The Electrothermal Ramjet

P. J. Wilbur,* C. E. Mitchell,* and B. D. Shaw†
Colorado State University, Fort Collins, Colorado

An electrothermal ramjet configuration is examined as a possible alternative to rail guns and mass drivers for high acceleration launch missions. For a specific mission (Earth escape), the idealized performance of electrothermal ramjet, electrothermal rocket and electromagnetic acceleration systems are compared. This comparison indicates that the gross performance of the ramjet compares favorably with that of the ideal electromagnetic acceleration system. A specific configuration for the ramjet is chosen, and models for the dynamics, thermodynamics, and fluid mechanics are presented. Results of calculations for a typical supersonic launch cycle suggest that pressure, temperature, and power demand profiles associated with ramjet operation should be reasonable. A light gas gun is proposed to accelerate the vehicle to the critical velocity where efficient ramjet operation can begin. At high velocities the theoretical performance of the ramjet is also shown to be substantially better than that of the light gas gun.

Nomenclature

B = ballistic coefficient, m^2/kg
C_D = drag coefficient
C_p = specific heat at constant pressure, J/kg-K
d = diameter, m
E = energy, J
F = thrust, N
g = acceleration due to gravity = 9.8 m/s^2
h = enthalpy, J/kg
m = mass, kg
$\dot{m}$ = mass flow rate, kg/s
P = pressure, N/m^2
$\dot{Q}$ = heat addition rate, W
R = gas constant, J/kg-K
S = compressive stress, N/m^2
t = time, s
T = temperature, K
U = exhaust velocity relative to vehicle, m/s
V = vehicle velocity, m/s
X = distance, m
γ = ratio of specific heats
η_R = ramjet efficiency
σ = acceleration, g

Subscripts

e = state of working fluid after leaving ramjet
esc = escape
f = final state of projectile
i = initial state of projectile or working fluid

Introduction

THE relatively massive expenditure of chemical fuel and oxidizer associated with the launch phase of space missions adds substantially to the cost of such missions. Not only are the propellants costly, but the additional mass of tankage and structure required to hold the propellant mass detracts from the payload mass and therefore adds substantially to the cost of the delivered payload. It is also desirable to simplify these launch systems and improve their reliability. For some missions where high acceleration levels can be tolerated, such alternative launch schemes as light gas guns,[1] rail guns,[2] and mass drivers[3] have been proposed as substitutes for conventional rockets. These missions could include ones in which various materials would be directed into space either for disposal or application there. While the capital investment in such systems is expected to be large, they hold the promise of lower cost per launch because of the large number of launches that should be realized over their design lifetimes.

Because of the high acceleration levels at which these devices could operate, the associated launch tracks could be relatively short and the terminal launch velocity could be achieved while the payload was close to the Earth's surface. Achieving terminal velocity in a short distance is considered desirable because the launch could be effected in a tube of reasonable size, which would be sealed during the launch sequence if it became necessary to abort the launch. This could facilitate containment if toxic or radioactive materials were being launched.

Another propulsion concept which may be useful in these high acceleration level missions is the electrothermal rocket concept.[4] In these devices onboard propellant is heated electrically and then discharged through a nozzle to produce thrust. Because the heating is accomplished electrically, hydrogen propellant with its attendant high specific impulse capability can be selected. There are several types of electrothermal rockets. In the resistojet, for example, the propellant is heated by passing it over current-carrying, resistive elements; and exhaust velocities as high as 8500 m/s have been achieved.[4] Higher exhaust velocities can be realized if the material limitations imposed by the heating elements are eliminated and joule heating is accomplished by passing current directly through the propellant in an arcjet thruster. Exhaust velocities as high as 15,000 m/s have been demonstrated in these devices.[4]

A basic electrothermal rocket vehicle which might be used in this application is shown conceptually in Fig. 1a. This rocket would carry onboard propellant which would be metered into the heating chamber, where its temperature could be raised by energy either beamed there electromagnetically or carried there in the form of electrical current from rails located in the launch tube.

For the mission under consideration here, where the launch is accomplished in a relatively short distance close to the Earth's surface, it is also practical to distribute the propellant in the launch tube. When this is done, a ramjet engine can be used to collect the propellant, heat it, and produce the desired

Presented as Paper 82-1216 at the AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982; submitted Aug. 2, 1982; revision received May 2, 1983.

*Professor, Department of Mechanical Engineering.
†Research Assistant, Department of Mechanical Engineering.

thrust as it moves down the tube. Physically the ramjet would operate in the manner suggested by Fig. 1b by simply drawing propellant in from the tube through an intake diffuser, heating it electrically, and then expelling it through a nozzle. Energy could again be transported into the heating chamber either electromagnetically or in the form of electrical current. No compressor or other rotating equipment would be needed, although an initial velocity would have to be imparted to the vehicle. This might be accomplished by a booster rocket, a light gas gun, or a low terminal velocity electromagnetic driver.

The purposes of this study are 1) to determine the potential of the electrothermal ramjet concept by comparing its gross performance capabilities with those of rocket and electromagnetic accelerator systems, 2) to select a ramjet configuration that appears to be promising, and 3) to examine the fluid mechanics and thermodynamics of operation of this configuration. The execution of this work should point out any basic physical limitations that make the concept impractical and illustrate its potential advantages over other launch vehicle concepts.

Gross Performance Comparison

In order to compare the performance of various propulsion systems a high acceleration Earth escape mission was selected. In this mission, sufficient velocity would be imparted to the payload at the Earth's surface so it would be at Earth escape velocity when it reached an altitude where atmospheric drag would be negligible. The thrusters to be compared are characterized by their exhaust velocities, with the values shown in Table 1 being selected as typical of the capabilities of the devices indicated.

