UNIVERSITY OF WASHINGTON RAM ACCELERATOR FACILITY

C. Knowlen, J.G. Li, J. Hinkey, and B. Dunmire

Aerospace and Energetics Research Program
University of Washington, FL-10
Seattle, WA 98195

42nd Meeting of the Aeroballistic Range Association
Adelaide, Australia
22-25 October 1991

ABSTRACT

A detailed description of the ram accelerator testing facility at the University of Washington is presented in this paper. The ram accelerator is a ramjet-in-tube projectile accelerator whose principle of operation is similar to that of a supersonic airbreathing ramjet. Several different ram accelerator propulsive cycles have been experimentally demonstrated in a 38 mm bore test facility over the Mach number range of 3 to 8.5, with peak velocities of nearly 2.7 km/sec having been achieved to date. The length and pressure rating of the current facility are such that velocities slightly above 3 km/sec are possible, based on recent experimental results. The ram accelerator concept itself has the potential launch projectiles to hypervelocities in the 7 to 9 km/sec range, and to scale up in bore size to a point where direct space launch is feasible. Current research goals are to demonstrate the maximum velocity potential of the facility and to investigate the operating principles of the high-speed propulsive modes needed to achieve orbital velocities.

INTRODUCTION

At the University of Washington, experimental research on hypersonic propulsion is being carried out using a ramjet-in-tube concept called the "ram accelerator."[1-10] Its aero-thermodynamic propulsive cycles are similar to those found in a conventional airbreathing ramjet or scramjet. As shown in Figs. 1 and 2, a projectile that resembles the centerbody of a conventional supersonic ramjet is accelerated through a stationary tube filled with a premixed gaseous fuel and oxidizer mixture; the projectile itself carries no propellant. The combustion process travels with the projectile, resulting in a pressure distribution which produces thrust. The pressure and composition of the gas mixture (hence the chemical energy density and speed of sound) can be easily adjusted, controlling the Mach number and acceleration profiles of the projectile. The ram accelerator is therefore a highly useful experimental tool with which to obtain data on hypersonic propulsive cycles over a wide range of Mach numbers, initial pressures, equivalence ratios, and accelerations.[9] Furthermore, the ease with which the device can, in principle, be scaled up in size gives it the potential to perform ground-based flight tests on relatively large, highly instrumented models and full-scale components at hypersonic velocities of interest to the NASP and other hypervelocity vehicles.[10]

Several modes of ram accelerator propulsion have been investigated experimentally and theoretically by the authors and their colleagues. One of these propulsive cycles is the thermally choked ram accelerator mode (Fig. 1), which operates at velocities below the Chapman-Jouguet (CJ) detonation speed of the propellant mixture (the "subdetonative" velocity range), with Mach numbers typically from 2.5 to 4.5. In this mode, the thrust is provided by the high projectile base pressure resulting from a normal shock system which is stabilized on the body by thermal choking of the flow at full tube area behind the projectile. The theoretical model of the thermally choked propulsive mode predicts that the normal shock recedes along the body as the projectile Mach number increases. At some limiting Mach number the normal shock is predicted to fall off the rear the projectile and the acceleration should cease. In the hypothetical case where the projectile tail tapers to a point and the flow is inviscid, the normal shock gradually falls back to the full tube area. A normal shock in a constant area duct followed by heat addition and thermal choking in steady flow constitute a CJ detonation wave. Therefore, this theoretical model predicts that the thrust goes to zero as the projectile velocity approaches the CJ detonation speed of a particular propellant mixture.[6,7]

While the projectile is operating at velocities below 85% of the CJ detonation speed of the propellant gas, it has been observed that the thrust as a function of Mach number is accurately predicted by the one-dimensional theoretical model of the thermally choked propulsive mode.[6,7] As the projectile velocity exceeds 85% of the CJ speed, however, the thrust on the projectile begins to exceed that predicted by the theoretical thermally choked model. Thrust reaches a minimum at projectile velocities near the CJ speed of the gaseous combustible mixture, and then increases as the projectile gains velocity. Experiments have shown that in this "transdetonative" velocity range (typically Mach 4 to 6), the projectile can accelerate smoothly from subdetonative to superdetonative velocities in a gaseous propellant without immediately generating a detonation wave in the passageways around the projectile body. Transdetonative experiments have accelerated projectiles with entrance Mach numbers of ~3 up to Mach 6 within the same propellant mixture, achieving single-stage velocity gains of over 1000 m/sec. This transdetonative behavior was an unexpected experimental finding that has significant implications for enhancing the muzzle velocity of single-stage ram accelerators and reducing the number of propellant mixtures required in multi-stage facilities.[5,9]

