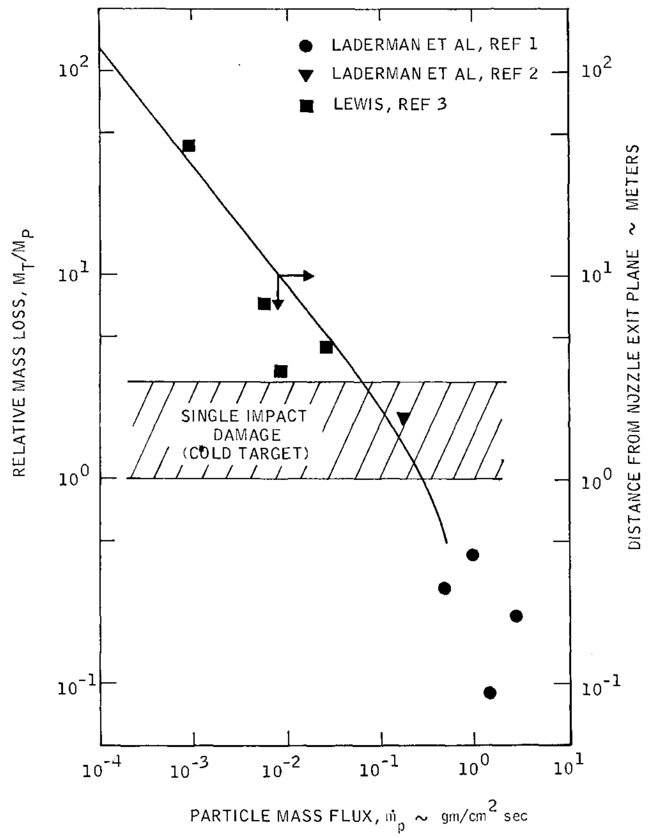

Fig. 1 Relative damage for particle cloud impingement on flat Teflon targets. The solid curve represents the particle mass flux as a function of distance from the nozzle exit plane for a typical solid-propellant rocket.

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‡ The metal targets included stainless steel and aluminum. The ablators were comprised of Teflon, carbon cloth phenolic, ATJ graphite, pyrolytic boron nitride, and quartz cloth phenolic which, with the exception of the latter, are pure subliming materials.