performed across a range of entrance velocities, propellant mixtures, and projectile/sabot configurations to be applicable for a variety of starting conditions.

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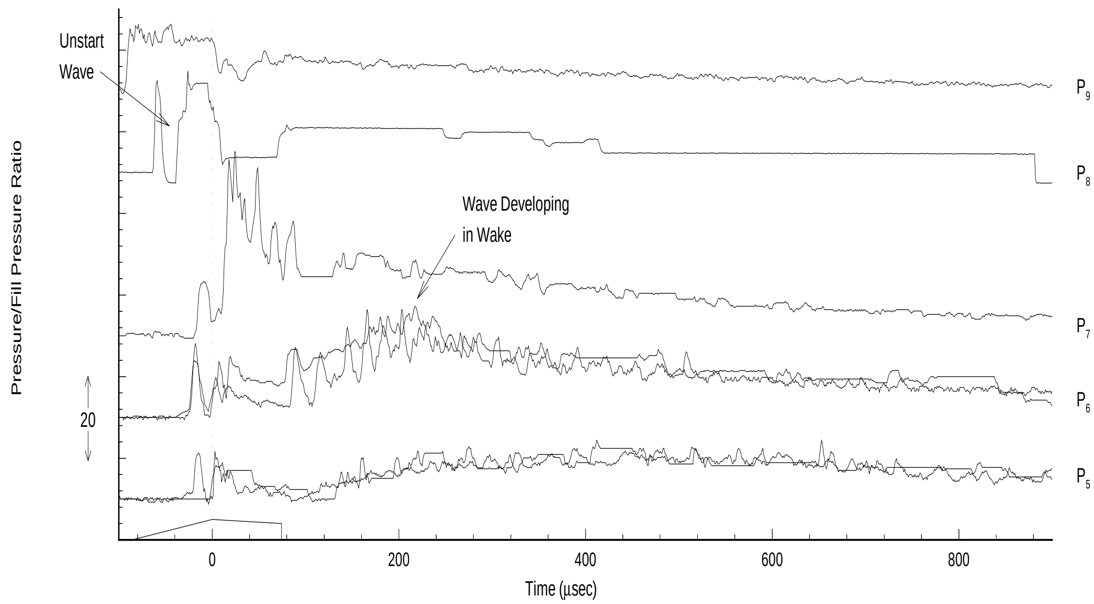
The sensitivity to low entrance velocity starting of the ram accelerator is not surprising. For example, chemical reaction rates are exponentially dependent upon temperature. A very slight change in temperature, which could be related to an even smaller change in Mach number (post-shock temperature is roughly proportional to the Mach number squared), may cause radically different results in a chemically reacting environment. This is one possible explanation for the sharp difference in ram accelerator starting results observed for small changes in velocity, sabot mass, and diluent concentration. Numerous contributing factors exist which create a very complex environment to study: chemistry properties such as energy content, reaction rates, activation energies, induction times, and sounds speeds; projectile properties such as nose geometry, body geometry, mass, and velocity; sabot properties such as mass and perforations; and a host of other parameters such as launch tube vacuum, light gas blow-by, and entrance diaphragms, just to name a few.

A second low entrance velocity start experimental series will be executed at the in the Spring of 1996. Shots will be made in methane and oxygen based mixtures with nitrogen diluent. These mixtures are currently the primary propellants used in the ram accelerator. The sound speed of these nitrogen diluted mixtures is higher, so the flow throat area about the projectile will be expanded to allow lower Mach number operation before a Kantrowitz unstart occurs.

Future research into low entrance velocity starting of the ram accelerator will include determining ignition limits for propellant mixtures of interest to ram accelerator operation. Highly desirable mixtures will have a broad envelope in which a stable combustion wave can be created, and which are difficult to detonate. Development of a rough ignition envelope through shooting pistons into mixtures of interest may be the most efficient way to generate ignition limit envelopes. Correlation of the piston shot ignition limits to those observed for the projectile/sabot combination will provide a rough ram accelerator starting envelope. This process can be stations 5 and 6. At station 7 a strong normal shock system exists just behind the throat, and then surges past the throat in a wave unstart at station 8. Interpreting the phenomena occurring during this shot is difficult with the available data. The pressure spike ahead of the throat remains a mystery. As for the pressure history behind the throat, perhaps the flow on the projectile ignited, quenched, and then re-ignited again. Or maybe the normal shock system at station 1 receded from the body without ever igniting the flow. A combustion wave may have been generated far back in the wake of the projectile, caught up to, and then overran the projectile. This phenomenon is similar to the results of combustion stripping experiments reported in Ref. 6. The combustion wave was stripped from a driving projectile by passing through an inert gas filled tube and then re-entering a combustible mixture. A combustion wave was observed to form in the projectile wake and then to overrun the projectile. The velocity history of this process caused the projectile to accelerate while initially in the combustible mixture, decelerate once the combustion was stripped, and then accelerate to a wave unstart upon combustible mixture re-entry.

Conclusions

Low entrance velocity starting of the ram accelerator seems to be a very sensitive process. At low velocities, the projectile and sabot generate conditions less conducive to igniting the propellant mixture. This leads towards the use of more reactive, “hotter”, mixtures which can be ignited by a low velocity projectile and sabot. Once these hotter mixtures ignite, however, their increased reactivity tends to cause an immediate wave unstart, sometimes resulting in a detonation of the mixture. Ignition of cooler, less reactive mixtures at lower velocities can be achieved by use of a more massive solid sabot. There are indications that as the sabot becomes more massive it can drive the normal shock system past the projectile throat, regardless of whether or not the mixture ignites. So there may be a limit to the amount of cooling the mixture and increasing the mass of the sabot that can be done to try to achieve a successful start.



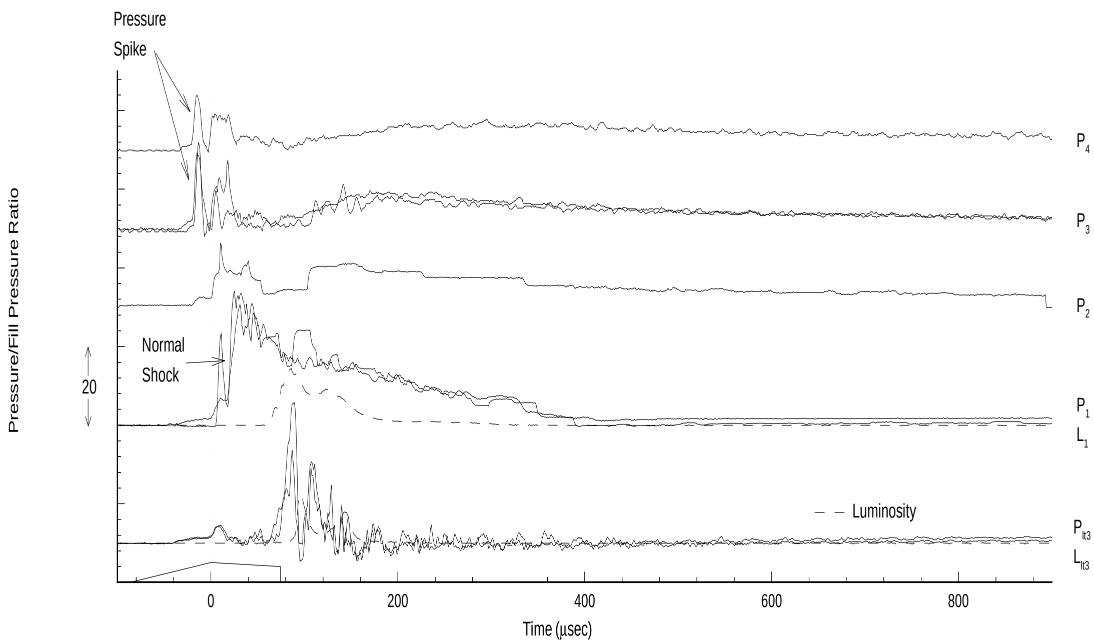


Fig. 17. Tube wall pressure and luminosity traces from HS1209.

experiments were to small changes in entrance velocity. A closer examination of the velocity histories for HS1206 and HS1207 reveals that these two experiments had entrance velocities differing by only 20 m/s into the same propellant mixture. Both shots resulted in a wave unstart, but with a slightly faster entrance velocity HS1207 resulted in a detonation. HS1207 luminosity data also indicate the presence of combustion, whereas HS1206 luminosity data do not.