For operating at higher Mach numbers an oblique detonation ram accelerator mode has been investigated both theoretically and experimentally.[4,8] This mode operates at velocities greater than the CJ detonation speed, in the "superdetonative" velocity range with Mach numbers typically exceeding 6. Experiments conducted entirely in the superdetonative velocity range have successfully demonstrated positive thrust at Mach numbers up to 8.5 (velocities up to 150% CJ detonation speed). It is believed that the propellant mixture is ignited by one of several reflected oblique shock waves, as shown in Fig. 2. Other combustion processes capable of providing thrust at superdetonative velocities have also been suggested, such as shock-induced combustion, supersonic combustion (scram), and mixed-mode combustion cycles (e.g., heat addition processes that occur in both subsonic and supersonic regions of the flowfield).[4,8-10]

Historical Perspective

The first experimental facility designed to investigate the internal ballistics of ram accelerator propulsion became operational at the University of Washington in October, 1985. The original test section consisted of three tubes having a 38 mm bore and a total length of 4.9 m. Techniques for igniting the propellant mixture were developed and proof-of-principle of the thermally choked propulsive mode was established.[1,6] The length of the ram accelerator test section was then extended to 12.2 m in March, 1987 and multiple-stage experiments were conducted.[2,3,7] The transients arising from sudden propellant mixture transitions did not inhibit performance and staging mixtures proved to be an effective way to reach high velocities. Proof-of-principle of superdetonative ram accelerator propulsion was then demonstrated and continuous acceleration through the CJ detonation speed of the propellant mixture was first achieved.[4]

During the winter of 1989, the ram accelerator facility was re-configured and the test section tubes were replaced with 8 tubes of equal length (2 m) and similar bore. The barrel length of the light gas gun was reduced by 64 calibers to accommodate the increase in the length of the test section to 16 m.[5] In addition, the projectile decelerator was redesigned to fit within the final dump tank. The density of instrumentation ports along the test section was increased to allow the use of more transducers at a given station. The gas handling system was upgraded to provide more accurate control of mixture composition for high pressure experimentation. The details of the current ram accelerator facility and supporting equipment are presented in the following.

EXPERIMENTAL FACILITY

The ram accelerator facility consists of a light gas gun, ram accelerator test section, final dump tank and projectile decelerator (Figs. 3 and 4). The 38 mm bore, 6 m long, single-stage helium gas gun is capable of accelerating the obturator and projectile combination (typical combined mass of 60-100 g) to velocities up to 1300 m/sec with a maximum breech pressure of 340 bar. The muzzle of the light gas gun is connected to a perforated-wall tube that passes through an evacuated tank which serves as a dump for the helium driver gas. A pair of opposing instrument ports, located 12.7 cm from the muzzle of the helium vent tube, allows monitoring the residual muzzle pressure and the time-of-passage of the projectile before it enters the test section.

The 16 m long ram accelerator test section consists of eight, 2 m long steel tubes having a bore of 38 mm, and an outer diameter of 102 mm. There are a total of 144 instrumentation ports at 40 regular intervals along the test section of the ram accelerator. Each of the tubes has five equally spaced axial instrument stations, alternating between three stations with four ports at right angles to each other and two stations with three ports located 120^{o} from each other. The instrument stations are located at 40 cm intervals. This design of multiple port stations permits the simultaneous use of either three or four transducers for examining the flowfield phenomena. Diametrically opposed ports also provide the ability to observe any asymmetries that may exist in the flow about the projectile. Dimensions of the instrument ports are such that standard piezoelectric pressure transducers (6 mm diameter access hole to the sidewall of the internal bore) can be located in any of these observation stations. Remaining ports are used to mount electromagnetic transducers and fiber-optic light guides. Multiplexing permits monitoring of over 100 separate input signals. A more detailed discussion of these transducers is provided later in this paper. Unused ports are sealed with blank steel plugs.

The maximum internal pressure that the tubes of the ram accelerator test section can experience without the stress of the inner fibers of the tube wall exceeding the yield strength of the material (4140 steel alloy, hardened to Rockwell C 32-36) is ~5500 bar, based on calculations using a yield stress limit of ~8600 bar and a minimum outside diameter of 63.5 mm (which is the O.D. of the male stub at the tube joints). The highest static pressures generated in the experiments result from overdriven detonation waves being pushed ahead of an "unstarted" projectile. Peak overdriven detonation pressure ratios of ~50 have been measured in some experiments. To maintain a safety factor of at least two, during the worst case scenario, the initial gas fill pressure is limited to 50 bar. Thin Mylar diaphragms, ranging in thickness from 0.2 mm to 1.6 mm, are placed in the tube joints to seal each end of the ram accelerator test section and to separate segments filled with different propellant mixtures. The current facility is plumbed for four stages and additional staging capability can be added as needed. The different gases are metered with individual sonic metering valves, brought together to mix, and then routed to the appropriate tube segments. The details of the gas handling system are discussed in a separate section.