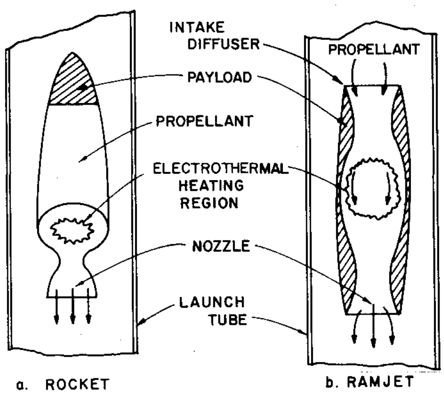

Fig. 1 Electrothermal thruster concepts.

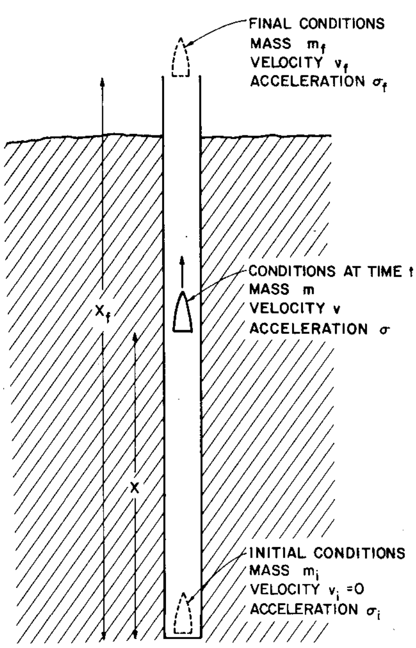

Fig. 2 Launch phase nomenclature.

Each of these thrusters will, for this preliminary analysis, be assumed to operate at a constant exhaust velocity. This is probably a reasonable assumption for the rockets, but it is not obvious that the ramjet is modeled adequately as a constant exhaust velocity device. Work contained in the next section of this paper shows, however, that from a theoretical point of view it is quite reasonable to model the ramjet in this way. In addition an ideal electromagnetic launcher will be used in the comparison. This device is idealized in the sense that all of the electrical energy input is assumed to be transferred to the moving payload mass and it therefore represents the ultimate launcher.

The velocity required at the surface of the Earth by a payload intended to escape the Earth and the maximum acceleration that such a payload can endure are also necessary inputs to the problem under consideration. These quantities can be defined if one considers the expulsion of the payload to consist of two phases, namely, the launch phase illustrated in Fig. 2 and the subsequent phase of vehicle passage through the atmosphere. A vertical launch trajectory is specified, and initially the vehicle is assumed to be at rest and to have a mass m_i. When the thruster is started, it generates a constant thrust F which produces an initial acceleration σ_i. The launch phase is assumed to continue until time t_f, when a terminal launch velocity v_f is reached. At this point the vehicle mass is m_f, the acceleration is σ_f, and the axial location measured from the initial location is x_f. Thrusting stops and the phase of vehicle passage through the atmosphere begins at this point. During this second phase the vehicle velocity decreases as a result of atmospheric drag and gravitational effects.

The maximum acceleration σ_f occurs at the end of the launch phase. In order to minimize track length, this acceleration should be as large as the vehicle can withstand; a value that is ultimately determined by the mechanical strength of the vehicle. If one assumes the basic vehicle is cylindrical and has a diameter d, the compressive stress S at the base of the vehicle is equal to the thrust force F divided by its cross-sectional area.

$$S = 4F/\pi d^2 = 4m_f\sigma_f g/\pi d^2 \tag{1}$$

Table 1 Exhaust velocities of electric thrusters

Thruster	Exhaust velocity (U), m/s
Chemical rocket	4,500
Resistojet rocket	8,500
Arcjet rocket	15,000
Resisto-ramjet	8,500
Arc-ramjet	15,000

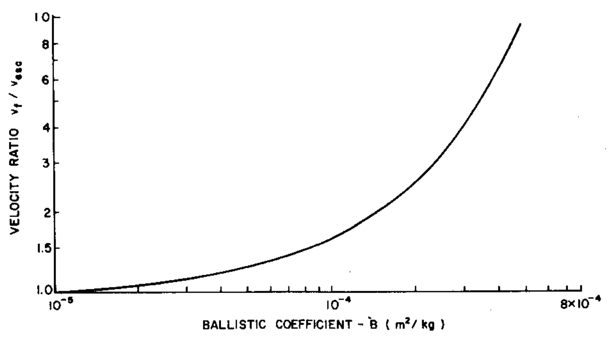

Fig. 3 Velocity loss through atmospheric drag.

In this equation, σ_f, the final (maximum) acceleration, is in g's and g is the acceleration due to gravity. The ballistic coefficient of the vehicle B, which characterizes vehicle drag during its movement through the atmosphere after launch, is given by

$$B = C_D \pi d^2 / 4m_f \tag{2}$$

In this equation, C_D is the vehicle drag coefficient and it should have a value near 0.1 for the velocities under consideration here.[5] Combining Eqs. (1) and (2) and solving for the maximum acceleration, one obtains

$$\sigma_f = BS/C_D g \tag{3}$$

Figure 3, which was obtained from data supplied by Ref. 6, shows the ratio of the velocity at the start of passage through the atmosphere to that after this passage as a function of the ballistic coefficient of the vehicle. For the case under consideration here, the velocity after atmospheric passage is the Earth escape velocity, as the vertical axis title suggests. From this figure it appears that a low but realistic ballistic coefficient might be 2×10^{-5} m²/kg. At this value, the ratio of atmospheric entrance velocity to the Earth escape velocity ($v_{esc} = 11{,}200$ m/s) is just under 1.2, and the terminal launch velocity (v_f) would therefore have to be about 13,000 m/s. If one specifies an allowable stress in the vehicle of 1.4×10^9 N/m² (200,000 psi), then the maximum allowable acceleration [Eq. (3)] becomes 30,000 g's. This acceleration, while high, is not considered unattainable. Light gas guns[1] have, in fact, been operated at projectile acceleration levels an order of magnitude higher than this. For this case, however, 30,000 g's should not be exceeded if compressive stresses are to be held below 1.4×10^9 N/m² during launch to a velocity of 13 km/s. This velocity will be sufficient to enable escape from the Earth when the vehicle diameter is given by Eq. (2). For a 10-kg mass having the ballistic and drag coefficients mentioned, this would correspond to a vehicle about 5 cm in diameter.