The pressure wave velocity was measured following all wave unstarts, and one of two profiles was always observed. Either the shock moving down the tube ahead of the projectile was steadily decaying in velocity, or it was traveling at approximately V_{CJ} for the propellant mixture. It is interesting to note that when combustion was indicated by luminosity at instrument stations 2 or 3, the wave unstarts always resulted in a detonation wave traveling down the tube. When combustion was not indicated by luminosity at stations 2 and 3, the unstart wave velocity steadily decayed. These phenomena may indicate that when the propellant was able to ignite, it immediately detonated, causing the wave unstart. This hypothesis points again to finding cooler mixtures which will combust without overrunning the projectile throat. The phenomena may also indicate that wave unstarts occurring without resulting in detonation had little to do with combustion, but rather caused by the sabot overdriving the normal shock system past the throat.

As previously mentioned, HS1209 demonstrated slight acceleration, gradual deceleration, and then acceleration followed by a wave unstart. Whether or not this shot represents a borderline case of a successful start will have to be left to future experiments, but it is worthwhile to analyze the data from the experiment and speculate as to what may have occurred. The tube wall pressure and luminosity data from HS1209 are presented in Fig. 17. A strong normal shock system is on the projectile base at lt3, expands and surges up to just behind the throat at station 1, and then seems to disappear. A pressure spike appears ahead of the nose at station 3, and remains there until the wave unstart occurs. The wave in the wake of the projectile increases in strength by

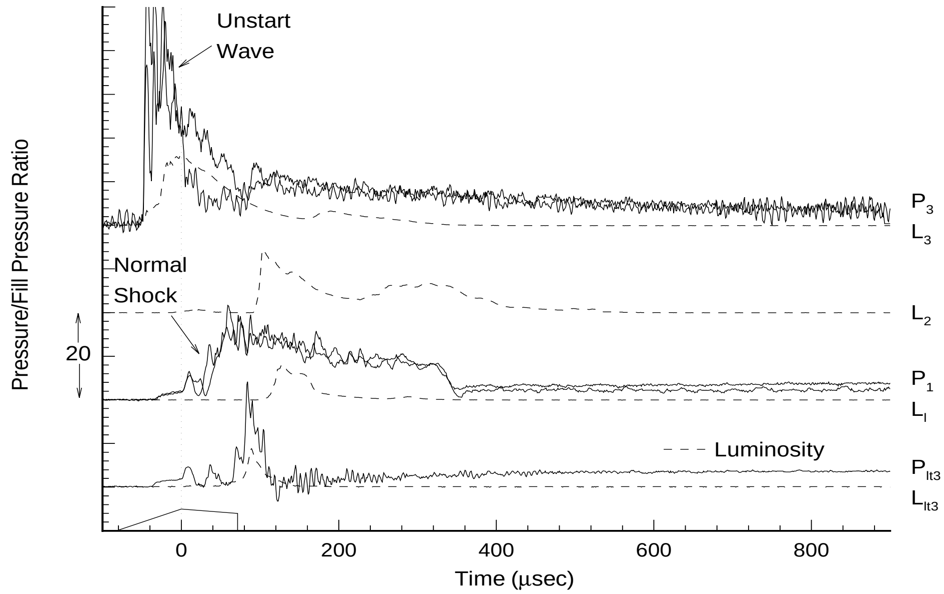


Fig. 16. Tube wall pressure and luminosity traces from HS1191.

high pressure ratio of the unstart wave is indicative of the mixture detonating. The luminosity traces show regions of combustion with the normal shock system.

A close look at all of the velocity versus distance data plots reveals that all of the shots exhibited some initial increase in velocity after piercing the entrance diaphragm. Possible contributing factors to this acceleration include the helium still accelerating the projectile once in the ram accelerator tubes. The normal shock system on the projectile body also generates high base pressure, accelerating the projectile momentarily. Notice that the initial velocity increase in the wave fall-off cases is greater for those projectiles shot with more massive solid sabots. This observation supports the hypothesis that the more massive solid sabots create a stronger normal shock system on the projectile body.

Previously mentioned was the sensitivity of these experiments to small variations in the amount of CO_2 diluent. For the same entrance velocity and sabot configuration, a change of CO_2 by as little as 0.1 mole produced a very different result. Also notice how sensitive these

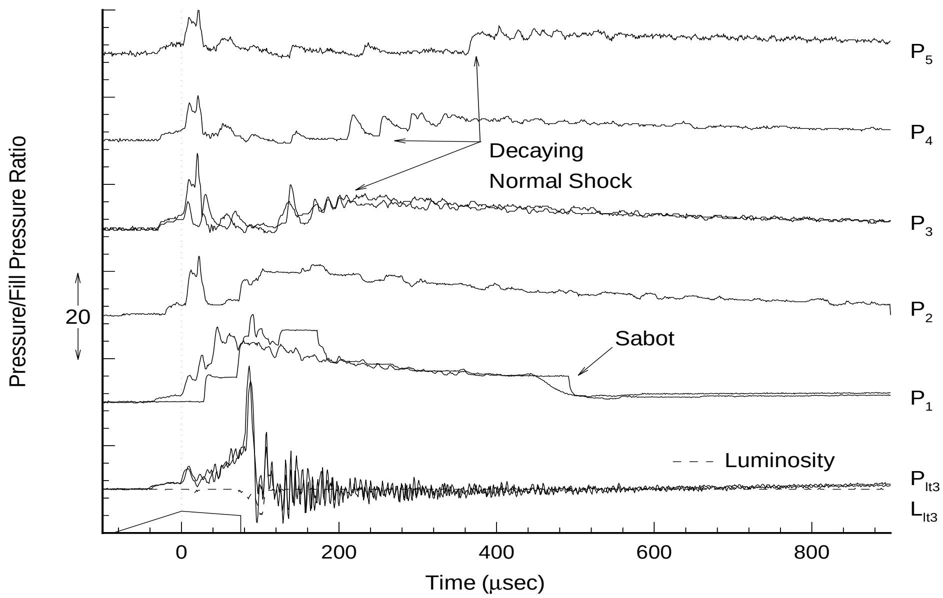


Fig. 15. Tube wall pressure and luminosity traces for HS1205.

Tube wall pressure and luminosity data from the first several instrumentation stations after the entrance diaphragm for HS1205 are presented in Fig. 15. These data traces are representative of the experiments in which a wave fall-off occurred. The normal shock system is initially just behind the throat, but recedes and falls off the body as the projectile travels down the tube. These traces look very similar to those presented for the non-reactive shot in Fig. 10, except for the speed with which the normal shock system decays behind the body. The increased residence time and strength of the normal shock system is a result of the more massive sabot used. This also caused a much larger initial acceleration than the non-reactive shot experienced.