The end of the ram accelerator test section is connected by a 0.76 m long drift tube of similar bore to a 2.4 m long evacuated dump tank, through which the projectile flies unconstrained. Two instrument stations, each having one pair of opposing instrument ports, are located in the drift tube to provide final velocity measurements and to examine the pressure field about the projectile as it exits the test section. The first station in the drift tube is 35.8 cm from the end of the ram accelerator test section and the interval to the second instrument station is 34.9 cm. The final dump tank has a pair of 25 cm diameter viewing ports for high-speed photography and additional velocity measurements.[2] The projectiles are brought to a stop by impacting metal witness plates and tightly packed rug remnants contained in a mild steel catcher tube located within the far end of the dump tank. The catcher tube has internal dimensions of 20 cm bore x 1 m long, and its wall thickness is 2.5 cm. The far end of the catcher tube is closed off by means of a 15 cm thick plate of 4150 steel alloy.

Ram Accelerator Test Section Instrumentation

Data from the experiment are collected and stored with a LeCroy data acquisition system (DAS) and are processed on an IBM-compatible 386 type micro-computer using the LeCroy Wave-Form Catalyst software. Major components of the DAS are two LeCroy CAMAC crates (Model #1434), five Quad 10-bit transient digitizing modules (Model #8210) with ten memory modules (Model #8800A), three Quad 12-bit transient digitizing modules (Model #6210), and two CAMAC to GPIB interfaces (Model #8910A). The eight digitizing modules (five 10-bit and three 12-bit) provide 32 data channels with a minimum memory time window of 16 msec at a sampling rate of

1 MHz. Maximum amplitude range for data storage is ±5 volts with a digitization level of 10 mV. Triggering of the DAS can be accomplished with the output signals from any of the sensors located along the ram accelerator test section.

Electromagnetic Sensors

The time-of-passage of the projectile at each instrument station is determined with an electromagnetic (EM) transducer that detects the magnets carried aboard the projectile.[11] The average velocity between transducers is calculated from these times and the measured distance between them, thus providing a velocity profile of the projectile throughout the test section. The EM sensors consist of ~20 turns of 32 gauge copper coil wire wrapped around a solid polycarbonate core having an O.D. of 2 mm. The sensing coil is inserted into a single-unit protective stainless steel casing that is designed to withstand the high pressure transients of the experiments. Typical output signal intensity of the EM sensors is ~5 mV and the typical sinusoidal period is ~15 μsec. Signals are amplified by a factor of 100 with amplifiers having a 2 MHz bandwidth, and then multiplexed through a summing amplifier. Multiplexed sensors are situated at stations that are typically 0.8 m to 2 m apart, which results in a minimum temporal separation of ~320 μsec for a projectile velocity of ~2500 m/sec. During normal ram accelerator operation, this has been found to be more than sufficient temporal separation to distinguish the axial location of a particular EM signal from the string of signals that result from multiplexing individual sensors. The outputs from all 43 EM transducers are stored on six digitizing channels in this manner.

Pressure Transducers

Pressure sensors are used to monitor the pressure field at the tube wall which is generated by the passing projectile and the associated combustion activity. The early experiments were plagued with inadequate and unreliable pressure transducers. After five years of working with the supplier of the piezoelectric pressure transducers (PCB Piezotronics Inc.), robust and reliable sensors have been developed which are currently providing high quality data on the ram accelerator pressure fields. The primary piezoelectric pressure transducers used in the experiment have model numbers: 119M39/402M99, 119M44/402M99, and P119A/402M99. They have natural resonant frequencies of 450 to 500 KHz and vary in sensitivity from 9 to 18 mV/bar. These pressure transducers have a 6800 bar maximum operating pressure rating and an inherent rise time of 1 μsec. The ability of the transducers to follow the transient behavior of the pressure waves about the projectile have made them invaluable in interpreting the gasdynamic phenomena generated by the projectile passage.

Pressure output signals from various stations are input into a special multiplexer which isolates the individual signals and monitors each sensor during the time frame of projectile passage. The circuit shown in Fig. 5 is capable of multiplexing eight signal inputs to a single output. In the quiescent state Channel 1 is continuously monitored by a comparator. When the output from Channel 1 exceeds 0.1 V, a timer is triggered, and this channel continues to be monitored for 2 msec. After this time, the multiplexer switches to monitor Channel 2, and the sequence continues in a similar manner through Channel 8. Multiplexed signals are DC coupled, and the bandwidth is approximately 10 MHz. The multiplexed pressure sensors are situated at stations that are spatially separated by 3 m to 5 m. This multiplexing configuration allows monitoring of up to four transducers on a single DAS channel for projectile velocities up to 2500 m/sec.