Results

A simple mathematical model based on a dynamical force balance and an energy conservation analysis can be applied to each of the thruster cases considered. In each of these cases a constant thrust and constant exhaust velocity in the frame of reference of the rocket or ramjet have been assumed. The basic equations used are given in Ref. 7. The results were obtained for a particular case where a 10-kg final mass was launched vertically on the Earth escape trajectory. The 10-kg final mass was selected rather arbitrarily, but the basic trends and comparisons made here are not affected by this selection.

Figure 4 shows the velocity profiles for the six thruster options being compared. The effect of increasing rocket exhaust velocity from 4,500 to 15,000 m/s is observed to be a three-to-fourfold reduction in the launch time and a two-to-threefold reduction in the required launch track length (x_f). This points out the great benefit of using the high exhaust velocity electrothermal rocket rather than the conventional chemical rocket motor, which is characterized by the lower exhaust velocity. By using a ramjet rather than a rocket, further reductions in launch time and track lengths are realized at a given exhaust velocity. This occurs because there is no onboard propellant being accelerated in the case of the ramjet. At an exhaust velocity of 15,000 m/s, the ramjet performs essentially the same as the electromagnetic accelerator in that it requires the same track length (285 m) and launch time (44 ms). The 8500-m/s ramjet is seen to exhibit performance comparable to the 15,000-m/s rocket.

Figure 5 shows the time profile of the vehicle acceleration for the various thrusters. The acceleration is limited to 30,000 g's, and this implies considerably lower initial accelerations for the conventional rockets in which the vehicle mass must decrease with time as onboard propellant is discharged. The shorter launch times and track lengths given in Fig. 5 occur, of course, for the cases where the acceleration remains closer to the limiting value throughout the launch.

A discussion of the variation in acceleration for the 8.5-km/s ramjet will facilitate an understanding of some of the physical characteristics of this thruster. Before a ramjet can be operated it is necessary to accelerate it, using an alternative force, to that velocity where it is processing adequate propellant mass. For the ramjet cases in Fig. 5, this is arbitrarily presumed to be accomplished using an auxiliary rocket motor. During the first 10 ms or so, the acceleration of the 8.5-km/s ramjet increases because this auxiliary rocket is operating and onboard mass is being expelled to accelerate the vehicle to the point where the ram pressure is sufficient to effect ramjet operation. This decrease in mass causes the

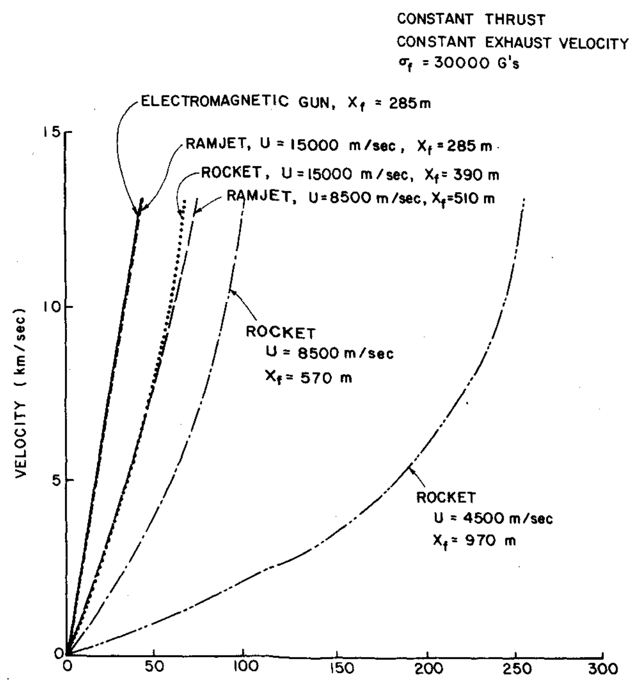

Fig. 4 Velocity profile comparison.

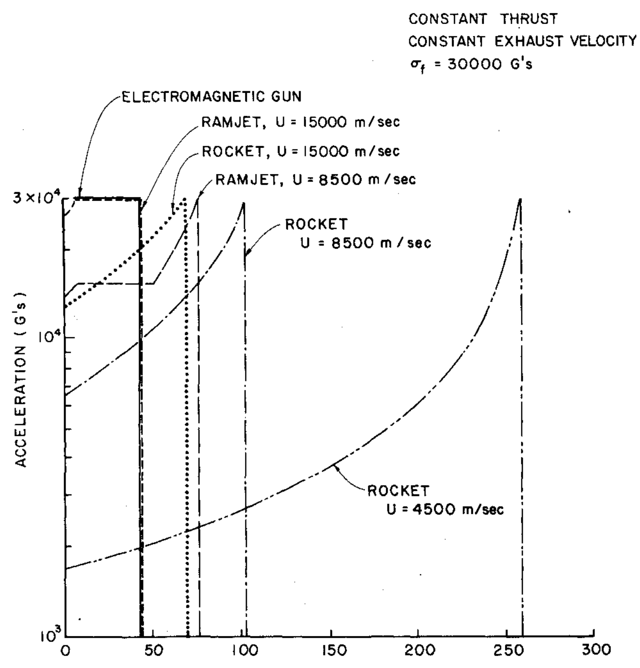

Fig. 5 Acceleration profile comparison.