Tube wall pressure and luminosity data from the first several instrumentation stations after the entrance diaphragm for HS1191 are presented in Fig. 16. These data traces are representative of the experiments in which a wave unstart occurred. The normal shock system is initially near the projectile base. As the projectile travels down the tube, the normal shock system moves closer to the throat. Finally, the shock system surges past the throat and unstarts the projectile. The very

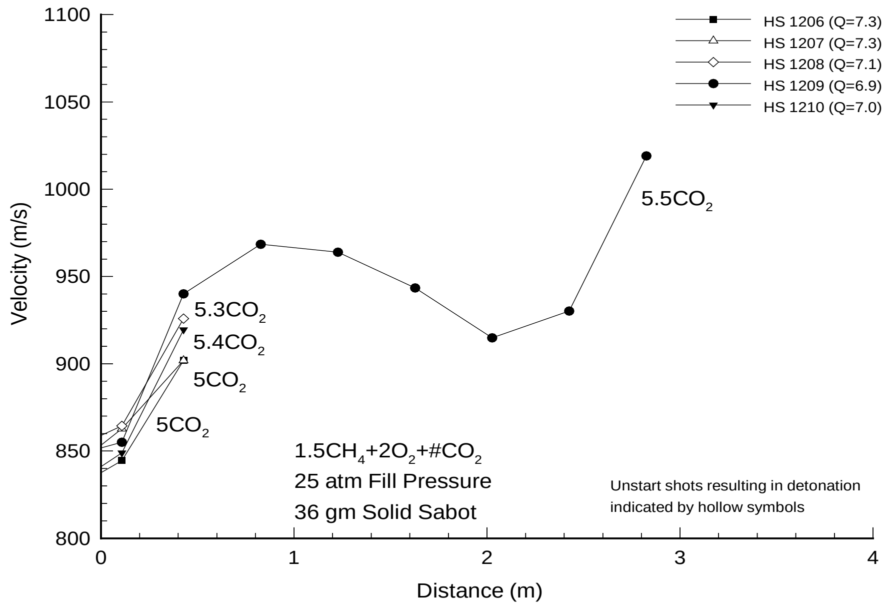


Fig. 14. Velocity versus distance data for 850 m/s entrance velocity with 36 gm solid sabot.

fall-off to wave unstart margin at 850 m/s entrance velocity with a 26 gm solid sabot is between 4.9 and 4.8 moles of CO_2.

The solid sabot mass was increased further to ignite a cooler mixture which wasn't so reactive as to immediately cause the combustion region to overrun the projectile. The velocity versus distance data from the 850 m/s entrance velocity experiments with a 36 gm solid sabot are presented in Fig. 14. Again, ram acceleration was exhibited in even cooler mixtures. None of these shots exhibited wave fall-off, but immediate wave unstarts occurred up to CO_2 amounts of 5.4 moles. HS1209, a shot at 5.5 moles of CO_2, accelerated, decelerated, and then accelerated again before wave unstarting almost 3 m down the tube. This result is different from any shot in this experimental investigation, and may have been an indication of an area where stable ram acceleration could be achieved. Unfortunately, all projectile resources were expended by this time.

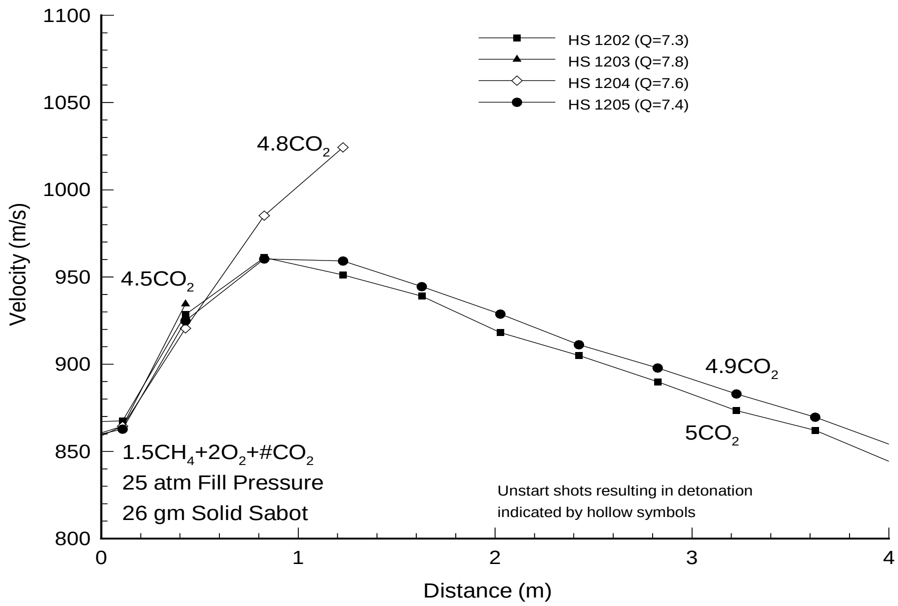


Fig. 13. Velocity versus distance data for 850 m/s entrance velocity with 26 gm solid sabot.

throat. In all shots where ram acceleration occurred, the projectile did not drive more than 1.4 m before unstarting.

If cooler mixtures, that is mixtures with greater amounts of CO_2, could be ignited, perhaps the combustion region would not overrun the projectile throat so that longer distances of ram acceleration could be achieved. In an attempt to investigate this hypothesis, the sabot was made solid and more massive. All shots with this sabot design were conducted at 850 m/s entrance velocity.

The next four shots were performed with a 26 gm solid sabot. Velocity versus distance data from these shots are presented in Fig. 13. Cooler mixtures were ignited; a wave unstart was observed at 4.5 moles of CO_2 with the 26 gm solid sabot whereas a wave fall-off occurred at the same CO_2 level with the 16 gm perforated sabot. However, the trend of high sensitivity to the amount of CO_2 between wave fall-off and wave unstart in a short distance remained. The wave

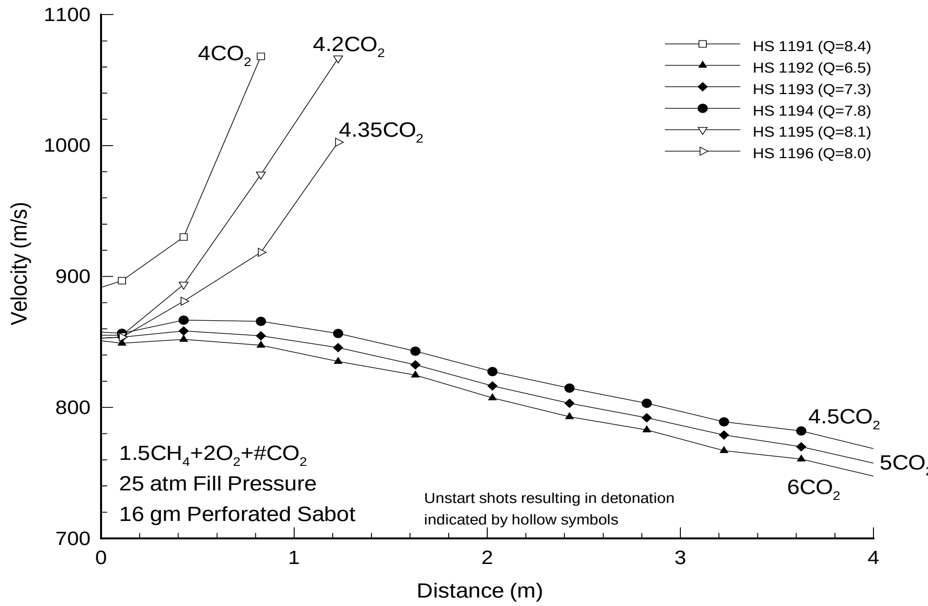


Fig. 12. Velocity versus distance data; 850 m/s entrance velocity with 16 gm perforated sabot.