Optical Fiber Probes

Luminosity probes have been developed which monitor the light emissions from the combustion phenomena occurring in the vicinity of the projectile. The fiber optic cable consists of a polymthyl-methacrylate core surrounded by a fluorine polymer cladding and a black plastic jacket

(O.D.≈1.5 mm). The fiber optic inner core measures 1 mm in diameter and has a 56° acceptance angle when mounted flush to the bottom of the probe, and it is inserted into the probe as shown in Fig. 6. This two-piece luminosity probe consists of a fiber guide housing manufactured from 4140 steel and a brass back plug for holding the optical fiber. Each piece contains a 1.5 mm diameter hole through its center to accommodate the sheathed optical fiber. The larger end of the steel housing is tapped and the fiber holding back plug has matching outside threads. As the brass back plug is threaded into the outer housing, its coned tip is forced into a coned seating surface having a slightly different angle. As a result, the tip of the brass plug crimps the fiber-optic cable, creating a pressure seal around the fiber and on the coned surfaces. The outer housing is dimensioned to fit inside the standardized instrument ports of the ram accelerator test section. This two-piece design for the luminosity probe was chosen for several reasons. Most importantly, the fiber-optic cable can be recessed in the probe housing to reduce the effective acceptance angle of the unit. This results in more accurate spatial discrimination of the signal output. A second advantage of this probe design is that the fiber can be easily adjusted or removed for maintenance or replacement.

The optical fiber guides the in-tube light emissions to a photodiode whose output is logarithmically amplified by the amplifier circuit shown in Fig. 7. Logarithmic amplification, as opposed to linear amplification, permits the examination of low intensity luminosity associated with shock waves and the high intensity luminosity resulting from combustion, without saturating the DAS voltage limits. The end of the optical fiber is manually aligned with the photodiode to maximize light sensitivity. The resulting signals are multiplexed in a manner similar to the pressure signals. Qualitative comparison of the outputs from different stations is based on the relative intensity levels of the luminosity data in the vicinity the projectile. The correlation of the luminosity data with the EM and pressure signals has provided significant information on the combustion phenomena that occur during ram accelerator operation.[5,9,10]

Propellant Gas Handling System

Propellant Gas Mixing

The gas handling system has the capability of remotely filling the ram accelerator test section with propellant mixtures having up to five different components. A photograph of the section where the propellant gases are mixed is shown in Fig. 8. Calibration of steady mass flow rates of various gases through the orifice of a micro-metering valve (Whitey Model #SS22RS4) is accomplished by timing the pressure rise in the test section volume at several different pressure settings upstream of the orifice. Measured mass flow rates are repeatable to within 0.5% for this calibration procedure. Hand regulators use nitrogen gas within the control bunker to remotely operate dome regulators which set the pressure ahead of the metering valves. (The plumbing lines for the constituents of the propellant mixture are kept outside of the control bunker to avoid exposing personnel to combustible gases.) Pressure settings for the desired propellant mixture are interpolated from the individual mass flow rate calibrations. Individual gases are metered and brought together through several T junctions to mix inside the long runs of stainless steel tubing (typical L/D >> 1000) which route the propellant mixture to the desired tube segments.

Regulating the pressure upstream of the metering valves provides a steady mass flow rate through their orifices as long as the back pressure on the downstream side remains below the critical choking pressure (unchoking of the orifice occurs when the back pressure is greater than approximately 1/2 the upstream pressure). Typical back pressures are less than 3 bar above ram accelerator fill pressure when three gases are combined at the flow rates associated with minimum dome regulator pressure settings of 70 bar. This allows the test section to be loaded with steady mass flow rates with fill pressures up to ~32 bar. The dome regulator settings required to charge the test section with a gaseous propellant mixture at 50 bar have to be set at or above 106 bar to minimize variations in propellant composition between experiments. Because of the lack of fine control of the hand regulators, the pressure at the dome regulators can only be adjusted to within 0.7 bar of the desired pressure setting for each component of the propellant mixture. This results in a maximum mixture variation between experiments of ±2% for propellant mixtures which are loaded in the test section when all dome regulator pressure settings are greater than 70 bar. Propellant fill pressures are monitored with 0.5% accurate vibration-resistant gauges which have been calibrated with a mirrored 0.25% accurate test gauge over the anticipated fill pressure range of the ram accelerator experiments. The observed nonlinearity of the test section pressure gauges introduces a maximum uncertainty in fill pressure of ±0.7 bar for every stage.

