

# Direct Space Launch Using Ram Accelerator Technology

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**Abstract.** The ram accelerator is a hypervelocity launcher that operates on the principles of a chemically propelled in-tube ramjet. This concept is unique in its potential to launch large-scale projectiles to Earth orbit velocity while controlling the in-tube acceleration. Experimental investigation of the operating characteristics of the ram accelerator at several different facilities around the world has resulted in the demonstration of many key gas dynamic principles and logistical aspects needed for a space launch facility. These experimental results have been used to determine the parameters for a ram accelerator system capable of launching a 2000 kg projectile having an effective density of  $1000 \text{ kg/m}^3$  at velocities of 6-8 km/s, without exceeding 1500 g. The results of this study indicate that a multi-stage ram accelerator system would be an effective means to launch large-scale projectiles into orbit.

## INTRODUCTION

Direct space launch systems using ram accelerator technology have significant potential to lower the cost of inserting payload into Earth orbit. Projectiles launched at near orbital velocities (6-8 km/s) need to be relatively massive ( $>100 \text{ kg}$ ) to survive atmospheric transit and reach apogee at low Earth orbit altitudes. Either an onboard rocket or interception by an orbit transfer vehicle is required to ultimately place the payload in the desired orbit. Since the effects of launch angle, muzzle velocity, muzzle elevation, and rocket propellant requirements on an impulsively launched projectile have been assessed by various authors (Bruckner, 1987; Kaloupis, 1988; Hunter, 1989; Bogdanoff, 1992; Tidman, 1995; Gilreath, 1999), they will not be addressed here. The focus of this study is on the scaling and system issues associated with only the ram accelerator component of the space launch facility.

The ram accelerator is a hypervelocity mass launcher in which a subcaliber projectile, shaped like the centerbody of a ramjet engine, is accelerated through a tube containing gaseous fuel and oxidizer mixtures (Hertzberg, 1988)). Its propulsive cycles are similar to those of ramjet and scramjet engines, and only chemical means are used to propel the projectile. The acceleration is controllable by adjusting the fill pressure, varying the propellant composition along the length of the ram accelerator, and tapering the inner diameter of the launch tube. In all modes of ram accelerator operation the propellant is moving at a much lower velocity relative to the tube wall than the projectile, thus the barrel erosion is minimal. These advantageous operating features have stimulated the experimental investigation of ram accelerator technology at research institutes around the world (Hertzberg, 1991; Giraud, 1998; Seiler, 1998a; Kruczynski, 1992; Chang, 1995; Sasoh, 1998; Liu, 1998).

Ram accelerator propulsive cycles are distinguished by the velocity regime in which they operate. In the subdetonative velocity regime; i.e., below the propellant Chapman-Jouguet (CJ) detonation speed, the propulsive cycle behaves as if the flow were thermally choked behind the projectile, as shown in Fig. 1a. Thermally choked ram accelerator operation has been demonstrated in the velocity range of 0.7 to 2.7 km/s with bores ranging from 25 to 120 mm. At superdetonative velocity the combustion process occurs completely within the confines of the annular region between the projectile and tube wall, as shown in Fig. 1b. Experimental investigations in the superdetonative regime carried out by Hertzberg (1991), Seiler (1998a), and Knowlen (1996) have demonstrated ram accelerator operation in the velocity and Mach number ranges of 1.8 to 2.5 km/s and 6 to 8.5, respectively.

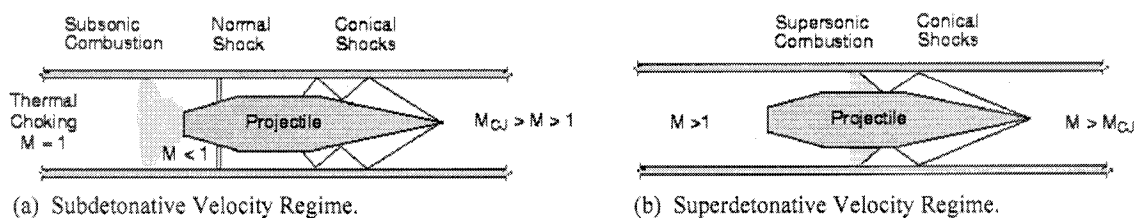


FIGURE 1. Aerothermodynamic Propulsive Cycles of the Ram Accelerator.

