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ANALYSIS OF RAM ACCELERATION FOR HIGH VELOCITY APPLICATIONS

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Ram acceleration is an emerging propulsion technology which appears capable of producing very high velocities with significant masses. Work at the University of Washington has demonstrated velocities in excess of 2.6 km/s in 38-mm caliber, while theory predicts velocities in excess of 10 km/s may be obtainable. Following a brief introduction to the theory of ram acceleration, advantages and disadvantages of the technology for large caliber hypervelocity applications are examined. An empirical performance analysis of a scaled-up ram accelerator (120-mm) is presented and compared to a theoretical analysis of conventional solid propulsion. A theoretical and experimental program ongoing at the Ballistic Research Laboratory to explore scaling the technology to 120-mm is then described.

14. SUBJECT TERMS
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TABLE OF CONTENTS

		Page
	List of Figures	v
	List of Tables	vi
	ACKNOWLEDGMENTS	vii
1.	BACKGROUND	1
2.	ADVANTAGES AND DISADVANTAGES OF RAM ACCELERATOR PROPULSION FOR LARGE CALIBER APPLICATIONS	2
2.1.	Advantages	2
2.1.1.	Propulsive Efficiencies	2
2.1.2.	Pre- and Post-Combustion Pressure Relationship	4
2.1.3.	Readily Available and Easily Tailored Fuel/Oxidizer	4
2.1.4.	Performance Potential	5
2.1.5.	Projectile Acceleration and Tube Recoil	5
2.2.	Disadvantages	5
2.2.1.	Preaccelerator Required	5
2.2.2.	Projectile Subcaliber by Nature	6
2.2.3.	Accelerator End Sealing Required	6
2.2.4.	Concept Unproven Beyond 3 km/s	6
3.	ACCELERATOR PERFORMANCE SUMMARY	7
4.	POTENTIAL USES OF A RAM ACCELERATOR	8
4.1.	The Ram Accelerator as a Research Tool	8
4.2.	The Ram Accelerator as a Weapon	8
5.	HYBRID INBORE RAM (HIRAM) ACCELERATOR PROGRAM	9
6.	CLOSING REMARKS	10
7.	REFERENCES	11
	DISTRIBUTION LIST	15

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LIST OF FIGURES

Figure | Page

1. Qualitative Plots of Pressure, Temperature, and Velocity for Flow Around a Ramjet Engine Centerbody in Supersonic Flow. 1

2. Qualitative Plots of Pressure, Temperature, and Velocity for Flow Around a Ram Accelerator Projectile in Supersonic Flow With Subsonic,Thermally Choked Combustion 2

3. Qualitative Plots of Pressure, Temperature, and Velocity for Flow Around a Ram Accelerator Projectile in Supersonic Flow With Supersonic, Oblique Detonation Wave Combustion 2

4. Plot Of Breech, Tube, and Projectile Base Pressure Relationships for a Conventional Solid Propulsion Cycle 3

5. Typical Pressure, Magnetic Sensor (EM), and Luminosity Data From Thermally Choked Ram Accelerator Combustion 3

6. Effective Pressure Distribution on a Ram Projectile Operating in the Subsonic-Combustion, Thermally Choked, Mode 4

7. Plot of Pre- and Post-Combustion Pressure Ratios for Several Pressurizations in 2.7 Ch_4 + $2O_2$ + $5.8N_2$ Fuel/Oxidizer/Diluent Mixtures With Approximately Same Mass Projectiles 4

8. Rear View of Projectile in Gun Tube Showing Diametric Clearance Between Projectile and Tube Walls 6

9. Schematic of Ram Accelerator End Sealing 6

10. Thrust Coefficient vs. Projectile Velocity for Several Fuel/Oxidizer/Diluent Mixtures 7

11. Velocity Versus Travel for Conventional Solid and Ram Accelerator Propulsion 8

12. 120-mm Hybrid Inbore Ram (HIRAM) Projectile Contrasted With 38-mm University of Washington Projectile 9

13. 120-mm Hybrid Inbore Ram (HIRAM) Cartridge 10

14. Overhead View of 120-mm Hybrid Inbore Ram (HIRAM) Test Facility Under Construction at the Ballistic Research Laboratory 10

LIST OF TABLES

Table | Page

1. Properties of Gas Fuel/Oxidizer Mixtures for Ram Acceleration 5

2. Potential Applications of a Large Caliber Ram Accelerator 9

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The author wishes to thank Mr. Ronald Anderson of the Ballistic Research Laboratory for his assistance in preparing the IBHVG2 data used in this report. Appreciation is also extended to Professor Adam Bruckner and the University of Washington's Aerospace and Energetics Research Program for use of and assistance in preparing data for this report. The author also wishes to thank Ms. Karen Marcou for assistance in the preparation of this manuscript.