Gas Handling Procedure for Experiments

All of the ram accelerator experiments begin by evacuating the test section segments, launch tube, and dump tanks of the facility down to ~1 torr. Hand regulators set the pressure on the dome regulators to within ±0.7 bar of the desired upstream metering valve pressure setting, and the flowing gases are brought together and allowed to mix as they flow out a dump line until the pressure transients from valve switching have died away (typically, one minute is sufficient). When the mass flow rates of each gas component have stabilized, the propellant mixture is routed to the appropriate tube segment. Gauges measuring the propellant fill pressure are monitored with a video camera as the propellant mixture is being loaded. After the ram accelerator stages have been loaded, the breech of the light gas gun is charged with helium to the appropriate pressure in order to bring the projectile-obturator combination up to the desired entrance velocity. Subsequent re-evacuation of the system removes the combustion products and spent helium driver gas before the recycle procedure begins.

Gas Chromatography

Analysis by gas chromatography of the propellant mixtures is used to validate the relative mole fractions of the individual components. The gas analysis system consists of a Scientific Research Instruments (SRI) model 8610 gas chromatograph controlled by an IBM compatible personal computer. A thermal conductivity detector (TCD) is employed, consisting of a single rhenium-tungsten filament, and is sensitive to 1000 ppm. Integration of detected peaks is accomplished by interactive software provided by SRI.

An evacuated sample cylinder, having a volume of approximately 75 cm^3, is filled to 3 to 7 bar with the propellant mixture of interest. The gas samples are drawn from the dump line before or after the stage of interest is filled to the appropriate pressure. This is accomplished by remote control, utilizing air-actuated valves to eliminate exposure of personnel to tubes filled with high pressure combustible gas mixtures. After completion of the experiment, the sample cylinder is attached to the gas chromatography system and serves as the reservoir for a loop attached to a gas sampling valve. As many as ten to twenty samples may be taken and analyzed from a single sample cylinder, depending on the size of the samples analyzed and the amount of gas sample available.

Typical sample volumes are 0.5 cm^3 at 1 bar pressure and are analyzed by using a VALCO 10-port sampling valve which permits better than 1% repeatability in sample size when combined with a Kistler type 4043A10 piezoresistive pressure transducer. Calibration of the system is accomplished by analyzing propellant mixtures of known composition (mixed by partial pressures) that are similar to those used in the ram accelerator, and by external calibration methods in which the detector response is determined for individual components of the mixture. The overall system has demonstrated better than 2% repeatability and better than 3% accuracy in determining the composition of the propellant mixtures used at the ram accelerator.

Further development of the gas chromatography system includes the replacement of the single filament TCD detector with a two-filament, Wheatstone Bridge TCD detector system that will improve sensitivity to 100 ppm and increase the accuracy of the analysis to within 1%, which is the current uncertainty of the calibration standards. Also being undertaken is the development of a more versatile remote gas sampling system which will allow direct in-tube sampling of the propellant gases before, during, or after filling of the stages as well as simultaneous samples of each stage. Techniques for directly sampling the gases near the projectile with a high-speed gas sampling probe, while the projectile is accelerating in the tube, are also being investigated.

Experimental Projectile Configuration

A schematic of the nominal projectile geometry used in most experimental work to date is illustrated in Fig. 9. The projectile is fabricated in two hollow pieces, nose cone and body, which thread together at the throat (point of maximum cross-sectional area). The hollow design helps minimize projectile mass and allows experimental operation at reduced fill pressures. The projectile shown has a measured volume of 66 cm^3 and has ranged in total mass from 45 to 100 g, depending on the variations in projectile material and geometry. The fins serve to center the projectile in the tube and the octagonal cross section of the body is simply a machining convenience. Thin rubberized magnetic sheets are mounted in the nose-body joint and in the base of the body to allow the EM sensors to distinguish these reference points as the projectile passes by.

Most experimental projectiles to date have been fabricated from either magnesium alloy (ZK60-AT5) or aluminum alloy (7075-T651). Currently, nominal projectiles are manufactured entirely from the aluminum alloy. Until recently these projectiles were manufactured in-house by our own machine shop. Due to machinery tolerance, however, discrepancies did exist between individual, theoretically identical projectiles, resulting in mass variation of up to 4%. In an investigation of whether these discrepancies affect projectile performance, computer numerically controlled (CNC) machined projectiles (average mass variation of 0.1%) are presently being used in ram accelerator experimentation. To date, the experiments have not revealed significant performance differences between the CNC projectile and the in-house machined projectiles.