The most effective ram accelerator propulsive cycle in the velocity range from 0.7 to 3 km/s is, in principle, the thermally choked mode (Bruckner, 1991). This propulsive cycle operates at the lowest Mach numbers ( $2.5 < M < 4.5$ ) and has a low peak cycle pressure,  $P_{max}$ . Subdetonative experiments at velocities greater than 2.5 km/s, however, have not yet been successful using propellants with  $Q > 6$ , where  $Q = \Delta q / c_p T_1$  and  $\Delta q$  is the chemical heat release,  $c_p$  is the constant pressure specific heat, and  $T_1$  is the static temperature of the quiescent propellant (Higgins, 1998). This constraint on heat release is imposed on the propellant options for the thermally choked stages of the space launch system and limits the practical upper velocity of the thermally choked propulsive mode to  $\sim 3$  km/s in  $H_2/O_2$  propellant.

In order to reach Earth orbit velocities, ram accelerator launchers must operate with a superdetonative propulsive cycle at in-tube Mach numbers ranging from around 6 to 10. Computational studies have shown that there are several mechanisms that can initiate and stabilize combustion on the body of a projectile to accelerate it at velocities greater than the CJ speed (Yungster, 1992; Li, 1995). The projectile-to-tube cross sectional area ratio and the projectile drag are crucial factors in determining the maximum velocity capability of the ram accelerator (Knowlen, 1996). The need for ablative or transpiration cooling systems for protecting the projectile during hypersonic operation has been examined in detail by Seiler (1998b) and Bogdanoff (1998) and will not be addressed here.

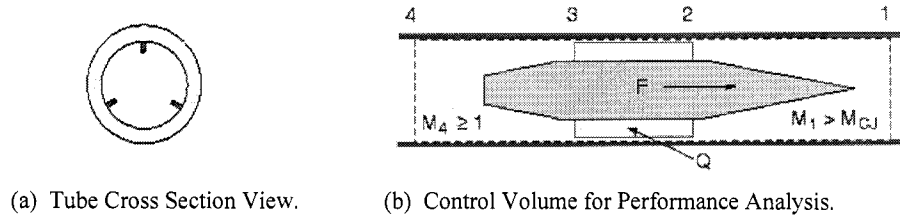
## DESIGN CONSIDERATIONS AND PERFORMANCE MODELING

The main components of the conceptual ram accelerator space launcher system are an initial launch gun, thermally choked ram accelerator section, and a superdetonative ram accelerator section (Bruckner, 1987). An initial launcher is required to accelerate the projectile from rest up to the minimum entrance velocity needed to enable thermally choked ram accelerator operation, which is approximately 0.7 km/s for  $CH_4/O_2/CO_2$  propellant. Kaloupis (1988) discusses the methane-air combustion-driven gas gun concept proposed for this purpose.

The ram accelerator sections are designed with a static pressure rating twice that of the corresponding peak cycle pressure. An ideal ram accelerator would have a propellant composition gradient that enables operation at nearly constant Mach number so that the projectile would experience minimal variations in acceleration. Although it is possible to reliably introduce mixture gradients in tubes, it may be more practical to use adjacent stages of various lengths having different propellants to control the in-tube Mach number and acceleration history of the projectile. For the system proposed here, the propellants are separated from each other with isolation valves that can be opened just prior to firing; thus, the fill pressure must be constant throughout the ram accelerator. This approach eliminates the need for the projectile to penetrate diaphragms between stages. A diaphragm at the entrance to the thermally choked section is still required; however, its effect on the projectile is negligible at 0.7 km/s entrance velocity. A frangible exit diaphragm that can be explosively burst just prior to the arrival of the projectile is preferred because it is unlikely that a large-scale valve could be opened quickly enough to keep from losing a substantial fraction of the propellant before the projectile exits the tube. The procedures used to determine the propellant composition and length of each ram accelerator stage, and the corresponding wall thickness are described below.