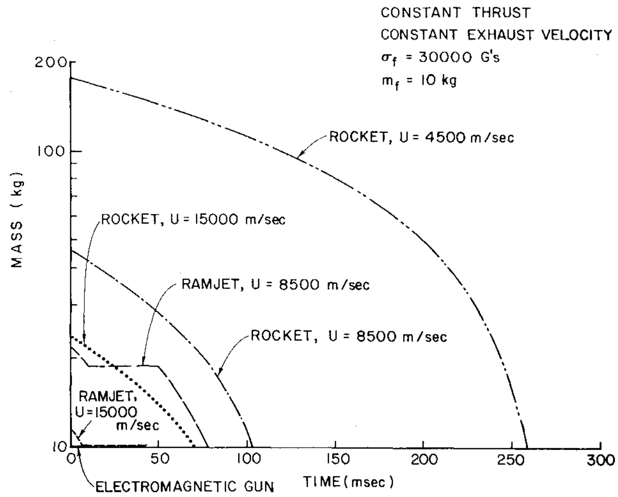

Fig. 6 Mass profile comparison.

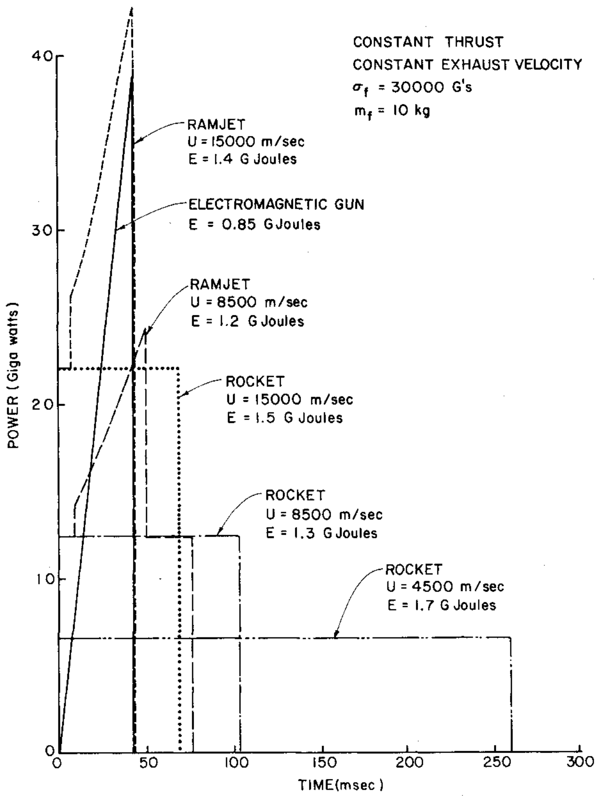

Fig. 7 Power profile comparison.

acceleration level to increase with time. During the interval from 10 to 50 ms, ramjet operation occurs and the vehicle acceleration is constant. Near the 50-ms point, the vehicle velocity gets sufficiently close to the thruster exhaust velocity so that the ramjet can no longer produce adequate thrust.‡ This means onboard propellant must again be used and acceleration again increases with time. This use of onboard propellant continues until the desired final velocity (13 km/s) is realized.

For the 15-km/s ramjet, the final phase wherein onboard propellant is used is not required because the desired final velocity is significantly less than the exhaust velocity. As this discussion suggests, it is desirable to have a ramjet exhaust velocity that is substantially greater than the desired vehicle velocity at the end of the launch phase. It is interesting to note at this point that constant exhaust velocity, constant thrust operation of a ramjet implies a prescribed mass flow rate. This would seem at first to be difficult to achieve in this case where the projectile velocity is continuing to increase. A desired mass flow rate could be realized, however, by either varying the ramjet intake area or the distribution of mass in the launch tube.

Figure 6 shows the variation in vehicle mass with time for each of the thrusters. These curves simply reflect the variations in acceleration observed in Fig. 5. It is noteworthy, however, that the 4500-m/s conventional rocket requires an initial mass of 180 kg to deliver a final mass of 10 kg at 13 km/s, while the 15,000-m/s ramjet can do it with 11.5 kg, and the ideal electromagnetic thruster requires only the desired 10 kg as an initial mass. It is also important to note that propellant tankage, structure, and thruster masses are neglected in this analysis. If these masses were included in the analysis, the differences between required initial masses would be even greater.

The power profiles for each operating condition are compared in Fig. 7. The total energy E required to accelerate the payload to the specified final velocity for each option is obtained by integrating under the power curves and is also shown in this figure. The variation in total energy required for the launch is seen to be relatively modest between the various modes, but the ramjet and electromagnetic designs are seen to require substantially greater peak power levels. Figure 7 shows that the peak power levels of the high exhaust velocity ramjet and the electromagnetic gun are comparable. The electromagnetic gun is observed to require the least energy of any option, but it is important to note that this is a highly idealized model. The energy stored in the magnetic fields of this device, when the vehicle leaves the launch track, as well as joule heating losses, will be substantial and they have not been included here. Their inclusion could well make the energy required for the electromagnetic gun more comparable to values obtained with the rockets and ramjets.

The modeling that has been used in this study is highly idealized. For example, losses due to aerodynamic and frictional drag and residual thermal energy in the propellants have been neglected for the launch phase, as have propellant pumping powers and losses associated with energy transport through conductors or windows. These could change absolute numbers significantly, although the comparative results are considered correct, and they suggest that the hydrogen ramjet thruster could exhibit performance that is comparable to that associated with the idealized electromagnetic thruster. It is therefore appropriate to examine specific ramjet configurations and to determine the mechanical complexity that might be required and the extent of the thermodynamic losses associated with their operation.

Ramjet Design Features

The conventional ramjet design shown in Fig. 1b could be used in the present application. In this configuration it would fly down the launch tube processing a portion of the hydrogen and bypassing the remainder through the region between its exterior surface and the launch tube wall. Such a design has several design problems including:

1) Transmission of electrical or electromagnetic energy through the ramjet sidewall into the heat addition core.

2) Control of the ramjet geometry to effect shock swallowing and efficient operation over the large vehicle velocity range that will be encountered.