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1. BACKGROUND

The University of Washington (UW) has pioneered inbore ram acceleration technology. While a detailed understanding of the fundamental physics and process involved is available in references (Hertzberg, Bruckner, and Bogdanoff 1986, 1988, 1987; Knowlen, Brucker, and Bogdanoff 1987; Bruckner and Hertzberg 1987; Bruckner et al. 1988a, 1988b; Kaloupis and Bruckner 1988; Bruckner, Hertzberg, and Knowlen, to be published), a brief summary of the ram process follows. Ram acceleration is related to the better known supersonic ramjet aircraft/rocket engine process. As schematically shown in Figure 1, a supersonic ramjet engine consists of an outer engine cowling (1), a centerbody (diffuser) (2), and fuel injectors and flame holders (3). In operation, air entering the engine at supersonic speeds is compressed and slowed in the inlet/supersonic diffuser while undergoing one or more oblique shocks resulting in a weak normal shock over the subsonic diffuser section. Behind this normal shock air is further compressed, then fuel is introduced into a subsonic combustion zone. The heated air/fuel products are then expanded in the exhaust nozzle lowering their static pressure as the gas velocity increases, resulting in a net forward thrust on the engine. Figure 1 shows qualitative plots of the static pressure, temperature, and velocity profiles throughout the ramjet engine.

In the inbore ram accelerator of Figure 2, a gun barrel-like tube replaces the cowling (1), the centerbody is replaced by a similarly shaped projectile (2), and the fuel injection process is replaced by a pressurized gas (fuel/oxidizer/diluent) mixture filling the gun tube (3). In operation the projectile enters the pre-fueled tube at a velocity substantially above the fuel/oxidizer/diluent sound speed. A complex series of oblique shocks occur which approach a normal shock structure behind the throat (projectile maximum diameter). A subsonic combustion zone is established behind this normal shock. Heat released in this zone creates thermal choking at a location downstream of the projectile. This thermal choking stabilizes the shock system and high pressure field on the projectile resulting in forward thrust on the projectile.

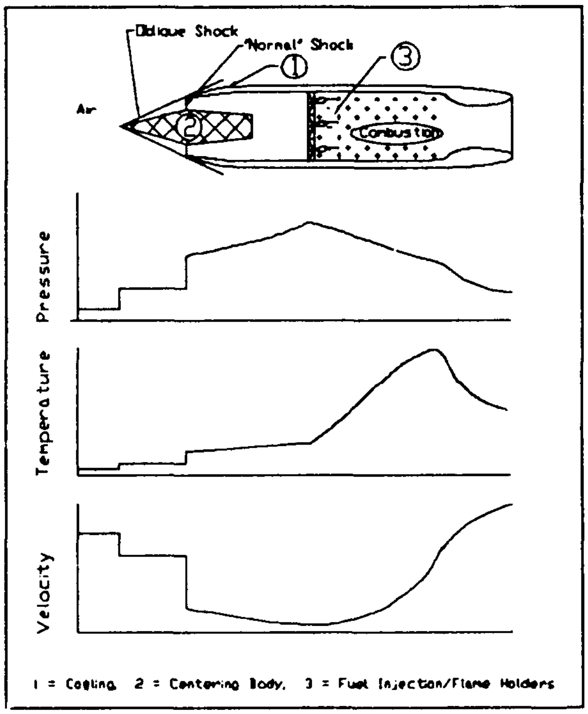


Figure 1. Qualitative Plots of Pressure, Temperature, and Velocity for Flow Around a Ramjet Engine Centerbody in Supersonic Flow.

At velocities above 3 km/s the ram projectile may proceed through several combustion regimes. These include, but are not limited to, mixed sub/supersonic combustion and fully supersonic mechanisms such as Oblique Detonation Wave (ODW) propulsion (Yungster, Eberhardt, and Bruckner 1989; Yungster and Bruckner 1989; Ostrander et al. 1987; Pratt, Humphrey, and Glenn 1987; Kull et al.

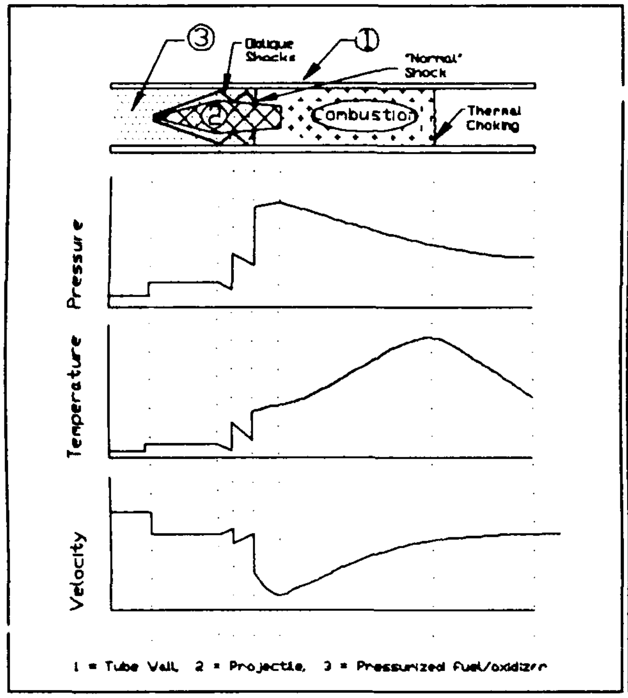


Figure 2. Qualitative Plots of Pressure, Temperature, and Velocity for Flow Around a Ram Accelerator Projectile in Supersonic Flow With Subsonic, Thermally Choked Combustion.