A large bore ram accelerator space launch system would use three rails to support axisymmetric projectiles, as shown in Fig. 2a. This allows the tube cross sectional area to be different in the thermally choked and superdetonative ram accelerator sections. The acceleration performance of both ram accelerator propulsive modes is determined in the projectile frame of reference using a quasi-steady one-dimensional analysis of the control volume shown in Fig. 2b. The Mach number dependence of the heat release parameter  $Q$  is calculated with a computer program that determines the chemical equilibria for adiabatic flow. Integration of the net thrust-velocity profile in each ram accelerator stage provides the velocity-distance history for the projectile throughout the launch system.

Brief descriptions of the flow field modeling used to predict performance for both ram accelerator propulsive modes are provided below, more detailed discussions of the numerical procedures and theoretical underpinnings can be found in Bruckner (1991) and Knowlen (1996, 1998).



**FIGURE 2.** Ram Accelerator Launch Tube Configuration and Flow Field Model.

Thermally choked ram accelerator performance is determined by calculating the chemical equilibria of the reactants and corresponding momentum flux at the exit plane of the control volume (station 4 in Fig. 2), assuming the flow is at sonic velocity there. The difference in momentum flux between the entrance and exit planes of the control volume is the theoretical net thrust, which is independent of projectile geometry under these circumstances. The detailed flow field model of the thermally choked mode assumes that the flow expands subsonically behind a normal shock on the body, which results in the peak cycle pressure occurring at the projectile base. For the propellants to be used in the proposed launcher system the resulting peak pressure is at most 20 times the fill pressure.

The ram accelerator performance in the superdetonative velocity regime is computed by assuming that all the heat release occurs supersonically in the annular throat region between the projectile and tube wall (between stations 2 and 3 in Fig. 2b), before the combustion products isentropically expand back to full tube area. Under these conditions, the larger the projectile-to-tube diameter ratio the higher the maximum velocity limit. The peak cycle pressure occurs at the position where the combustion process ceases (station 3) and is at most 50 times greater than the fill pressure. The details of the projectile drag and combustion modeling are discussed in Knowlen (1996).

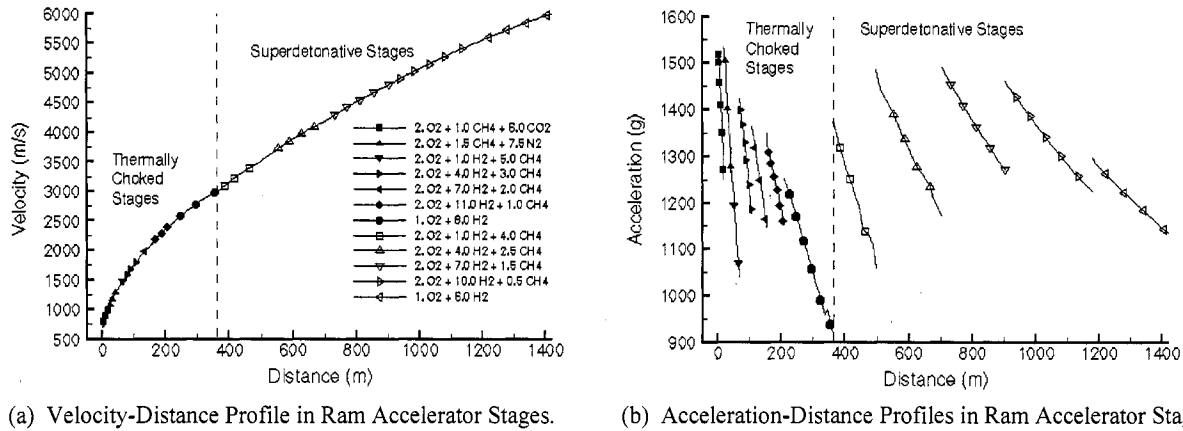
## RAM ACCELERATOR SPACE LAUNCHER PARAMETERS

The general characteristics of a ram accelerator system capable of launching a 2000 kg projectile to 6-8 km/s with a peak acceleration of 1500 g are discussed in this section. The tube walls are assumed to be fabricated from steel alloy having a yield stress of 1200 MPa and are thick enough to provide a safety factor of at least 2 based on the theoretical peak cycle pressure. This overall launch system configuration is then used as the reference case for an investigation into the design trade-off between projectile density and mass, fill pressure and acceleration, and the mass of the ram accelerator.