3) Control of the radial position of the vehicle within the tube.

A more suitable design would be one in which the heat addition zone was located external to the ramjet, and the tube wall could serve to guide it down the tube. Figure 8 shows a

‡Application of the momentum balance equation demonstrates that the thrust ($F = \dot{m}[U - v]$) goes to zero as the vehicle velocity v approaches the exhaust velocity U.

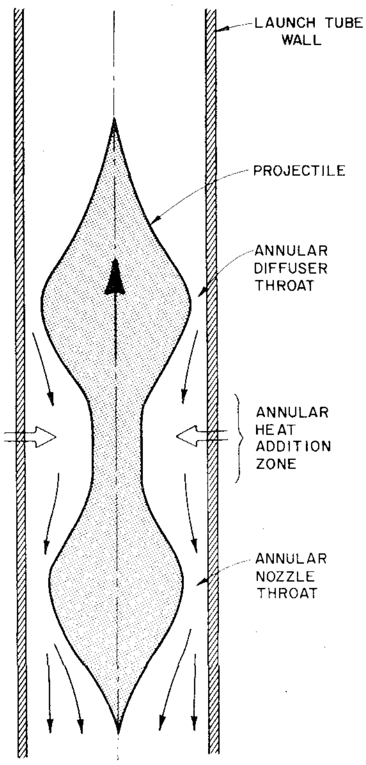

Fig. 8 Annular flow ramjet configuration.

schematic diagram of such a design which is designated the annular flow ramjet configuration. This axisymmetric design utilizes a launch tube of circular cross section, and all of the propellant flow is forced to pass through the ramjet. The converging-diverging diffuser and nozzle passages are observed to be formed by the undulating configuration of the projectile coupled with the essentially straight launch tube wall. The conceptual advantages of this configuration over the conventional design follow:

1) Heat addition can be affected outside the ramjet body directly from the tube wall. This eliminates the need for windows in the ramjet for the case of beamed energy heating and sliding current contacts for arc discharge heating schemes.

2) Shock losses will probably be lower with the annular flow design because a conical shock attached to the projectile would be expected while a bow shock would be driven ahead of the conventional ramjet.

3) Direct mechanical or fluid mechanical forces induced between the tube wall and projectile should tend to stabilize and center it.

4) The structural design of the projectile appears to be relatively simple.

5) Variations in fluid flow areas needed to achieve proper flow conditions as the projectile velocity increases can be introduced by varying the cross-sectional area of the launch tube as a function of axial position.

It is noteworthy that by eliminating the need to transfer electrical energy to the projectile itself and by introducing the self-centering capability just alluded to, two of the problems associated with such electromagnetic devices as the rail gun are mitigated. These problems relate to the design of sliding electrical contacts and the maintenance of a tight tolerance on launch track straightness. Relaxation of the tolerance should, for example, permit longer track lengths and lower acceleration levels than those required for railguns.

Fluid Mechanics Model

Since fluid mechanical forces propel the vehicle, it is appropriate to begin an analysis of the annular flow ramjet by determining the magnitudes of thermodynamic and fluid

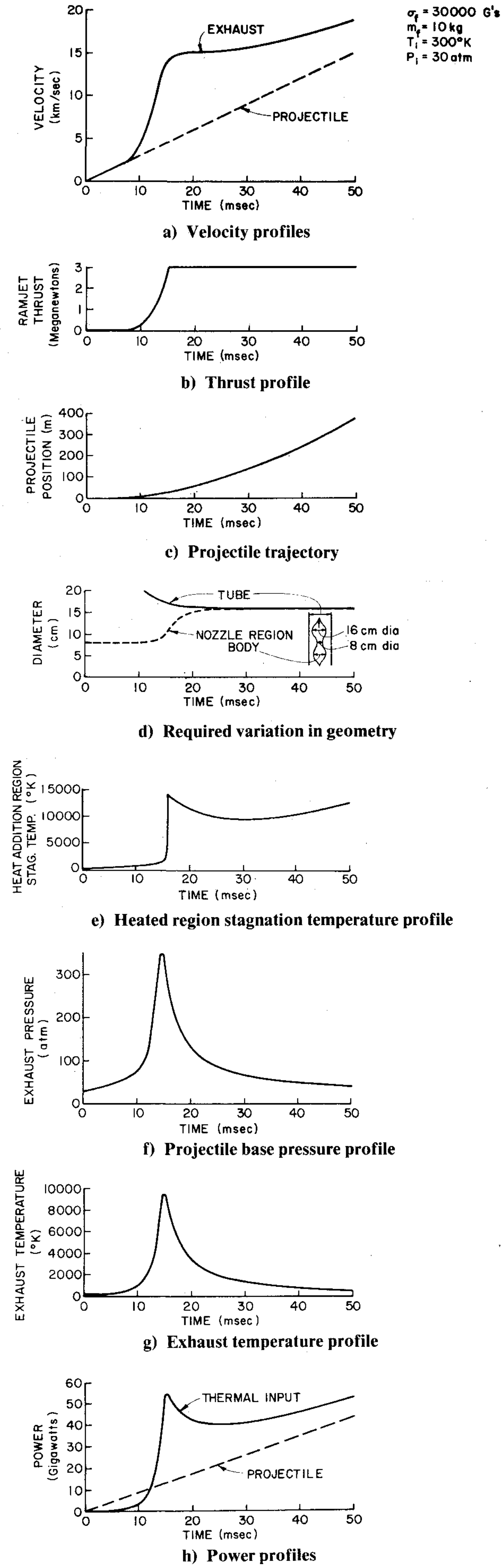

Fig. 9 Typical electrothermal, hydrogen ramjet launch cycle.

mechanical variables required to produce the desired thrust level. This analysis must be considered preliminary and, as a result, very much simplified. The first major assumption in this analysis is that the process can be considered quasisteady. It is recognized that, at the acceleration levels being considered, this cannot, in fact, be accurate. However, including unsteadiness introduces major complications in the analysis. Estimates of the errors involved have indicated that though they are fairly substantial, they are not so large as to render these preliminary calculations valueless.