velocity versus distance data plots for the 780 m/s and 850 m/s entrance velocities, respectively. The CO_2 concentration was varied for each shot to try to obtain propellant ignition and long ram acceleration distance. The CO_2 mole number was varied in increments as small as 0.15 moles. Results from both entrance velocities indicate a very high sensitivity to the amount of CO_2 diluent in the mixture. Taking the 850 m/s case for instance, at 4.5 moles of CO_2 a wave fall-off occurs as the projectile decelerates down the tube, while at 4.35 moles of CO_2 the propellant seems to ignite as the projectile rapidly accelerates and then wave unstarts 1.4 m past the entrance. Very similar results are observed at entrance velocities of 780 m/s, although it is worth noting that the same results occurred at lower CO_2 concentrations. The wave fall-off to wave unstart margin at 780 m/s entrance velocity is between 3.9 and 3.8 moles of CO_2, while for 850 m/s entrance velocity this margin falls between 4.5 and 4.35 moles of CO_2. Qualitatively the data indicate that a mixture with too much CO_2 resulted in the driving wave falling off the projectile body. Conversely, too little CO_2 caused ignition, but the combustion wave quickly overran the projectile

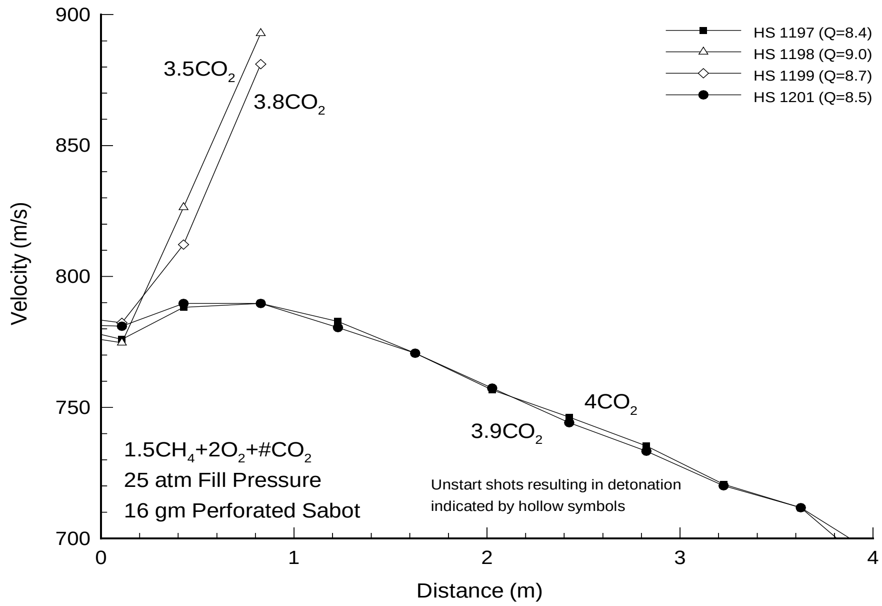


Fig. 11. Velocity versus distance data; 780 m/s entrance velocity with 16 gm perforated sabot.

synchronized with the pressure trace data. The consistent operation of the luminosity sensors is very erratic, but when light is detected this is taken as evidence of some form of combustion. Examination of the pressure traces reveals an initial slight rise in pressure on the tube wall due to the conical shock generated by the nose tip. A series of pressure spikes that follow this rise are created by multiple oblique shock reflections between the projectile and the tube wall. Stations lt3 and 1 show an area of high pressure (the normal shock system) on the rear end of the projectile. In pressure traces 3, 4, and 5 it is evident that this shock system falls away from the body, a “wave fall-off”. In Fig. 9, a Kantrowitz unstart is indicated by the greater than normal deceleration of the projectile approximately 7.4 m down the tube. The projectile velocity of 665 m/s at unstart corresponds to a Mach number of 2.3 in this mixture, which is in excellent agreement with the quasi-one dimensional theoretical prediction from Eq. 1.

The next ten shots into reactive mixtures were performed with the standard 16 gm perforated sabot at 780 m/s and 850 m/s entrance velocities. Figs. 11 and 12 are projectile

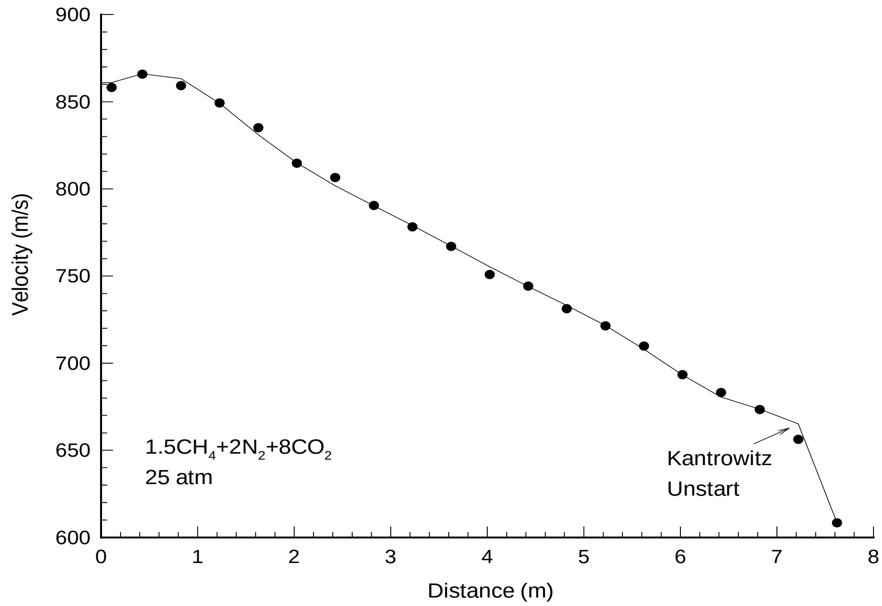


Fig. 9. Velocity versus distance data for shot into non-reactive mixture.

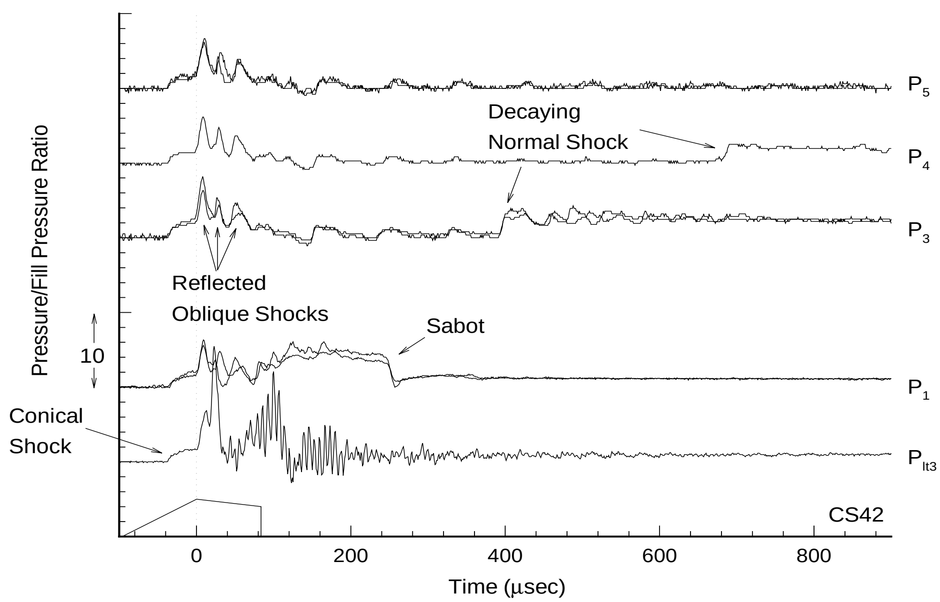


Fig. 10. Tube wall pressure traces for shot into non-reactive mixture.