Nose Cone

The primary variables considered in the design of the nose cone are the cone half-angle and mass distribution. Nose cones with large half-angles (>15°) tend to reduce the upper operating Mach number limit of the thermally choked ram accelerator mode due to pre-ignition of the propellant mixture by one of the reflected conical shock waves. Experiments have indicated that nose cones with a small half-angle (<8°) result in excessively long and heavy noses that move the projectile's center of gravity (CG) ahead of the fin leading edge. (This assumes a nominal body length of 72 mm). This is believed to reduce the upper velocity potential due to asymmetric pressure forces on the nose arising from a canted projectile. Wide operating Mach number ranges have been observed with projectiles having nose cone half-angles between 8° and 12.5°. The nominal nose cone used has cone half angle of 10° and a base diameter of 30 mm (Fig. 9).

It has been calculated that the nose tip requires less wall thickness than the throat to withstand the experimental pressures. Consequently, current nose cones have a smaller internal angle than the outside angle in order to provide a wall thickness which decreases toward the nose tip. This provides the nose cone with greater resistance to implosion than a cone having a constant wall thickness but made with the same amount of material. The depth of internal coning is a primary factor in determining the CG of the nose cone, consequently, it is a factor in the location of the overall CG of the assembled projectile.

Body Configuration

The design of the projectile body has many variables. Material properties, CG location, external geometry and aerodynamic effectiveness are all factors considered in the design of the appropriate body configuration. Desirable mechanical properties of the body material include high strength-to-mass ratio, low chemical reactivity in a reducing atmosphere (most propellant mixtures used to date are fuel rich) and high temperature capability. Additionally, high impact and abrasion resistance reduces the amount of fin wear the projectile experiences. Resistance to destabilizing forces arising from asymmetric pressure fields about the projectile is enhanced by maintaining an overall projectile CG behind the leading edge of the fins.

Primary body variables that interact with the flow are: the fin dimensions and their leading edge configuration (blunt or sharp), body length, and the effective throat and base diameters (i.e., the diameter of a circle having an area equal to the actual cross-sectional area). The leading edges of the fins affect the area profile in the region behind the throat and also interact with the system of reflected conical shock waves generated between the cone and tube wall. Fin thickness is a significant contributor to the flow area profile along the body. The body length determines fin length (for a given leading edge geometry) and the separation distance between the recirculating zone, at the base of the projectile, and the projectile throat. Body length and nose cone half-angle determine the turning angle of the flow around the nose-body joint for different projectiles having the same base and throat cross-sectional areas. The current nominal projectile has a body length of 72 mm and fin thickness of 3.8 mm, with a leading edge rake angle of 12.5°. The fins are dimensioned for a diametric clearance of 0.1 mm between the projectile and the tube wall (Fig. 9).

The nose cone base diameter normally sets the maximum diameter of the projectiles used in the experiments, and this determines the throat-to-tube flow area ratio. Details of the external shape of the leading edges of the fins and the projectile body geometry at the nose-body joint, however, govern the actual area profile in the throat region, defined here as the region between the projectile throat and the point where the fins first contact the tube wall. The effective flow area is nearly constant throughout this region for the nominal projectile configuration. Throat area ratio and aerodynamic efficiency have significant effects on both the starting Mach number and the static temperature of the propellant gas flowing through the throat region. The turning angle of the flow over the nose-body joint is expected to be a factor in the separation of the flow over the rear part of the projectile body and is under current computational and experimental investigation.

Obturator Configuration

In early experiments the projectile carried within it an ignitor consisting of a pistol primer and a small charge (0.5 g) of black powder.[1,2] An important modification has been the development of an external ignition system, which does not require igniting an on-board gunpowder charge.[12,13] The key element of the ignition system is the obturator. To date, two types of obturator have been tested, both fabricated from polycarbonate (Lexan). The first type is a 8 mm thick solid cylindrical slug of material having a mass of 12 g. The second is a two piece assembly with a combined mass of 15 g (Fig. 9). The main body has a length-to-diameter ratio of 0.42 and is perforated axially with a series of regularly spaced holes (19) whose total cross-section area is approximately 40% of that of the tube. A thin flat plate of the same material is used to seal these perforations against the driving gas (helium) in the light gas gun. This plate is snugly fitted into a shallow cavity machined in the back of the main body of the sabot. The back plate is dislodged from the main body by the high frontal pressures experienced upon entering the test section.[12,13]

The obturator serves several functions in the starting process. When the projectile is fired from the light gas gun, it provides a solid surface for the driver gas to push against during launch.