The projectile is a cone-cylinder-cone configuration, as shown in Fig. 2b. The half angles of the nose and rear cones are  $15^\circ$  and  $20^\circ$ , respectively. The cylindrical midbody has a diameter of 0.85 m and length 2.70 m. To enhance the flame holding capability of the projectile when operating in the thermally choked mode, the rear cone is truncated to give a 0.5 m-diameter base. For a net mass of 2000 kg, the density of this projectile is  $1000 \text{ kg/m}^3$  and its geometry is compatible with ram accelerator operation in all propulsive modes. The outer structure is used only as an aeroshell during the launch process and then discarded at the muzzle exit to release an aerodynamically stable atmospheric transit projectile. Various means of stripping the aeroshell have been proposed (Bruckner, 1992); however, the details of payload integration are beyond the scope of the work presented here.

The velocity-distance and acceleration-distance profiles of a projectile being accelerated from 0.7 to 6 km/s in the uniform fill pressure (5 MPa) ram accelerator section of the proposed direct space launch system are shown in Fig. 3. The first seven ram accelerator stages are designed for thermally choked operation in the velocity range of 0.7 to 3 km/s, and have a bore of 1.13 m to provide a projectile-to-tube diameter ratio of 0.75. The propellant, stage length, entrance and exit velocities ( $V_{in}$  and  $V_{out}$ ), and average acceleration for each stage are listed in Table 1. In accordance with experimental results, the heat release is limited to  $Q \leq 6$  in all thermally choked stages operating at velocities greater than 1.0 km/s. The entrance and exit Mach numbers of each stage are typically 3 and 3.7, respectively, which results in accelerations of  $1200 \pm 300 \text{ g}$ . The peak cycle pressure under these conditions is

100 MPa, which dictates that the wall thickness be at least 10 cm to maintain the desired safety factor. The total length of the thermally choked ram accelerator section is 362 m, which results in a tube mass of  $1.12 \times 10^6$  kg.



**FIGURE 3.** Performance of a 5 MPa Fill Pressure Ram Accelerator System for Launching an 85-cm Diameter, 2000 kg Projectile to 6 km/s. Entrance to First Thermally Choked Stage is at 0 m.

**TABLE 1. Parameters of a 5 MPa Ram Accelerator Launcher System for an 85 cm Diameter, 2000 kg Projectile.**

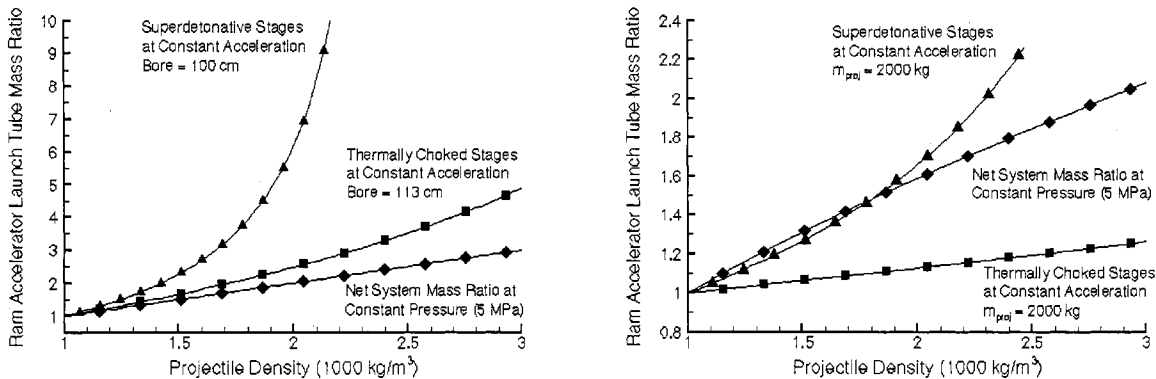
Launch Section	I.D. / O.D. (m)	Length (m)	$V_{in}$ (km/s)	$V_{out}$ (km/s)	Average Acceleration (g)
<i>Thermally Choked Stages</i>					
1.0CH <sub>4</sub> + 2O <sub>2</sub> + 6.0CO <sub>2</sub>	1.13 / 1.33	18.3	0.70	1.00	1420
1.5CH <sub>4</sub> + 2O <sub>2</sub> + 7.5N <sub>2</sub>	(all)	24.9	1.00	1.30	1410
5.0CH <sub>4</sub> + 2O <sub>2</sub> + 1.0H <sub>2</sub>		24.6	1.30	1.50	1160
3.0CH <sub>4</sub> + 2O <sub>2</sub> + 4.0H <sub>2</sub>		38.6	1.50	1.80	1310
2.0CH <sub>4</sub> + 2O <sub>2</sub> + 7.0H <sub>2</sub>		47.4	1.80	2.10	1260
1.0CH <sub>4</sub> + 2O <sub>2</sub> + 11 H <sub>2</sub>		55.3	2.10	2.40	1240
8.0 H <sub>2</sub> + 1O <sub>2</sub>		152	2.40	3.00	1080
<i>Superdetonative Stages</i>					
4.0CH <sub>4</sub> + 2O <sub>2</sub> + 1.0H <sub>2</sub>	1.00 / 1.56	135	3.00	3.50	1220
2.5CH <sub>4</sub> + 2O <sub>2</sub> + 4.0H <sub>2</sub>	(all)	206	3.50	4.20	1330
5.0CH <sub>4</sub> + 2O <sub>2</sub> + 7.0H <sub>2</sub>		200	4.20	4.80	1380
0.5CH <sub>4</sub> + 2O <sub>2</sub> + 10 H <sub>2</sub>		275	4.80	5.50	1340
6.0 H <sub>4</sub> + 1O <sub>2</sub>		242	5.50	6.00	1210
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6.0 H <sub>4</sub> + 1O <sub>2</sub>		173	6.00	6.30	1090
7.0 H <sub>4</sub> + 1O <sub>2</sub>		551	6.30	7.00	862
8.0 H <sub>4</sub> + 1O <sub>2</sub>		1240	7.00	8.00	616