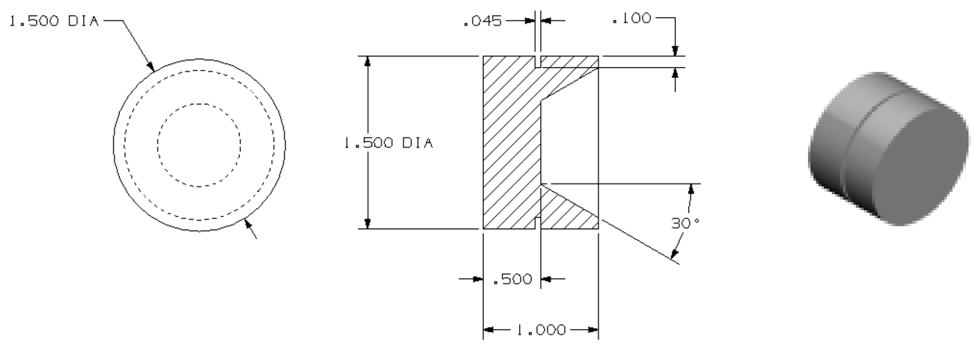


Fig. 8. Solid sabot with a Bridgman seal.

to prevent blow-by from the light gas pre-launcher, as the sabot base expands under the gas pressure to fill the entire tube area. The lack of perforations in the solid sabot results in a stronger normal shock system and faster sabot deceleration. Thus, although a solid sabot generates a stronger normal shock system with a higher temperature ratio, the shock may have less residence time on the projectile body.

Experiment Results and Discussion

The first shot was into a non-reactive mixture of $1.5CH_4+2N_2+8CO_2$ to collect tare velocity, pressure, and luminosity data for subsequent shots in reactive mixtures. A velocity versus distance history is plotted in Fig. 9, followed by tube wall pressure data in Fig. 10 from the first several instrumentation stations after the entrance diaphragm. A projectile outline, scaled to the average velocity, is sketched in Fig. 10 to illustrate the projectile location relative to the pressure data. When two pressure traces appear on top of one another, this indicates the presence of two pressure transducers opposite each other at one instrumentation station. This “symmetry view” provides a rough estimation of the projectile canting (Ref. 5). If a data trace appears to be omitted, the transducer was determined to have provided a faulty signal. Where the luminosity sensors detected light emission, luminosity data traces are indicated by dashed line time experiments, such as the projectile design, launch tube vacuum, entrance diaphragm thickness, and tube conditions, were kept as constant as possible from one experiment to the next.

780 m/s and 850 m/s were the entrance velocities used in these experiments. A higher velocity versus a lower velocity results in increased Mach numbers, providing a greater margin above the Kantrowitz Mach number to keep the diffuser started. The projectile imparts more energy to the flow at higher velocities, potentially increasing the chance for ignition of the propellant mixture. The higher velocity sabot creates a stronger normal shock system on the projectile body upon entrance, thereby increasing the temperature ratio across the shock system and again increasing the chance for propellant ignition. A faster projectile may also decrease the chance of the normal shock system moving forward fast enough to overrun the projectile throat.

Propellant composition was changed by varying the amount of CO_2 diluent. Increased CO_2 concentration decreases the mixture sound speed, resulting in a higher Mach number for a given velocity. The addition of more CO_2 also "cools" off the mixture by lowering the energy content (Q) and limiting the mixture reactivity. These effects presumably drive ignition limits higher, in that more energy must be added to ignite the propellant.

Sabot design was the third parameter varied. The mass of the sabot was increased two times from the 16 gm standard in 10 gm increments. Since the kinetic energy of the sabot is proportional to its mass, a more massive sabot will have more energy available to impart upon the flow for a given velocity. Higher energy input to the propellant increases the chances of ignition. A more massive sabot will also decelerate less quickly and therefore affects the flow field about the projectile for a longer period of time. This could increase the residence time of the normal shock system on the projectile body to increase the chances of propellant ignition. The sabot geometry was also modified from the standard design of a perforated obturator with backplate to a solid sabot with a Bridgman seal, as shown in Fig. 8. The Bridgman seal on the solid sabot exists

Methane (CH_4) and oxygen (O_2) are the primary fuel and oxidizer in the University of Washington ram accelerator. Carbon dioxide (CO_2) has a very low sound speed that makes it ideal for keeping the projectile Mach number above the Kantrowitz Mach number during low velocity starts. Methane and oxygen mole numbers were fixed at 1.5 and 2, respectively, throughout all of this experimental series. A slightly fuel-rich mixture was chosen based on past experience that this condition provides more consistent results and less projectile erosion. The carbon dioxide mole number was varied from 3.5 to 8 over the course of the experiments to tailor the mixture sound speed and reactive properties. The mixture fill pressure was always 25 atm, limited by a combination of the facility's gas handling system and carbon dioxide's low liquefaction pressure at room temperature. The University of Washington gas handling system provides absolute mixture accuracy to within 5%, with the relative precision when varying mixtures of approximately 1%.

The instrumentation stations following the entrance diaphragm are labeled "lt3", "1", "2", "3", and so on. Station lt3 is located 12 mm after the entrance diaphragm, followed by station 1 227 mm down the tube, and then approximately 400 mm between subsequent stations. All stations were instrumented with electromagnetic transducers and piezoelectric pressure transducers. Stations lt3 through 3 also contained fiber optic luminosity sensors. The pressure transducer located at station 1 is designated P_1, while the luminosity sensor located at station 1 is designated L_1.

The experimental series consisted of one shot into a non-reactive mixture (cold shots are designated by CS##) and 20 shots into reactive mixtures. Three parameters (entrance velocity, sabot design, and propellant mixture composition) were varied in an effort to successfully start the projectile at low velocity. These parameters are described below, along with a qualitative analysis of their potential effects on the ram accelerator starting process. All other parameters in the

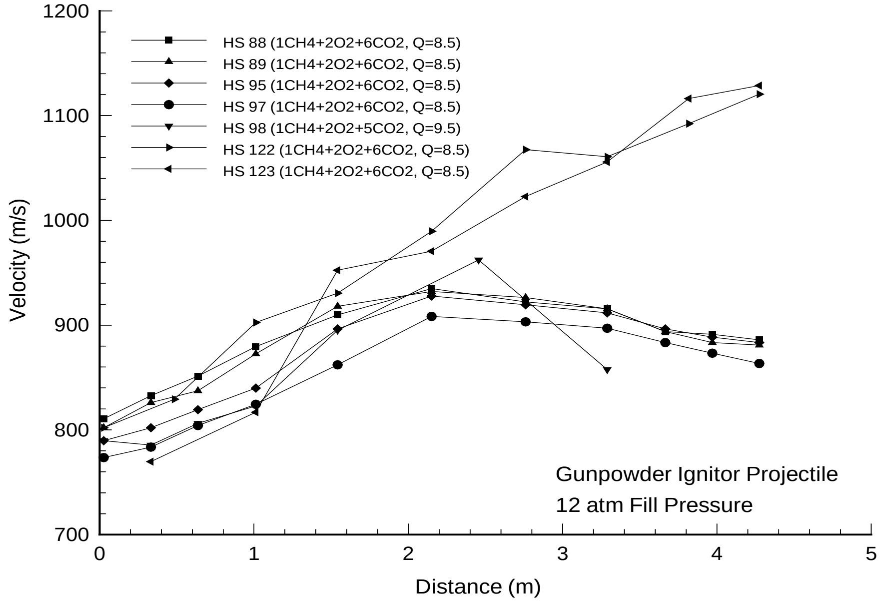


Fig. 7. Velocity versus distance data for early low entrance velocity shots.

ram accelerator tube. The current experimental investigation was based in methane, oxygen, and carbon dioxide mixtures primarily because of this past successful low velocity starting experience.