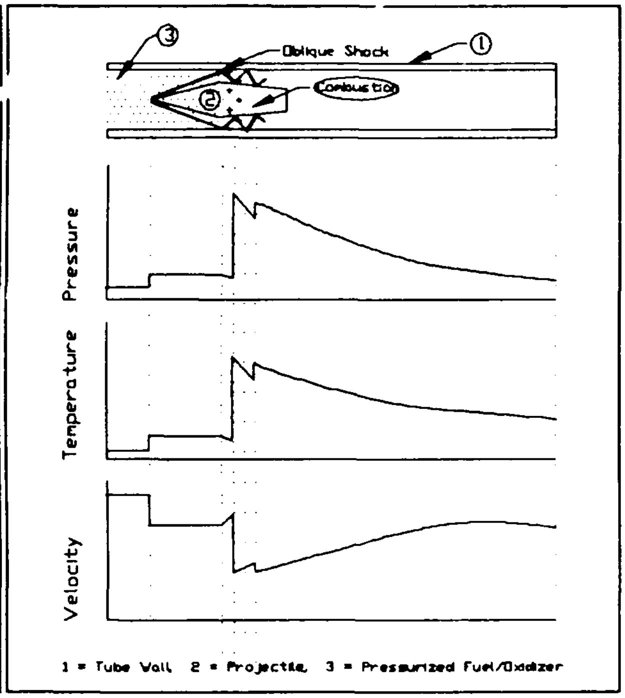


Figure 3. Qualitative Plots Of Pressure, Temperature, and Velocity for Flow Around a Ram Accelerator Projectile in Supersonic Flow With Supersonic , Oblique Detonation Wave Combustion.

1989; Burnham et al. 1985; Adamson and Morrison 1955; Lehr 1972; Pratt and Glenn 1987; Wang et al. 1988; Glenn and Pratt 1988). In this regime the oblique shock is sufficient to detonate the fuel/oxidizer. If the location of this detonation is tailored to occur behind the throat, this supersonic detonation wave may provide thrust to the projectile to velocities in excess of 10 km/s. This process is shown schematically in Figure 3.

2. ADVANTAGES AND DISADVANTAGES OF RAM ACCELERATION FOR LARGE CALIBER APPLICATIONS

2.1. Advantages

2.1.1. Propulsive Efficiencies. The primary benefit of ram acceleration is the ability to better tailor the pressure field and resultant acceleration of a projectile, as compared to conventional solid propulsion, over relatively long times and distances. Conventional chemical propulsion is quite efficient at quickly providing high propulsive pressures. However, due to the inherit nature of the pressure gradient involved, the efficiency drops off very quickly as much of the energy produced later in the cycle does not perform useful work on the projectile. This is mainly due to the fact that the propellant is burning well behind the projectile and must propel its own gases forward in an attempt to keep up with the projectile. As an example, IBHVG2 (Anderson and Fickie 1987) modeling calculations which depict the chamber, tube, and projectile base pressure profiles for a 120-mm gun,

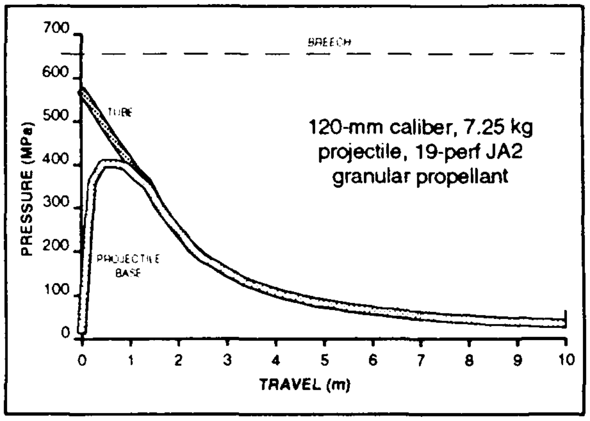


Figure 4. Plot of Breech, Tube, and Projectile Base Pressure Relationships for a Conventional Solid Propulsion Cycle.

firing a 7.26-kg (16-lb) projectile using nearly optimized 19-perforation, JA2, granular propellant are shown in Figure 4. For this calculation the peak breech pressure was fixed at 655 MPa (95 kpsi). Note that due mainly to the pressure gradient noted above, only a portion of the pressures that must be sustained by the breech, and to a lesser degree the early portions of the gun tube, act upon the projectile (for a short duration) to increase its acceleration.