Staring the projectile through the application of an external force will be addressed later. For purposes of this analysis we assume the projectile has been accelerated to a substantial supersonic velocity. Though it is likely that there will be a conical shock attached to the nose of the projectile, the strength of this shock can be controlled to some extent by the contour and half-angle of the projectile nose. Consequently, for this preliminary analysis, the diffusion process is modeled as an isentropic one. After diffusion, the hydrogen working fluid undergoes heat addition at a subsonic velocity in a constant area duct and this is followed by an isentropic expansion to a supersonic exhaust velocity. For this analysis, propellant velocities were computed in the frame of reference of the moving projectile. The fact that the tube wall, which is the outer boundary to this flow, is moving in this frame of reference was assumed to have no effect on the behavior of the flow. The basic equations of compressible fluid mechanics (conservation of mass and energy coupled with a thermodynamic path equation) were applied separately to the diffusion, heat addition, and expansion processes.

Thrust was computed by applying the momentum equation in the frame of reference of the control volume moving with the projectile. It should be noted that the boundary conditions associated with the annular flow ramjet are different than those associated with conventional ramjet operation. In the present case, the inlet and outlet flow areas are equal and the flow area in the heat addition zone must be less than this inlet/outlet area. In the conventional ramjet case, the static inlet and outlet pressures are set equal, while in the annular flow ramjet, the static pressure of the outlet stream will typically be greater than that at the inlet.

The thermodynamic properties of the hydrogen working fluid will vary over the range of temperatures and pressures encountered during ramjet operation, primarily because of the effect of dissociation. For this preliminary analysis, however, it was desirable to avoid the complications of temperature- and pressure-dependent specific heats and gas constants. In general, during ramjet operation, increases in temperature are accompanied by corresponding increases in pressure. Consideration of the specific heat and gas constant of hydrogen under these conditions[8] suggests that it is not too unrealistic to treat these two parameters as constants. For the results contained in this paper, ideal gas behavior was assumed and a ratio of specific heats (γ) of 1.4 and a gas constant (R) of 4160 J/kg-K were used.

Extensive analysis of the early phase of ramjet operation when a bow shock was propagated ahead of the projectile was also undertaken. Modeling of this phase of operation was successful and showed that with proper lunch tube design the bow shock would become attached as a conical shock without difficulty. However, it also showed that positive ramjet thrust could not be produced at the subsonic diffusion inlet condition that accompanies operation with a bow shock. It was therefore assumed that acceleration to supersonic speeds and initiation of the assumed isentropic diffusion process would be accomplished by some alternative acceleration scheme.

Typical Supersonic Launch Cycle

If one assumes that the projectile will be acted upon by either the ramjet force or some externally applied force needed to produce the desired acceleration, the projectile trajectory will be known. With the projectile velocity profile known, the propellant flow velocity relative to the ramjet is known at each position along the launch track. One can now prescribe the diffuser throat area required at each position along the tube so that the flow will remain sonic at this throat. One can also prescribe the heat supplied in the subsonic heat addition region so that the specified thrust will either be produced or the Mach number at the exit of the heating region (in the projectile frame of reference) reaches its maximum allowable value of unity. After heat has been added, the flow is accelerated isentropically in the nozzle to the maximum supersonic Mach number achievable under the constraint of the area change available. The static pressure at the nozzle exit is determined by this expansion and it will vary with projectile position. Proper control of this pressure at the base of the projectile would have to be achieved in an actual device by proper design of the launch tube. Such a tube would consist of two sections: a cavity section into which hydrogen processed by the ramjet would be collected, and the launch section through which the projectile would pass. It has been assumed in this analysis that the cavity section could be designed to have the length and cross-sectional area needed to accommodate the propellant and facilitate maintenance of the necessary projectile base pressure. While it seems possible to do this intuitively, the examination of the unsteady fluid mechanics describing the process has not yet been attempted.

Figure 9 shows the results of such an analysis for the case where a constant thrust of 3×10^6 N is maintained on a 10-kg mass and the hydrogen in the launch tube is initially at 300 K (T_i) and 30 atm (P_i). The projectile selected for this example has a fixed 16-cm diameter at the diffuser throat and an 8-cm diameter in the heat addition region. These diameters are considered adequate to assure the structural integrity of the projectile during launch. As Fig. 9a shows, the projectile velocity (in the launch tube frame of reference) increases linearly with time. Since the propellant is initially at rest, relative to the tube wall the projectile velocity is equal to the propellant inlet velocity in the projectile frame of reference. The exhaust velocity (in the projectile frame of reference) is observed to be equal to the inlet velocity during the first ~ 8 ms of operation, so during this time interval, essentially no net thrust is produced through the mechanism of momentum change of the propellant. After about 16 ms of operation, however, the exhaust velocity has risen to about 15 km/s and has begun to level off. During the time between ~ 8 and ~ 16 ms, all of the heat that can be added without choking the flow (achieving unity Mach number at the end of the heat addition region) is being added.

As Fig. 9b shows, the net ramjet thrust is inadequate to meet the 3×10^6 N thrust requirement at times less than 16 ms. Thus an alternative accelerating scheme, such as the constant pressure gun (discussed in the next section), would have to be used during this time interval. As the projectile velocity increases, more heat can be added and this causes the increase in exhaust velocity shown in Fig. 9a. After ~ 16 ms, both the exhaust velocity and the mass flow rate have risen to the point where the desired thrust level can be produced and the Mach number after heat addition begins to drop below unity.