Experiment Setup and Procedure

As the projectile entrance velocity is decreased, the projectile Mach number approaches the lower limit Kantrowitz Mach number necessary to keep the diffuser started. The experimental series for this investigation used a standard projectile, which has a flow throat to tube area ratio of 0.42. From Eq. 1, this area ratio gives a Kantrowitz Mach number of approximately 2.3 for γ=1.31. Entrance Mach numbers were kept above 2.5 to account for the ideal nature of Eq. 1, effects of entrance diaphragm impact, and drag deceleration of the projectile in the finite time required to initiate positive ram acceleration. For a desired entrance velocity of 750 m/s, this Mach number demands propellant sound speeds on the order of 300 m/s.

Likewise, a low pressure pre-launcher will also mandate the use of low entrance velocities in a facility. A third justification for low velocity starting is to utilize the improved efficiency provided by the ram accelerator over conventional guns. Finally, sabot construction is sensitive to the fill pressure of the pre-launcher. Very high breech pressures have been linked to shattering the sabot upon breech gas impact, causing start failure. Operation at lower breech fill pressure provides more flexibility in sabot construction, but requires a low entrance velocity capability.

Several ram accelerator experiments were performed with low entrance velocity in 1986. The propellant mixture was typically methane, oxygen, and carbon dioxide at 12 atm fill pressure in mole ratios of 1:2:6, respectively. The facility used at the time was similar to the one currently in operation. A major difference between the standard projectile employed today and the projectile used in the past low velocity start attempts was a gunpowder ignitor system (Ref. 1). A pellet mounted at the center of the entrance diaphragm was swallowed by a pitot tube in the nose tip, causing burning gunpowder to eject from the projectile base. This rather complicated starting mechanism was employed until it was discovered that starting was possible without the ignitor. Very few data exist on the performance of the gunpowder ignitor, and therefore it is impossible to determine the influence of the ignitor on the starting process.

Velocity versus distance data from the past low entrance velocity shots are presented in Fig. 7. Shots into reactive propellant mixtures are referred to as “hot shots”, and given the designation HS##. Note the erratic ram accelerator performance exhibited in this plot. Most of the shots were at entrance velocities within 20 m/s of each other into very similar mixtures and yet the results range from wave fall-off to wave unstart. For instance, HS89 and HS122 have identical entrance velocities into the same mixture. The latter exhibits a wave fall-off approximately 2 m from the entrance, while the former produces ram acceleration for over 4 m. Nevertheless, two of the seven shots presented do indicate a successful start and drive through the

A successful start occurs when the flow in the diffuser is supersonic and the normal shock system driven by the sabot is stabilized on the body. The propellant ignites in the region behind the normal shock system or at the projectile base, and travels with the projectile down the tube. The high pressure caused by the combustion supported normal shock system on the projectile body produces a thrust force which continuously accelerates the projectile.

A few additional points regarding the starting process were reported by Burnham in Ref. 4 and should be emphasized here. If light gas blow-by is significant, it increases the pressure ahead of the projectile in the launch tube and can lead to premature bursting of the entrance diaphragm. In one sense, more preheated launch tube gas could help ignite a propellant mixture not so easily ignited otherwise. However, early breaking of the entrance diaphragm almost always results in a start failure. Burnham also found that perforated sabots seemed to be more forgiving, hypothesizing that the gas flow through the perforations weakened the normal shock system, preventing it from overrunning the throat. Also, through pressure and luminosity data, he documented the aforementioned preheating of the launch tube gas ahead of the projectile by a series of reflected shocks through pressure and luminosity data, and argued that this preheated gas was the primary ram accelerator ignition source. Cited as proof of this theory was the inability to start the ram accelerator when a buffer section of inert gas was placed between the evacuated launch tubes and the propellant filled ram accelerator tubes.

Low Velocity Starting

Typical entrance velocities at the University of Washington ram accelerator facility are on the order of 1150 m/s. The primary starting mixture is methane and oxygen diluted with nitrogen. The “low” velocity start range investigated in the present study is between 700 and 900 m/s. Low velocity starting is of importance in several applications of the ram accelerator. Facilities requiring minimum launch tube length will be limited in the entrance velocity they can achieve.

number less than the Kantrowitz Mach number, the flow velocity reaches sonic conditions ahead of the throat. A normal shock forms at this point and propagates downstream, and the projectile rapidly decelerates in the high pressure region behind the normal shock. A Kantrowitz unstart will also occur if the projectile Mach number decreases below the Kantrowitz Mach number anywhere in the ram accelerator tubes. This situation could occur due to combustion ahead of the throat or the projectile decelerating due to drag. When the projectile is travelling through the propellant-filled tubes at supersonic velocity with no normal shock ahead of the throat, the diffuser is said to be started. Starting of the diffuser is a necessary, but not sufficient, condition for a successful ram accelerator start, and thus forms the low Mach number limit for attempting to start the ram accelerator.

A wave unstart occurs when the normal shock system on the projectile body moves forward of the throat; it may happen with or without combustion. If no combustion is present, the situation could be that the sabot drives a strong normal shock system onto the body with such a forward velocity that it overruns the throat. If combustion does occur, the wave unstart could be due to the combustion region driving the normal shock system past the throat, or the mixture may detonate. In the latter case, a detonation wave propagates ahead of the throat and runs down the ram accelerator tube at V_{CJ} of the propellant mixture.

A wave fall-off occurs when the normal shock system recedes from the projectile body; it may also happen with or without combustion. The projectile outruns the normal shock wave, and decelerates due to supersonic drag as it travels down the tube. If combustion does not occur, nothing exists to stabilize the normal shock system on the projectile body after the sabot decelerates. If wave fall-off occurs in spite of combustion, it is because the heat release is not sufficient to stabilize the normal shock system on the projectile body.

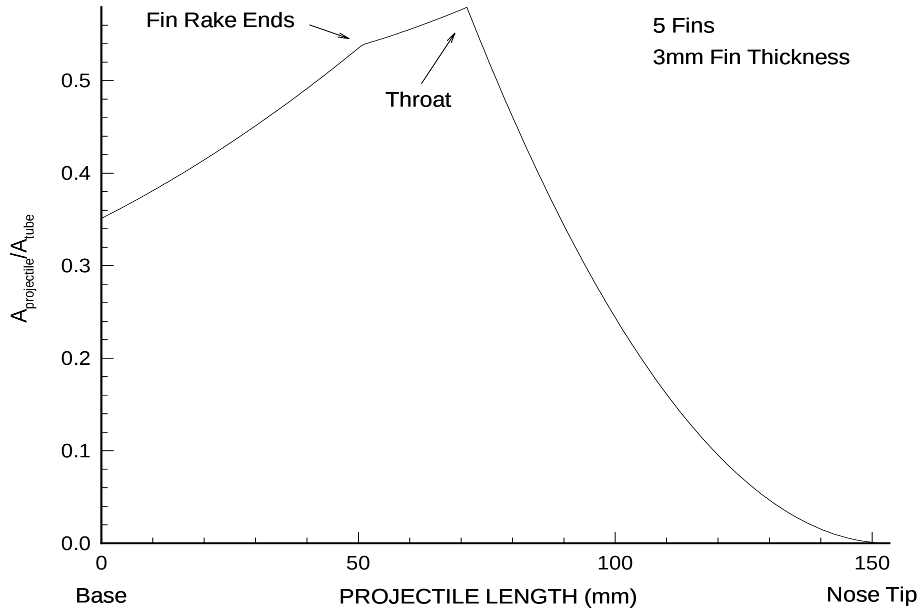


Fig. 6. Projectile area profile.

throat of the standard ram accelerator projectile. The throat is typically taken to be the point of maximum geometric projectile area (minimum flow area) where the nose cone joins the body. However, due to the fins extending up to throat, the standard projectile has an almost constant area section from the nose/body joint back to the point where the fins meet the wall. The projectile area cross section plot in Fig. 6 illustrates this.