The remaining stages of the ram accelerator section are designed for operation in the superdetonative velocity regime. The bore of this section is 1.00 m, which results in a projectile-to-tube inner diameter ratio of 0.85. Five superdetonative stages are used to accelerate the projectile from 3 to 6 km/s (Fig. 3) in a distance of 1058 m (dashed line in Table 1). The propellants were chosen to limit the acceleration to 1500 g while operating in the Mach number range of  $7 \leq M \leq 8$  for velocities up to 6 km/s. This resulted in an average acceleration of ~1300 g. To reach 7 or 8 km/s, extra stages are required (Table 1) in which the projectile operates up to Mach 9 or 10, respectively. The performance of the superdetonative propulsive mode decreases at velocities greater than 6 km/s because the benefits of reducing Mach number by adding more hydrogen are offset by the reduction in heat release due to the increased dilution of the fuel-rich propellant. Even though the average thrust decreases as the projectile accelerates beyond 6 km/s, reasonable length accelerator tubes are feasible for muzzle velocities up to 8 km/s. Higher acceleration could be realized in the 6 to 8 km/s range by tapering the bore; however, for the purposes of this study, the bore of the superdetonative section was kept constant. The peak cycle pressure is 250 MPa for the superdetonative propulsive mode, which results in a wall thickness of 0.28 m and launch tube masses of  $9.53 \times 10^6$ ,  $16.0 \times 10^6$ , and  $27.2 \times 10^6$  kg for muzzle velocities of 6, 7, and 8 km/s, respectively.

## RAM ACCELERATOR SCALING CONSIDERATIONS

The parameters of the reference case for a ram accelerator system capable of launching a 2000 kg projectile having a density of  $1000 \text{ kg/m}^3$  indicate that the launch tubes would not be excessively massive. Due to the length of such a system, the launch tube would be segmented and the support structure would have to maintain the precision tube alignment required for hypervelocity muzzle velocity. The technical difficulty of the support structure should not be greater than that needed for any launch system having similar average acceleration and muzzle velocity capabilities. It is of interest to consider the impact on the dimensions of the launcher if the projectile density (and thus mass) is increased. Conversely, determining what is the densest projectile having a mass of 2000 kg that can be launched is useful for evaluating the trade-off between system length and wall thickness. This information will be needed for any detailed economic study attempting to optimize the profitability of a direct space launcher system.