Figure 9c, which indicates projectile position as a function of time for this case of constant acceleration, shows a launch tube about 400 m long would be required to accelerate the 10-kg mass to the terminal velocity of 15,000 ms in ~ 50 ms. Figure 9d shows the variation in tube and projectile diameters that would have to be effected to satisfy fluid mechanical constraints imposed on the ramjet. As the sketch suggests, the projectile diameter at the diffuser throat and in the heat addition region have been treated as fixed at 16 and 8 cm, respectively. The reduction in tube diameter required to yield unity Mach number at the diffuser throat as the projectile velocity increases is shown by the solid line. Data from this line taken together with the position profile of Fig. 9c specify how the tube diameter would have to vary along its length.

Figure 9d also shows that the projectile diameter at the nozzle throat would have to increase as the projectile velocity increases and the input power is varied to induce the desired thrust level. The fact that this diameter must change during the launch cycle represents a significant mechanical complication in the system. It is noted, however, that the amount of change in this diameter becomes very small after about 20 ms when the projectile velocity is ~ 5 km/s. It is anticipated that a pressure- or temperature-sensitive scheme might be designed to facilitate this change in projectile diameter at the nozzle throat. Alternatively, one could hold the projectile diameter in the nozzle region fixed, reduce the tube diameter slightly more rapidly than Fig. 9d suggests, and abrade the diameter of the projectile at the diffuser throat using protrusions from the tube wall.

Figures 9e, 9f, and 9g indicate how the stagnation temperature in the heat addition zone and the static pressure and temperature at the nozzle exit should vary to conform to the problem specifications. The peaks in temperature and pressure occur at the point where the power input is a maximum (Fig. 9h). This, in turn, occurs at the time when the thrust has just reached its design value and the Mach number at the end of the heat addition region is still at unity. At this condition, the exhaust velocity is still relatively low and the bulk of the thrust is being produced by the static pressure difference across the projectile. If one did not start using the ramjet until after ~20 ms into the launch, the exhaust pressure and temperature would lie in a very moderate range throughout the period of ramjet operation. Note that it is the pressure profile of Fig. 9f that would have to be matched through proper design of the cavity section of the launch tube. This might be achieved by selecting not only the length and cross-sectional area of this section, but also by the inclusion of accumulator chambers that could be connected into the tube at the proper time.

The heat addition zone stagnation temperature (Fig. 9e) is observed to remain near 10,000 K after about 16 ms. It is noteworthy that this is in the temperature range where adequate coupling between hydrogen and electromagnetic radiation can occur through the mechanism of inverse bremsstrahlung.[9] Hence, after 16 ms, use of this energy addition scheme should be possible.

Figure 9g shows the thermal power input profile required to effect operation as well as the actual profile of mechanical power input to the projectile. After the ~20-ms period over which the auxiliary starting force would be applied, it is observed that the ratio of projectile power to thermal input power rises above ~50%. (An approximate mathematical relationship for this ratio is given in the next section.) The ramjet is observed to become increasingly efficient as the launch cycle proceeds. This suggests that the ramjet will be more efficient at the higher velocities, where the efficiencies of electromagnetic launchers drop off. The difference between the projectile and thermal input powers represents the power being deposited as kinetic and thermal energy in this hydrogen propellant. It should be noted here that frozen flow losses in the nozzle and electrical-to-thermal power conversion losses as well as frictional losses have been neglected in this preliminary analysis.

Analyses similar to the one leading to the results of Fig. 9 have been carried out at other values of parameters such as the initial tube pressure and the diameter of the projectile at the diffuser throat. They suggest that inadequate mass flow rates are brought on by low projectile diameters and low initial tube pressures. This, in turn, leads to excessively high exhaust pressures and temperatures, as well as extremely high thermal power demands. It has also been determined that the device will work if the propellant is exhausted from the nozzle at a subsonic Mach number and a high static pressure.

Constant Pressure Gun—Ramjet Combination

As discussed above, efficient ramjet operation does not occur until some critical projectile velocity is attained. Below this speed, an auxiliary thrust device is required in order to maintain the constant acceleration level assumed. In the example whose characteristic parameters are shown in Fig. 9, this velocity was reached at approximately 20 ms. At this point, the projectile velocity was about 5900 m/s and the distance down the tube about 59 m. One way of attaining this necessary velocity would be to accelerate the projectile as in a gun and delay ramjet operation until this velocity was reached. In this process, energy would be added to a fixed quantity of gas at the base (in back of) the projectile, and the projectile would completely occupy the tube cross section. If acceleration is to be constant and the tube cross-sectional area and projectile mass are constant, then the pressure in the tube must be maintained at a constant value as well during the acceleration. It is anticipated that the transition from the gun to the ramjet phase of operation would be accomplished when the projectile passed through a diaphragm confining the hydrogen to the section of the tube to be used for ramjet operation. The section of tube between the initial projectile location and the diaphragm would be at low pressure initially, so no significant amount of gas would be compressed ahead of the projectile during the constant pressure phase.

A simple relationship between the required rate of energy deposition to the gas $\dot{Q}$ and the projectile velocity v is obtained easily for the constant pressure (gun) phase of acceleration from the principle of energy conservation if frictional effects are ignored. This relationship is

$$\dot{Q}=m_f\sigma_f gv[\gamma/(\gamma-1)] \tag{4}$$

Since the rate of kinetic energy increase of the projectile is $m_f\sigma_f gv$, the efficiency of the process (ratio of rate of kinetic energy increase torate of energy supplied to driven gas) must be $(\gamma-1)/\gamma$. If hydrogen is taken to be the driver gas, $\gamma=1.4$, the efficiency is about 28.6%. This is constant throughout the acceleration process. The energy not appearing as kinetic energy of the projectile must reside in the thermal energy of the driven gas. The temperature of the gas driving the projectile must therefore increase substantially during the acceleration. The magnitude of the rise is, of course, dependent on the mass of driver gas used.