To first order, the projectile flight Mach number necessary for a supersonic throat (known as the Kantrowitz Mach number) is given for isentropic, calorically perfect, quasi one dimensional flow by,

$$\left(\frac{A_{tube}}{A_{throat}}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}} \tag{1}$$

where A_{tube}/A_{throat} is the tube to flow throat area ratio and $\gamma=C_p/C_v$ is the ratio of specific heats of the propellant mixture. When a projectile enters the propellant supersonically but at a Mach

The projectile starts at rest with the sabot attached to its base to prevent excessive gas blow-by in the pre-launcher, and to assist in propellant ignition once the projectile enters the ram acceleration tubes. The projectile and sabot are accelerated down the evacuated launch tubes once helium in the light gas is released using a double diaphragm technique. Some helium does overrun the projectile and sabot. This blow-by gas, along with the residual air in the launch tubes after evacuation, is subjected to a series of reflected shocks between the entrance diaphragm and the sabot as the projectile moves towards the ram accelerator tubes. Significant heating of the shocked launch tube gas has been documented by rising pressure and luminosity measurements taken immediately before the entrance diaphragm (Ref. 4).

The projectile pierces the entrance diaphragm at “entrance velocity” and enters the combustible gas mixture with the sabot and preheated launch tube gas. The sabot drives a normal shock system onto the projectile body as it separates from the projectile and rapidly decelerates. If the sabot is perforated and contains a backplate, the backplate dislodges and some of the flow expands through the exposed sabot perforations. From this point on, the exact mechanism by which the flow is ignited and combustion stabilized behind the throat is unclear. Potential contributing factors include the projectile imparting energy to the propellant upon impact, the normal shock system driven by the sabot creating a high temperature region on the aft end of the projectile, and the preheated launch tube gas entering the combustible gas mixture with the projectile. The ignition process is probably dependent in some way on all of these factors along with the reactive characteristics of the propellant (activation energy, induction time, reaction rates, heat release, etc.) and projectile geometry (size and shape of nose, body, and fins).

There are four possible results of a ram accelerator start attempt at supersonic entrance velocity: Kantrowitz unstart, wave unstart, wave fall off, and a successful start. Each of these phenomena are described in the paragraphs below. One fact should be emphasized regarding the speed and the mixture energy parameter, $Q=\Delta q/C_pT$, which is the nondimensionalized potential heat release of combustion.

The propellant energy is released in a combustion zone located behind the normal shock system and projectile base. The combustion region stabilizes the normal shock system on the projectile body creating a high pressure zone at the base of the projectile, resulting in sustained acceleration as it travels down the tube. A useful tool for visualizing the ram accelerator propulsion mechanism is to think of the projectile as surfing down the tube on a wave of combustion.

Several ram accelerator modes of propulsion have been identified relative to the Chapman-Jouguet detonation velocity (V_{CJ}) of the combustible gas mixture (Refs. 2 and 3). The subdetonative regime exists at projectile velocities up to approximately 90% V_{CJ}, the transdetonative regime between 90% and 110% V_{CJ}, and the superdetonative mode of propulsion at projectile velocities above 110% V_{CJ}. The experimental investigation described here lies completely within the subdetonative regime, which is mainly characterized by a normal shock system on the projectile body followed by a region of subsonic combustion. An idealized sketch of the subdetonative mode of propulsion is presented in Fig. 1.

Starting Process Overview

A successful "start" is defined as obtaining supersonic flow past the throat, igniting the flow behind the throat, and stabilizing a combustion zone on the rear part of the projectile. Conditions which result in a supersonic throat are easily predicted, while the various parameters and their interaction with one another that influence the combustion process are extremely difficult to characterize. Investigations of various aspects of the ram accelerator starting process are reported in Ref. 4.

accelerator section. The standard sabot material is polycarbonate and is fabricated in two pieces, a perforated obturator and a backplate which are glued together.

Experimental data are collected through instrumentation stations spaced approximately every 400 mm down the length of the ram accelerator tubes. Each 2 m long tube has 5 instrumentation stations along its length, each with alternating four and three ports located about the circumference of the tube. Electromagnetic transducers provide a location history of the projectile by detecting the magnetic ring in the projectile throat. Piezoelectric pressure transducers supply pressure data from the tube wall, resulting in the pressure profile at the wall during the ram acceleration process. Fiber optic luminosity sensors detect visible light emissions in the tube, useful for indicating regions of combustion.

Ram Accelerator Operation

The light gas gun, usually helium filled, is used as a pre-launcher to initially accelerate the sabot and projectile down the evacuated launch tubes. The helium disperses into the first dump tank through vent holes in the final launch tube. Thin mylar diaphragms separate the evacuated launch tubes from the propellant filled ram accelerator tubes. The projectile pierces these diaphragms and enters the ram accelerator section supersonically with the sabot. The sabot drives a normal shock system onto the projectile body as it separates from the projectile and rapidly decelerates.

The propellant, composed of premixed fuel, oxidizer, and diluent, is ram compressed up to the projectile throat, expands past the throat and over the body where it encounters the normal shock system. This normal shock system is typically idealized as a single normal shock, but is more likely a system of reflected oblique shocks which renders the flow subsonic relative to the projectile. The propellant characteristics are tailored by the type and amounts of fuel, oxidizer, and diluent used in the mixture. Mixture properties of interest in ram acceleration include sound

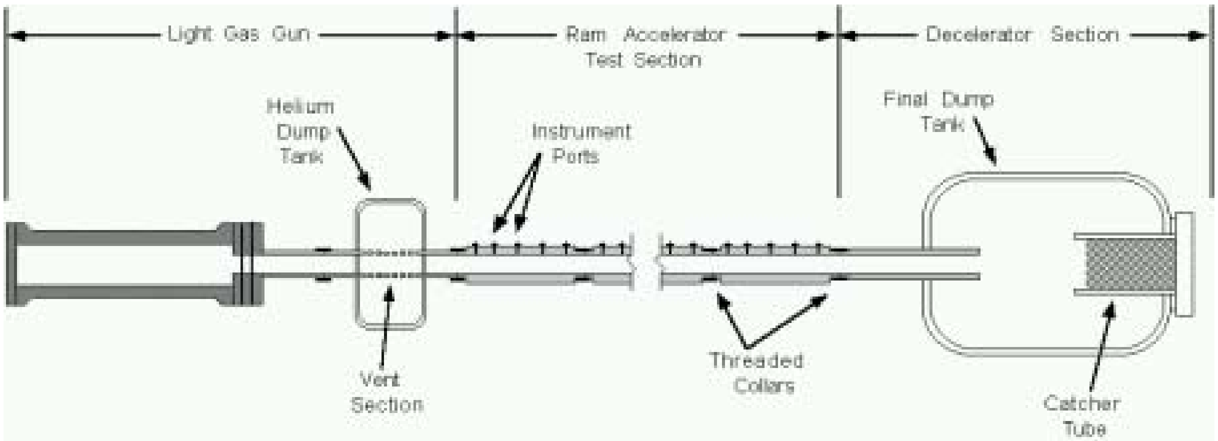


Fig. 3. Ram accelerator facility schematic.