After the projectile-obturator combination is up to speed, the obturator has the dual purpose of establishing a normal shock on the body and igniting the flow. In the two piece design, the perforations in the main body provide enough flow area to reduce the strength of the normal shock on the projectile, thus keeping it from unstarting the projectile. Within the first meter of the ram accelerator test section the obturator falls far enough behind the projectile that thermal choking is achieved, thus gasdynamically decoupling the projectile from the obturator. This ignition technique has demonstrated reliable operation over a wide range of propellant fill pressures, obturator geometries, and projectile entrance velocities.[12]

EXPERIMENTAL RESULTS

Experiments to date on the thermally choked mode have been carried out with a variety of propellant mixtures using methane, ethylene, and hydrogen as the fuels, and oxygen as the oxidizer. Diluents such as carbon dioxide, nitrogen, argon, helium, excess methane, and excess hydrogen are used to adjust the acoustic speed of the mixtures so that the initial Mach number of the projectile exceeds the minimum required to start the diffuser, and to tailor the heat release of combustion to a level that assures reliable ignition and reduces the likelihood of a premature detonation.

Figure 10 displays typical transducer signals obtained in the thermally choked ram accelerator propulsive mode. The time intervals are shown in increments of 60 μsec and pressure is shown in units of atmospheres. The fill pressure was 40 bar, the projectile's in-tube Mach number was 3.6, and the propellant mixture consisted of $2.7CH_4 + 2O_2 + 5.6N_2$. The upper trace displays the output of an electromagnetic (EM) transducer located at the same axial station as the pressure transducer and fiber-optic probe. The zero crossing of the signal identifies the point in time at which the annular magnetic disk located at the projectile throat (the point of maximum projectile diameter) passes by the sensor. This signal provides a reference point from which the position of the shock system can be determined relative to the projectile. The projectile configuration was exactly that shown in Fig. 9 and its silhouette, with the length scaled to the local velocity, is also shown with its throat aligned with the EM signal.

The middle trace in Fig. 10 is a typical tube wall pressure profile for the thermally choked operating mode. The first abrupt rise in pressure is generated by the lead conical shock and its reflection; subsequently, the pressure rises gradually until the shock reflecting off the nose cone strikes the tube wall again, in the throat region of the projectile diffuser section. Several more reflected shocks are observed in the region of supersonic flow over the projectile body. A normal shock system follows on the rear half of the projectile, producing a high base pressure. This shock system, which is believed to consist of a complex series of oblique and normal shocks, decelerates the flow entering the combustion zone to a subsonic Mach number. The decay in pressure following the peak is consistent with the assumption of subsonic heat addition (which accelerates the flow to thermal choking) and the subsequent non-steady expansion of the combustion products behind the choke point.

The bottom trace in Fig. 10 shows the output from a fiber-optic probe located at the same station as the pressure and electromagnetic probes. The fiber-optic probes are used to examine broadband light emitted as the projectile and chemically reacting gas pass by the instrument stations. Light intensity is logarithmically amplified to enable monitoring of the weak luminosity observed in the shock waves and the intense light emissions associated with combustion. The luminosity trace peaks approximately one projectile length behind the base of the projectile in the region of decaying pressure. This observation is typical of low Mach number ($M<4$) operation in most of the propellant mixtures investigated to date, indicating that the combustion reactions are completed within one to two projectile lengths behind the projectile.

Velocities up to 2650 m/s have been attained with the thermally choked mode of propulsion. An example of the velocity-distance (v-x) profile for a thermally choked experiment is shown in Fig. 11. This experiment was conducted with a four-stage configuration in which the first three stages were filled to approximately 40 bar and the fourth stage to 33 bar. The ram accelerator tube was loaded with successive combustible gas mixtures whose acoustic speeds increased towards the muzzle. The compositions of the propellant mixtures are tabulated in Fig 11. In this manner the projectile Mach number was kept within relatively narrow limits (approximately 3 - 4) in each stage. The projectile mass was 68 g and its geometry was the same as that shown in Fig. 9. The entrance velocity to the first stage was 1175 m/sec and the peak velocity of the experiment occurred ~15 m down bore at a velocity of 2650 m/sec. The normal shock system was then disgorged over the nose of the projectile and the "unstarted" projectile decelerated. The solid curves in the figure represent the theoretical performance predicted by the one-dimensional thermally choked model. Close agreement between theory and experiment is demonstrated for all four propellant mixtures, supporting the assumption that the projectile was accelerated by a thermally choked propulsive cycle.