Ram acceleration has, by design, a new supply of "propellant" available as it travels downbore. In addition, this gas mixture is consumed around or immediately behind the projectile. Thus a nearly constant, if somewhat oscillatory, pressure field is produced directly behind or around the projectile for the duration of the propulsion cycle. A typical pressure pulse measured at the tube wall as the projectile and associated combustion field pass is shown in Figure 5. By comparing the peak pressures measured at the tube wall during projectile passage with effective pressures to which the projectile would have had to be exposed to achieve measured velocity increases, one can infer the average efficiencies at which these peak tube wall loads are being transferred to the projectile to perform useful work. This is somewhat analogous to comparing breech and tube pressures to projectile base pressures and resultant velocities for solid propulsion as noted previously. For the ram acceleration process in subsonic combustion, this ratio of effective projectile drive pressure to maximum measured tube pressure has been termed the Thrust Pressure Ratio (TPR). Experimental data from UW firings have indicated that this value ranges from 0.15 to well over 0.70, with 0.60 being a readily achievable value for well tested fuel/oxidizer/diluent mixtures. Figure 6 plots a calculation of average tube versus projectile base pressures for a ram accelerator system operating at 655 MPa (95 kpsi) peak pressure. Note that these peak pressures are similar to those shown for the solid propulsion case of Figure 4. The advantages of ram acceleration as tube length increases become apparent by comparing Figures 4 and 6.

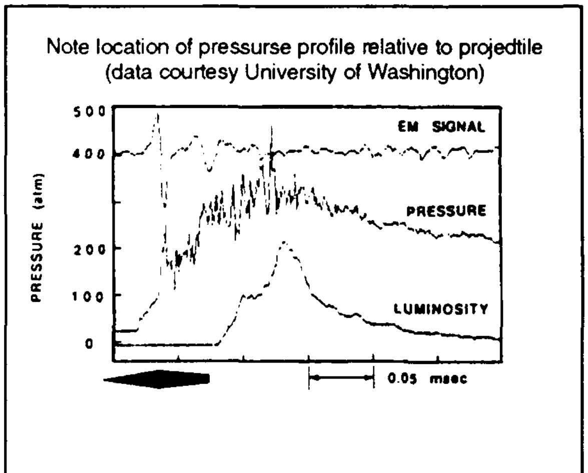
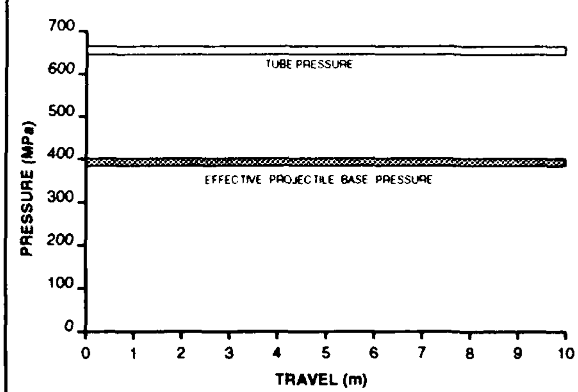


Figure 5. Typical Pressure, Magnetic Sensor (EM), and Luminosity Data From Thermally Choked Ram Accelerator Combustion.

Before leaving the subject of propulsion efficiency, it is illustrative to point out that the inbore ram acceleration process does have some similarities to the much investigated traveling charge effect, in that combustion takes place near or around the projectile base for an extended period of time providing additional thrust to the projectile beyond that from a conventional, chamber-emplaced charge. However, it differs in two important aspects: first, since the gas mixture is not carried by the projectile, but is supplied in the gun tube, there is no penalty associated with accelerating the traveling charge itself; second, in the inbore ram concept, fuel/oxidizer/diluent is always available irrespective of the propulsion cycle time/length (i.e., propellant does not burn out prematurely).



Prediction for 655 MPa system with a TPR of 0.60

Figure 6. Effective Pressure Distribution On a Ram Projectile Operating in the Subsonic Combustion, Thermally Choked Mode.

2.1.2. Pre- And Post-Combustion Pressure Relationship. Experimental work carried out to date at the UW has shown that, for most test conditions exhibiting thermally choked combustion, there is a nearly linear relationship between the gas mixture pre- and post-combustion pressures. This relationship is shown in Figure 7. If this relationship holds at high pressures, it would allow considerable flexibility in the manner in which the ram accelerator is used. For example, to launch a projectile of a given mass at a given velocity, the accelerator designer may select a tube with long travel employing gas mixtures at low pressure, or an accelerator of shorter travel using gases at higher pressure, limited only by the vapor pressure of the gases.

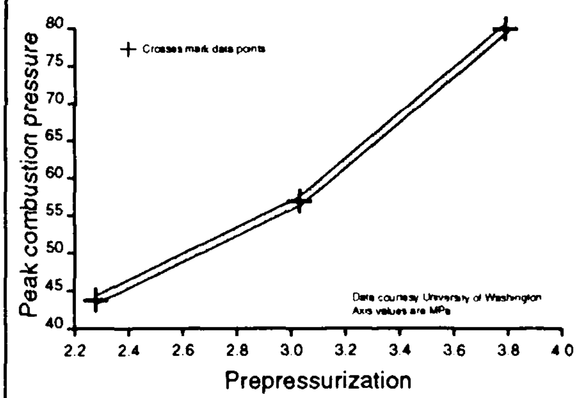


Figure 7. Plot of Pre- and Post- Combustion Pressure Ratios for Several Pressurizations in $2.7\ CH_4 + 2O_2 + 5.8N_2$ Fuel/Oxidizer/Diluent Mixtures With Approximately Same Mass Projectiles.