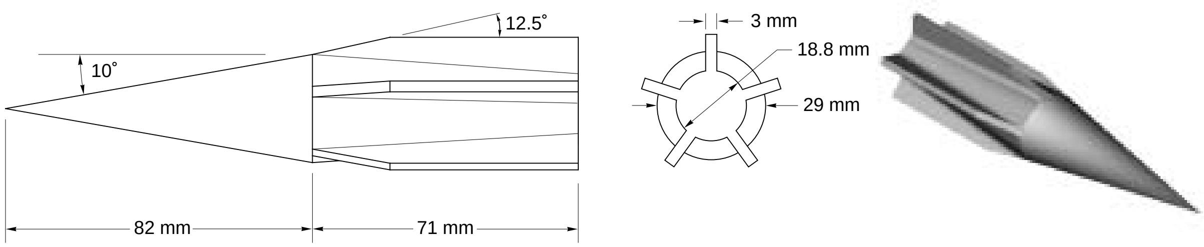


Fig. 4. Standard ram accelerator projectile.

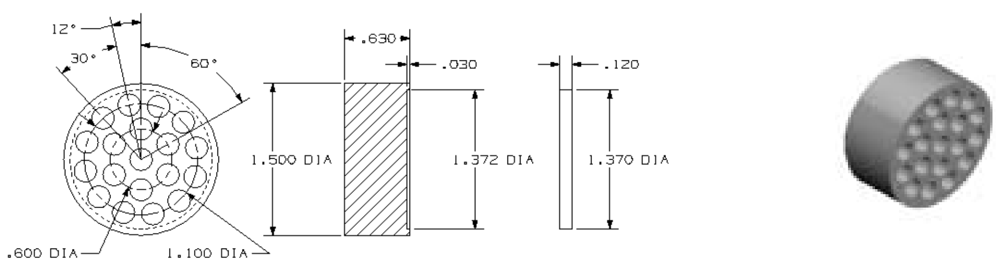


Fig. 5. Standard perforated sabot.

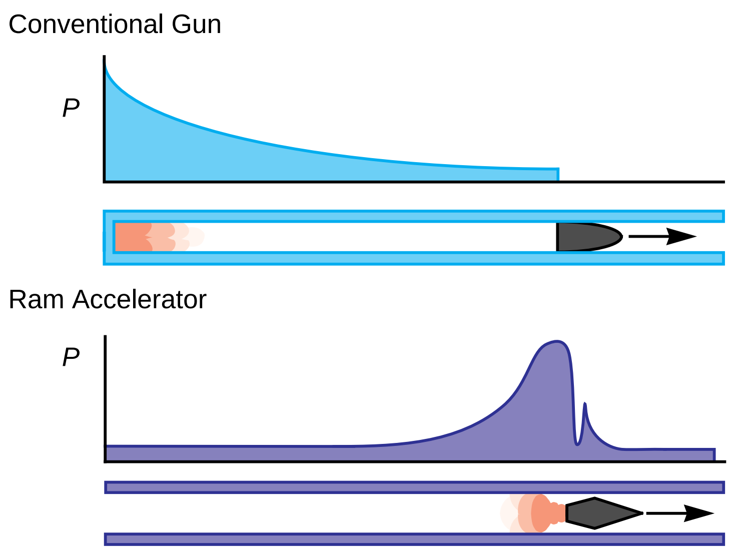


Fig. 2. Pressure profiles of a conventional gun and a ram accelerator.

flow computational fluid dynamic codes, tactical and strategic defense, and direct launch to orbit of acceleration-insensitive payloads. A number of other ram accelerator facilities are now in operation in the United States and abroad due to the wide range of basic and applied research opportunities available.

Facility

A schematic of the University of Washington ram accelerator facility is presented in Fig. 3. It consists of a light gas gun pre-launcher, a light gas dump tank, 16 m of ram acceleration tubes (each tube is 2 m long), a final dump tank, and a catcher tube. The standard projectile, presented in Fig. 4, is fabricated of 7075-T6 aluminum and consists of two pieces, the nose and body, which screw together at the throat. Primary characteristics of the standard projectile include a 10° half-angle nose, 5 fins, a flow throat to tube area ratio (A_{throat}/A_{tube}) of 0.42, and a ring magnet in the throat. A sabot, presented in Fig. 5, is glued to the projectile base to prevent blow-by of the gas from the pre-launcher, and to assist in igniting the propellant gas in the ram

Introduction

The ram accelerator is a hypervelocity launcher in which a projectile, similar in shape to the centerbody of a ramjet, travels supersonically through a tube filled with premixed gaseous fuel and oxidizer propellant. A typical in-tube ram accelerator projectile is shown in Fig. 1. The propellant flowing over the nose of the vehicle is ram compressed by a series of reflected shocks, passes the vehicle throat (minimum flow area), and then expands over the rear of the projectile. The propellant energy is released by a combustion zone present on, or immediately behind, the rear of the vehicle. The region of combustion travelling with the projectile constitutes the primary difference between the ram accelerator and a conventional gun, as illustrated in Fig. 2. The region of highest pressure in a conventual gun is in the breech. In a ram accelerator, a high pressure region near the projectile aft end is generated by the combustion process, producing sustained thrust as the projectile travels down the tube. The gasdynamics of the ram accelerator is such that the device can easily be scaled up or down in size.

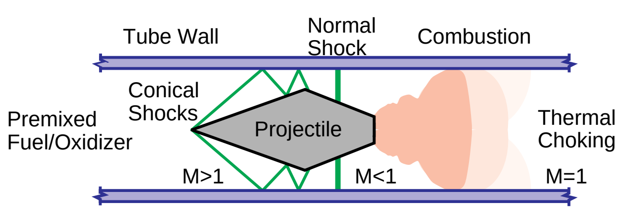


Fig. 1. Ram accelerator subdetonative mode of propulsion.

The ram accelerator was conceived at the University of Washington in 1983 as reported in Ref. 1. The current University of Washington facility is 16 m long and has a 38.1 mm bore. In-tube projectile velocities and Mach numbers are typically in the ranges from 1 to 2.7 km/s and 2.5 to 8, respectively. Sustained accelerations are commonly on the order of 25,000 g's, with peak accelerations up to 50,000 g's. Applications of the ram accelerator include hypersonic vehicle flight testing, supersonic and hypersonic propulsion research, validation of hypersonic reacting

Ignition of the Ram Accelerator at Low Projectile Entrance Velocity

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San Luis Obispo, CA
March 28-30, 1996

Abstract

Ram accelerator operation with low projectile entrance velocity (~800 m/s) is investigated. The ram accelerator is a hypervelocity launcher in which a projectile, similar in shape to the centerbody of a ramjet, travels supersonically through a tube filled with premixed gaseous fuel and oxidizer. A successful ram projectile start is defined as obtaining supersonic flow past the throat, while initiating and stabilizing combustion behind the throat. The primary objective of this study is to start the ram projectile at low entrance velocities in low sound speed propellant mixtures. Low velocity starting is important for facilities with launch tube length constraints or low pressure pre-launchers. Knowledge of the low velocity start process will also further the understanding of ram accelerator starting at all entrance velocities. Experiments were performed using carbon dioxide diluted mixtures of methane and oxygen at 25 atm fill pressure to examine low velocity starting of a five-fin projectile having a flow throat to tube area ratio of 0.42. The current understanding of the ram accelerator starting process is summarized, and low entrance velocity start experimental data are presented. Starting at low velocity is extremely sensitive to perturbations in the amount of diluent present, the entrance velocity, and the sabot mass. Future research in this area will explore increasing the flow throat area to start at lower entrance velocities in higher sound speed mixtures, and developing ignition limit envelopes for mixtures used in the ram accelerator.

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