Once the velocity necessary for effective ramjet operation is reached, operation of the projectile as a ramjet in the mode described in the preceding section is initiated. It is of interest to develop an expression for the efficiency of this process and to compare it with the efficiency of the constant pressure gun process. Application of conservation of energy to the ramjet results in the following expression:

$$\dot{Q}=\dot{m}\frac{U^2-v^2}{2}+\dot{m}(h_e-h_i) \tag{5}$$

where the subscripts e and i denote respectively exit and inlet conditions for the device, and h and $\dot{m}$ represent respectively enthalpy and mass flow rate. Combination of this relationship with the thrust equation $F=\dot{m}(U-v)+(P_e-P_i)A$, where A is the tube cross-sectional area, and P is the pressure, gives after rearrangement:

$$\dot{Q}=\frac{F(U+v)}{2}\left(1-\frac{(P_e-P_i)A}{F}+\frac{\dot{m}C_p(T_e-T_i)}{F(U+v)/2}\right) \tag{6}$$

Since $F=m_f\sigma_f g$, the expression above can be written:

$$\dot{Q}=m_f\sigma_f gv\left(\frac{U}{2v}+\frac{1}{2}\right)\left(1-\frac{(P_e-P_i)}{F}A+\frac{\dot{m}C_p(T_e-T_i)}{F(U+v)/2}\right) \tag{7}$$

Comparing this to the rate of kinetic energy gain of the projectile, $Fv=m_f\sigma_f gv$, allows the definition of the ramjet efficiency:

$$\eta_R=\left(\frac{U}{2v}+\frac{1}{2}\right)\left[1-\frac{(P_e-P_i)}{F}A+\frac{\dot{m}C_p(T_e-T_i)}{F(U+v)/2}\right]^{-1} \tag{8}$$

The efficiency clearly varies with the projectile velocity v. At the beginning of ramjet operation, for the case given in Fig. 9, at $t=20$ ms,

$$\eta_R = \frac{1}{(1.25+0.5)(1-0.062+0.212)} = 0.497 \tag{9}$$

and at $t=50$ ms (end of acceleration),

$$\eta_R = \frac{1}{(0.624+0.5)(1-0.007+0.023)} = 0.876 \tag{10}$$

These calculations indicate that the efficiency of the ramjet is always substantially higher than that of the constant pressure acceleration (0.286) and increases with increasing projectile velocity.

The overall efficiency of the ramjet acceleration process can be estimated easily if the term

$$1 - \frac{(P_e - P_i)A}{F} + \frac{\dot{m}C_p(T_e - T_i)}{F(U+v)/2}$$

is taken to be unity, and if U is taken to be constant. The first assumption introduces a fairly small error of about 15% at the start of ramjet operation and a very small error of about 1.6% at the conclusion of the acceleration. The constancy of U depends on the ramjet parameters chosen. For the example of Fig. 11 it is not a bad approximation. With these two assumptions, the expression for the rate of energy consumption becomes

$$\dot{Q} = (U/2v + 1/2)\, m_f \sigma_f g v \tag{11}$$

Integrating the above expression over any period of time, say between t_1 and t_2

$$Q = m_f \sigma_f g (x_2 - x_1)(U/2\bar{v} + 1/2) \tag{12}$$

where $\bar{v} = (v_1 + v_2)/2$ is the average projectile velocity between t_1 and t_2. Since $m_f \sigma_f g(x_2 - x_1)$ is equal to the change of kinetic energy of the projectile, the overall efficiency for the ramjet acceleration process is the standard one for an external-breathing jet engine, namely,

$$\bar{\eta}_R = \frac{1}{U/2\bar{v} + 1/2} \tag{13}$$

For the example of Fig. 9, $\bar{\eta}_R = 77.3\%$. For the combined constant pressure acceleration-ramjet acceleration process, the efficiency is approximately 68%.

Conclusions

Much analysis remains to be done to investigate completely the effects of all of the parameters of concern. In particular, the effects of high acceleration and unsteady gasdynamic effects need to be considered, and solutions that yield higher system efficiencies and/or more readily accommodated geometry changes need to be sought. Results presented in Fig. 9 suggest, however, that the electrothermal ramjet designed to produce thrust after being given an initial velocity cannot be rejected on the basis that it violates a basic principle of fluid mechanics or thermodynamics. Moreover, on the basis of the same results it appears that the efficiency of the ramjet energy conversion process has the potential of being fairly high.

Acknowledgment

This work was supported under NASA Grant NGR-06-002-112.

References

[1] Siegel, A. E., "Theory of High-Muzzle-Velocity Guns," *Interior Ballistics of Guns: AIAA Progress in Astronautics and Aeronautics*, edited by H. Krier and M. Summerfield, Vol. 66, AIAA, New York, 1979, pp. 135-175.

[2] Kolm, H., et al., "Electromagnetic Propulsion Alternatives," 79-1400, Fourth Princeton/AIAA Conference on Space Manufacturing Facilities, May 1979.

[3] Snow, W. R. and O'Neill, G. K., "Construction and Testing of the 2.5 m Mass Driver," AIAA Paper 79-2095, Princeton/AIAA/DGLR 14th Electric Propulsion Conference, Oct. 1979.

[4] Jahn, R. G., *Physics of Electric Propulsion*, McGraw Hill, New York, Chap. 6, 1968.

[5] Hildebrand, R. B., "Aerodynamic Fundamentals," *Handbook of Astronautical Engineering*, edited by H. H. Koelle, McGraw Hill, New York, 1961, pp. 5-24.

[6] Kerslake, W. R., Private communication of unpublished results, NASA Lewis Research Center, Oct. 1980.

[7] Wilbur, P. J., "Ion and Advanced Electric Thruster Research," NASA CR-165253, Dec. 1980, p. 118.

[8] Svehla, R. A., "Thermodynamic and Transport Properties for the Hydrogen-Oxygen System," NASA SP-3011, 1964.

[9] Kemp, N. H. and Root, R. G., "Analytical Study of Laser Supported Combustion Waves in Hydrogen," NASA CR-135349, Aug. 1977.