2.1.3. Readily Available And Easily Tailored "Propellant". It has been well demonstrated at the UW that combustion in the subsonic regime behind the normal shock is most efficient if the projectile Mach number (relative to the gas mixtures) ranges between 2.5 to 4. This Mach number, among other properties, can be adjusted by varying the gas mixtures employed. Table 1 gives several examples of how these properties can be tailored. Since the ram accelerator uses commonly available gases such as methane,

Table 1. Properties of Gas Mixtures for Ram Acceleration.

Formulas	Projectile Mach Number			Detonation Velocity (m/s)	Molecular Weight	Gamma	Density (kg/m^3)
	1	2.5	4.0				
	Projectile Velocity (m/s)						
2.6 CH_4 + 2O_2 + 5.6N_2	363	908	1452	1740	25.74	1.369	1.052
2.5 CH_4 + 2O_2 + 12He	640	1600	2560	2854	9.22	1.527	0.377
24H_2 + 2O_2	897	2243	3588	3805	4.32	1.404	0.177

Typical current (first two) and proposed gas fuel oxidizer mixtures

hydrogen, oxygen, nitrogen, and helium for fuels, oxidizers, and diluents, the necessary mix can be custom made on site for the appropriate application.

2.1.4. Performance Potential. As previously mentioned, there are well documented calculations (Hertzberg, Bruckner, and Bogdanoff 1986, 1988; Knowlen et al. 1987; Kaloupis and Bruckner 1988) that reveal that ODW ram acceleration may be capable of extremely high velocities, on the order of 10 km/s or higher. Additionally, the processes for both thermally choked and ODW ram acceleration should be scalable to very large masses. There are many attendant problems such as projectile ablation and material integrity that are unrelated to propulsion at these very high velocities; however, the requisite propulsion technology may be available in ram acceleration. Recent research at the University of Washington (Bruckner et al. 1988; Knowlen et al. 1988; Bruckner, Hertzberg, and Knowlen, to be published; Yungster and Bruckner 1989) suggests that transition from thermally choked (subsonic) combustion to mixed mode (sub/supersonic) combustion is achievable with single projectile designs and single gas mixtures. It is unclear at this point if this transition can be maintained up to and through fully supersonic propulsion schemes such as ODW.

2.1.5. Projectile Acceleration And Tube Recoil. Finally, there may be benefits of ram propulsion in terms of acceleration tailoring of sensitive cargoes, and reduced recoil loads on propulsion test beds.

2.2. Disadvantages

2.2.1. Pre-accelerator Required. As with the aircraft ramjet engine, the ram accelerator requires that the projectile have an initial velocity before the process will commence. In general, this initial velocity is on the order of several times the sound speed of the gas mixtures used. This prerequisite necessitates the use of a "start up" propulsion technique such as a light gas gun or a conventional solid propellant gun. This hybrid propulsion complicates the use of the technology in applications where total system constraints such as length, weight, and volume are fixed. However, it is a relatively minor burden for research applications unencumbered by such restrictions.

2.2.2. Projectile Subcaliber By Nature. Due to a need for a flow of propulsive gases around the ram projectile, the projectile is by design subcaliber. In practice this means that, unlike conventional projectiles, which through the use of obturators and/or sabots are full caliber, the ram projectile does not provide full bore projected area on which the propulsive pressures may act. This is illustrated in Figure 8. Current ram projectiles fill approximately 60 percent of the bore area not including projected area of the fin. Some theoretical work (Yungster and Bruckner 1989) indicates this area ratio may be increased to well above 70 percent with no penalty in efficiencies.

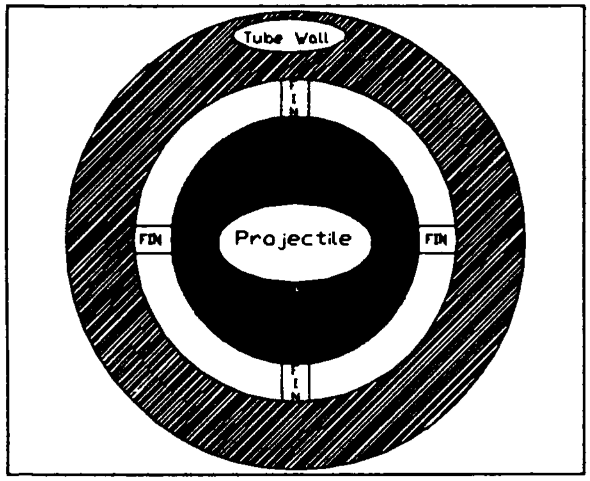


Figure 8. Rear View of Projectile in Gun Tube Showing Diametric Clearance Between Projectile and Tube Walls.