If a more massive payload is placed aboard the projectile, its effective density will increase. In order to maintain the same acceleration profile as the reference case, the fill pressure and  $P_{max}$  must increase in proportion to the projectile density. Since  $P_{max}$  and the bores of the thermally choked and superdetonative stages are different, the effects of increasing projectile density on the corresponding ram accelerator stages differ, as shown in Fig. 4a. Also shown is the change in net system mass due to lengthening the launcher while keeping the fill pressure at 5 MPa, thus allowing the acceleration to decrease with increasing projectile mass. Doubling the projectile density (increasing its mass to 4000 kg) results in a 2.5-fold increase in the thermally choked tube mass and 6-fold increase in the superdetonative tube mass, whereas increasing the length of the launcher to accommodate lower average acceleration only increases the system mass by a factor of 2. Tube strength is not significantly enhanced by increasing the tube O.D. above 3 times the bore, thus the practical limit of scaling the wall thickness in the superdetonative stage is reached once the projectile mass is  $\sim 4800 \text{ kg}$ , which corresponds to  $2400 \text{ kg/m}^3$  density for the projectile. Higher strength tube materials or a more sophisticated tube design (e.g., pre-stressed sleeved barrels, constraining rings, etc.) are needed to maintain the design safety factor for more massive projectiles.



(a) Increasing Projectile Mass Without Changing Geometry. (b) Scaling Projectile Geometry Without Changing Mass.

**FIGURE 4.** Ram Accelerator Tube Mass Ratio (Normalized to Mass of System in Fig. 3) as Function of Projectile Density:

Reducing the diameter of a 2000 kg projectile while maintaining the same flow area ratio reduces the bore of the ram accelerator stages; however, the fill pressure must increase to maintain the same acceleration profile. The increase in peak cycle pressure results in thicker walls, as indicated in Fig. 4b by the increase in the mass of both the thermally choked and superdetonative ram accelerator sections. The outer diameter of the superdetonative tube wall is  $\sim 3$  times the bore when the projectile density is  $1600 \text{ kg/m}^3$ , thus the acceleration performance of the reference case cannot be met in the superdetonative stages for denser projectiles without using different launch tube materials or structural design. If the ram accelerator stages were limited to a fill pressure of 5 MPa, then the acceleration would drop off at a rate inversely proportional to projectile density raised to the  $2/3$  power, and the length of the launcher would increase. Note that the increase in net system mass resulting from increasing wall thickness for higher fill pressure is less than that of lengthening the tube as the projectile density increases up to  $\sim 1800 \text{ kg/m}^3$ ; at higher projectile density the increase in launch tube mass is less for the system having 5 MPa fill pressure. It is evident that the trade-off in ram accelerator acceleration and structural expense, amongst many other details, must be considered when evaluating launch system configurations for a fixed mass payload.

## SUMMARY

The parameters have been determined for a ram accelerator system capable of launching a 2000 kg projectile having an effective density of  $1000 \text{ kg/m}^3$  at velocities of 6-8 km/s, without exceeding 1500 g. Seven thermally choked and five superdetonative stages (1420 m total length) at 5 MPa fill pressure provide an average acceleration of 1275 g in the velocity range 0.7 to 6 km/s. Two additional stages at the same fill pressure can provide an average acceleration of  $\sim 730 \text{ g}$  while keeping the in-tube Mach number below 10 to reach a muzzle velocity of 8 km/s. Sizing the wall thickness to withstand twice the peak cycle pressure results in a net steel launch tube mass of  $\sim 11 \times 10^6 \text{ kg}$  for the ram accelerator sections of the 6 km/s system. The scaling investigation found that the material strength of the tube wall (1200 MPa) limited the launch mass of an 85-cm diameter projectile to  $\sim 4800 \text{ kg}$  and the density of a 2000 kg projectile to  $1600 \text{ kg/m}^3$ . Higher strength tubes are required to handle the fill pressures needed to launch more massive or denser projectiles with the same acceleration profiles. The increase in system mass arising from lengthening the ram accelerator stages while maintaining a uniform fill pressure of 5 MPa was found to be less than that from increasing the wall thickness to accommodate operation at higher fill pressure, when the projectile diameter is constant. The results of this study indicate that a multi-stage ram accelerator system would be an effective means to launch large-scale projectiles into orbit.

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