2.2.3. Accelerator End Sealing Required. The ram accelerator must currently be sealed at its ends to contain the pressurized propulsive gases as shown schematically in Figure 9. For research applications this appears to be only a minor drawback with the exception of accelerators with very high prepressures which require skillful seal design to contain the gases while presenting minimum resistance to the entrance of the ram projectile. For applications requiring rapid firing rates, end sealing requires a more complex engineering solution. There has been research (Fisher and Chandra, to be published) into eliminating the seals altogether. These techniques, a discussion of which is beyond the scope of this paper, offer the promise of both sealless systems and rapid accelerator charging.

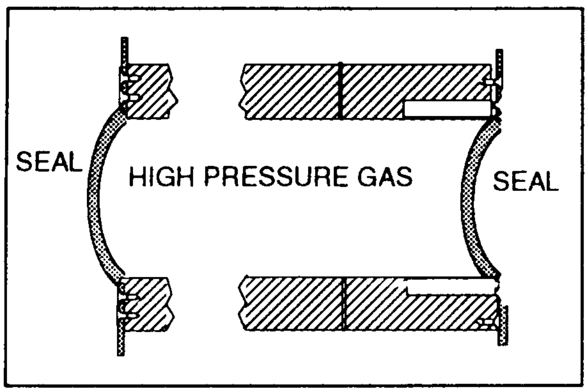
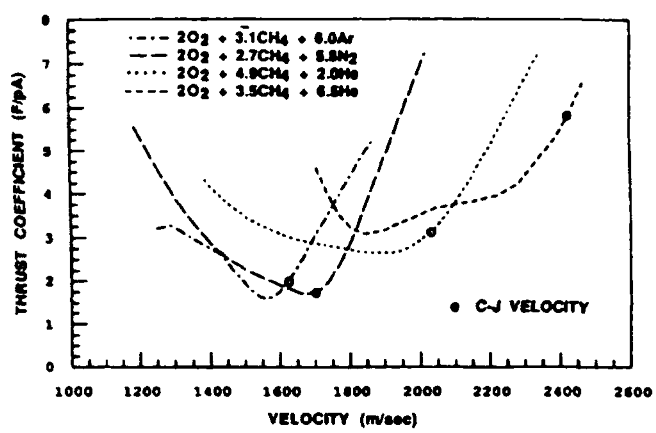


Figure 9. Schematic of Ram Accelerator End Sealing.

2.2.4. Concept Unproven Beyond 3 Km/s. As research at the University of Washington approaches projectile velocities of 3 km/s, it is becoming apparent that the underlying combustion processes are more complicated than originally believed. Previous work (Hertzberg, Bruckner, and Bogdanoff 1986, 1988; Bruckner et al. 1987; Knowlen et al. 1987) predicted that propulsion efficiencies would decrease with a single projectile shape and gas mixture as relative projectile velocity increased due to the combustion front moving further behind the projectile and would approach zero near the Chapman-Jouguet (CJ) number. Experimental results, however, differ dramatically. As shown in Figure 10, as the CJ number is approached, thrust performance increases dramatically (particularly for the lower CJ number mixes). Recent work by Nusca (1991) suggests that the combustion front is indeed moving rearward, exposing less of the projectile to the high pressure field; however, the pressure levels increase dramatically which results in a net thrust increase. It also appears that the shock structure becomes more stable above the CJ number. It is not known at this time if further transition to fully supersonic combustion can be obtained without projectile or fuel/oxidizer/diluent changes (i.e. higher cone angles and/or higher CJ number mixes). However, these recent findings suggest that combustion modes not previously demonstrated are obtainable.

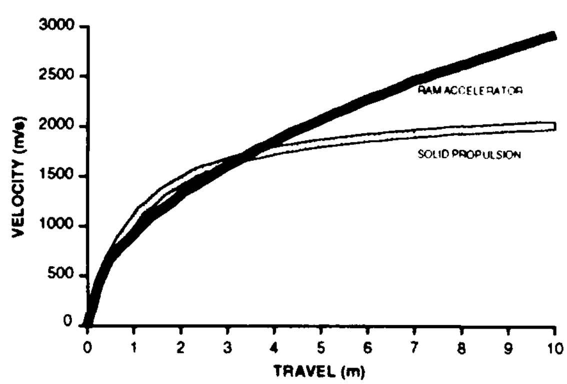


Note the trust upswings beyond the Chapman-Jouguet number (data courtesy University of Washington)

Figure 10. Thrust Coefficient vs. Projectile Velocity for Several Fuel/Oxidizer/Diluent Mixtures.

3. ACCELERATOR PERFORMANCE SUMMARY

Velocity versus travel plots for the conventional and ram propulsion processes previously discussed (Figures 4 and 6) appear in Figure 11. The conventional calculations were performed using the IBHVG2 lumped-parameter interior ballistic code with a Pidduck-Kent pressure gradient (Anderson and Fickie 1987). Ram calculations were performed using a modified constant base pressure algorithm. The calculations assume that the gun tube is capable of operating at pressures of 655 MPa (95 kpsi) over the entire length of travel. For comparative purposes both projectiles are started from rest and a maximum tube pressure of 655 MPa is applied. In the conventional case this implies a very quick ramp up in pressure followed by a quick fall off as the projectile moves down bore and volume is opened up faster than gases can be generated to fill it. For the ram process the 655 MPa pressure on the tube is held constant for the entire length of travel. Note that neither the conventional projectile nor the ram projectile experience the complete 655 MPa pressure at its base. In the



Calculations shown are for 7.25 kg projectile in 120-mm caliber system.

Figure 11. Velocity vs. Travel for Conventional Solid and Ram Accelerator Propulsion.

conventional case, the peak base pressure occurs 0.70 meters from the start of travel and is 62 percent of the breech pressure or 403 MPa and then quickly falls off. For the ram projectile an average base pressure of 60 percent of tube pressure or 393 MPa is applied to the projectile as it travels downbore (a TPR of 0.60). Additionally, in the ram accelerator calculation the effective base pressure is applied only to the subcaliber projected base area (70 percent of bore), unlike the conventional calculation which uses the full bore area as projectile base area.

Note that for the conditions in this calculation the ram accelerator begins to overtake the performance of a conventional propulsion system after 3.5 meters of travel. This type of system specific evaluation is useful in revealing where the ram accelerator performance benefits lie as well as pinpointing optimum take-over points (transition to ram propulsion) for hybrid systems.

Since these calculations represent a nearly optimized conventional propulsion system which is well understood, it is unlikely that the conventional performance could be increased significantly. However, potential increases in the ram projectile diameter and efficiency of the combustion process may improve the ram accelerator performance further.

4. POTENTIAL USES OF A RAM ACCELERATOR

4.1 The RAM accelerator as a research tool. As a technique for generating high velocities with projectiles/payloads of significant mass where the length of the system and the firing rates are not critical, the ram accelerator appears quite promising. Table 2 presents some of the generic uses for such a technique. Ram acceleration has been and continues to be considered for use in programs ranging from the National Aerospace Program (NASP), Strategic Defense Initiative (SDI) applications, and Air Force and Army hypervelocity programs. There is also considerable interest in the European research community centered around efforts at the Institute for French-German Research located in Saint Louis, France where both 38- and 90-mm ram accelerators are being constructed.

4.2. The RAM accelerator as a weapon. There is, at present, too little known about the physics and engineering of the ram acceleration process (scaling, system charging, hybrid effects, performance, etc.), to make any definitive statements regarding its use in mobile, rapid firing systems. However, there may be implementations in the near future for fixed position, low firing rate applications such as ground based interceptors.

Table 2. Potential Applications of a Large Caliber Ram Accelerator.

- IMPACT STUDIES
  - HIGH VELOCITY AND / OR MASS STUDIES OF:
    - PENETRATION
    - LETHALITY
    - MATERIALS ANALYSIS
- PROJECTILE / VEHICLE STUDIES OF:
  - ABLATION
  - STRUCTURAL INTEGRITY
  - FLIGHT DYNAMICS
- PROPULSION STUDIES OF:
  - RAM / SCRAM ANALOGY STUDIES
  - GAS DYNAMICS AND HEAT TRANSFER AT HIGH MACH NUMBERS

5. THE HYBRID INBORE RAM (HIRAM) ACCELERATOR PROGRAM

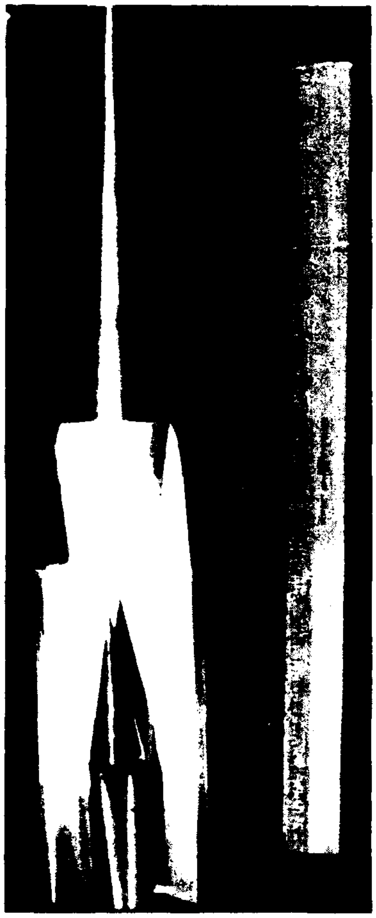


Figure 12. 120-mm Hybrid Inbore Ram (HIRAM) Projectile Contrasted with 38-mm University of Washington Projectile.

The US Army Ballistic Research Laboratory (BRL) has initiated a research program to examine the feasibility of inbore ram acceleration technology for large caliber hypervelocity launch, flight, and penetration studies. The primary goal of this effort is to examine the basic physics and chemistry of the process in sufficient detail to support the design and fabrication of a 120-mm ram accelerator research facility. Additionally, BRL will support assessment of inbore ramjet technologies for tactical and strategic applications as the technology matures.

The progress to date in the analytical and modeling areas is beyond the scope of this paper and is partly covered in other references (Nusca 1991a, 1991b). The remainder of this paper is devoted to the engineering and experimental aspects of the HIRAM program.

The selection of 120 mm for the scale up is based on several factors. First, facilities currently exist in this caliber which can be modified for use as both a preaccelerator and the accelerator itself. The preaccelerator will be a standard 120-mm tank gun using standard and advanced solid propellants. The accelerator sections will be mounted in a preexisting facility modified for such use. Secondly, it was deemed desirable to demonstrate the scaling capabilities in a system capable of achieving high velocity launches of significant masses of interest to the ballistics research community, (i.e., 5-10 kg). A scaled up version of the UW projectile is shown in Figure 12 contrasted with a typical UW 38-mm projectile. The projectile assembled in a cartridge for firing in a 120-mm accelerator is depicted schematically in Figure 13.

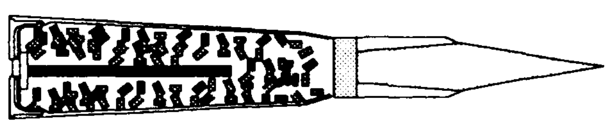


Figure 13. 120-mm Hybrid Inbore Ram (HIRAM) Cartridge.

This projectile with a granular charge propulsion package has been tested in conventional 120-mm gun firings to velocities of 1500 m/s and should be capable of preaccelerator injection velocities exceeding 2000 m/s.

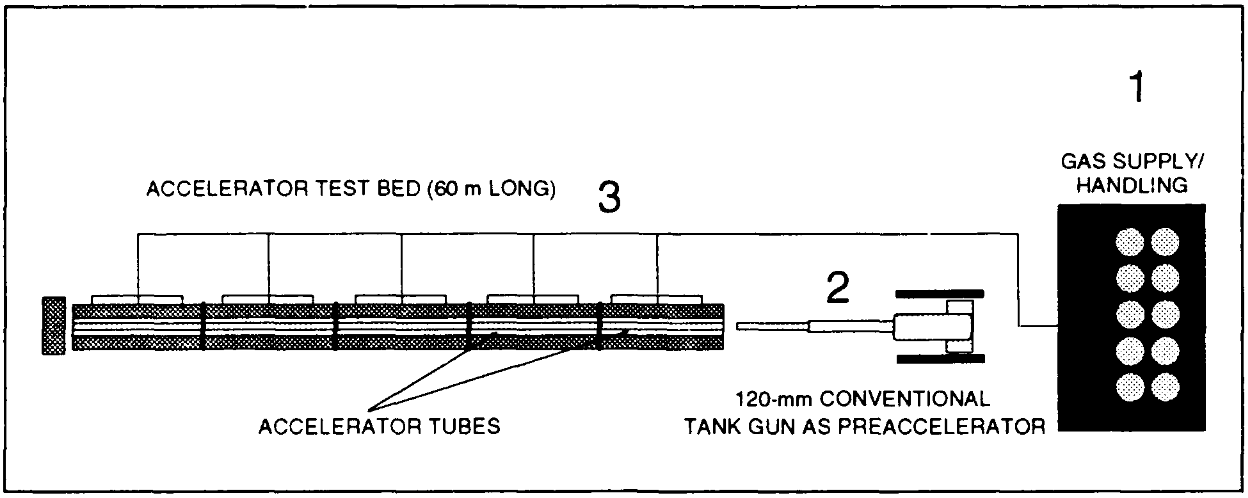


Figure 14. Overhead View Of 120-mm Hybrid Inbore Ram (HIRAM) Test Facility Under Construction at the Ballistic Research Laboratory.

system capable of handling combustible and inert gases to pressures of 34.5 MPa (5 kpsi). These gases include but are not limited to methane, hydrogen, helium, oxygen, and nitrogen. The gases selected will be pumped individually into accelerator sections mounted in a test bed downbore of the preaccelerator. The gases will be mixed by partial pressure in one or more accelerator sections mounted in the accelerator test bed. The accelerator test sections will initially be made from retired 120-mm gun tubes appropriately sectionalized, sealed, and mated. It is anticipated that up to three sections each of 4.7 meters in length will initially be employed. The accelerator test bed is capable of mounting up to 60 meters of accelerator sections.

Since standard 120-mm gun tubes will be initially used, the maximum accelerator post-combustion pressures will be limited to 207 MPa (30 kpsi). It is hoped to eventually have custom tubes made, capable of constant pressures of 690 MPa (100 kpsi) over their entire length, to fully exploit the advantages of ram acceleration.

6. CLOSING REMARKS

Ram acceleration has been demonstrated in medium caliber to velocities approaching 3 km/s. Theoretical calculations predict that the propulsion technology may be capable of delivering significant masses to velocities over 10 km/s. The technology appears viable for near-term use in laboratory hypervelocity launchers and fixed position low firing rate weapons. The Ballistic Research Laboratory has initiated a program of theoretical and experimental studies to scale the technology to 120-mm caliber for laboratory hypervelocity studies of launch, flight, and terminal ballistics. Assessment of potential for tactical applications will continue as the technology matures.

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