CONCLUSION

The ram accelerator test facility has demonstrated the ability to gather significant data on high velocity projectiles undergoing high levels of acceleration. The pressure, luminosity and EM sensors have provided invaluable information on the gasdynamic phenomena associated with ram accelerator projectiles which has facilitated the successful development of this new accelerator technology. This test facility also provides an excellent test bed for developing new sensor concepts. Having demonstrated that the ram accelerator principle is a reliable, high-speed launching technique, the University of Washington ram accelerator facility will continue to be used to develop hypersonic propulsive cycles that are of interest to the aerospace and aeroballistic range communities.

Acknowledgments

This work was supported by NASA Grants NAG-1-327 and NAG-1-1061, USAF Contract F08635-89-C-0196, and by a grant from the Olin Corporation. The authors are deeply indebted to Edward Burnham, Gilbert Chew, Jacqueline Auzias de Turenne, Matt Jardin, and Andrew Higgins for their assistance in performing the experiments, and to Malcolm Saynor and Dennis Peterson for their skillful fabrication of the projectiles. We are also indebted to Adam Bruckner and Abraham Hertzberg for their helpful comments on this manuscript and to Tom Mattick for his amplifier and multiplexer designs.

References

1. Hertzberg, A., Bruckner, A.P.and Bogdanoff, D.W., "The Ram Accelerator: A New Chemical Method of Achieving Ultrahigh Velocities," Proceedings of the 37th Aeroballistic Range Association Meeting, Quebec, Canada, September 9-12, 1986.

2. Bruckner, A.P., and Hertzberg, A., "Development of the Ram Accelerator Hypervelocity Launcher," Proceedings of the 38th Aeroballistic Range Association Meeting, Tokyo, Japan, October 6-9, 1987.

3 Knowlen, C., Scott, K.A., Bruckner, A.P. and Hertzberg, A., "Recent Developments in Ram Accelerator Technology," Proceedings of the 39th Aeroballistic Range Association Meeting, Albuquerque, New Mexico, October 10-13, 1988.

4. Bruckner, A.P., Hertzberg, A., Kull, A.E., Burnham, E.A., Knowlen, C. and Yungster, S., "High Velocity Modes of the Ram Accelerator," Proceedings of the 40th Aeroballistic Range Association Meeting, Paris, France, September 25-28, 1989.

5. Knowlen, C., Burnham, E.A., Kull, A.E., Bruckner, A.P. and Hertzberg, A., "Ram Accelerator Performance in the Transdetonative Velocity Regime," Proceedings of the 41st Aeroballistic Range Association Meeting, San Diego, CA, October 22-25 1990.

6. Hertzberg, A., Bruckner, A.P., and Bogdanoff, D.W., "Ram Accelerator: A New Chemical Method for Accelerating Projectiles to Ultrahigh Velocities," AIAA Journal, Vol. 26, 1988, pp. 195-203.

7. Bruckner, A.P., Knowlen, C., Hertzberg, A., and Bogdanoff, D.W., "Operational Characteristics of the Thermally Choked Ram Accelerator," J. Propulsion and Power, Vol. 7, 1991, pp. 828-836.

8. Yungster, S., Eberhardt, S., and Bruckner, A.P., "Numerical Simulation of Hypervelocity Projectiles in Detonable Gases," AIAA J. Vol. 29, February 1991, pp 187-199.

9. Chew, G., Knowlen, C., Burnham, E.A., Hertzberg, A. and Bruckner, A.P. "Experiments on Hypersonic Ramjet Propulsion Cycles Using a Ram Accelerator." AIAA Paper 91-2489, June 1991.

10. Bruckner, A.P., Chew, G., Auzias de Turenne, J., and Dunmire, B., "Investigation of Hypersonic Ramjet Propulsion Cycles Using a Ram Accelerator Test Facility," Paper No. IAF-91-275, 42nd Congress of the International Astronautical Federation," Montreal, Canada, October 5-11, 1991.

11. Bogdanoff, D.W., Knowlen, C., Murakami, D. and Stonich, I., "A magnetic Detector for Projectiles in Tubes," AIAA Journal vol. 28, 1990, pp 1942-1944.

12. Bruckner, A.P., Burnham, E.A., Knowlen, C., Hertzberg, A. and Bogdanoff, D.W., "Initiation of Combustion in the Thermally Choked Ram Accelerator," Paper No. F13, Proceedings of the 18th International Symposium on Shock Waves, Sendai, Japan, July 21-26, 1991, in press.

13. U.S. Patent No. 4,982,647 "Method and Apparatus for Initiating Stable Operation of a Ram Accelerator," Hertzberg, A., Bruckner, A.P., Bogdanoff, D.W., Knowlen, C., University of Washington, Seattle, WA, 1991.

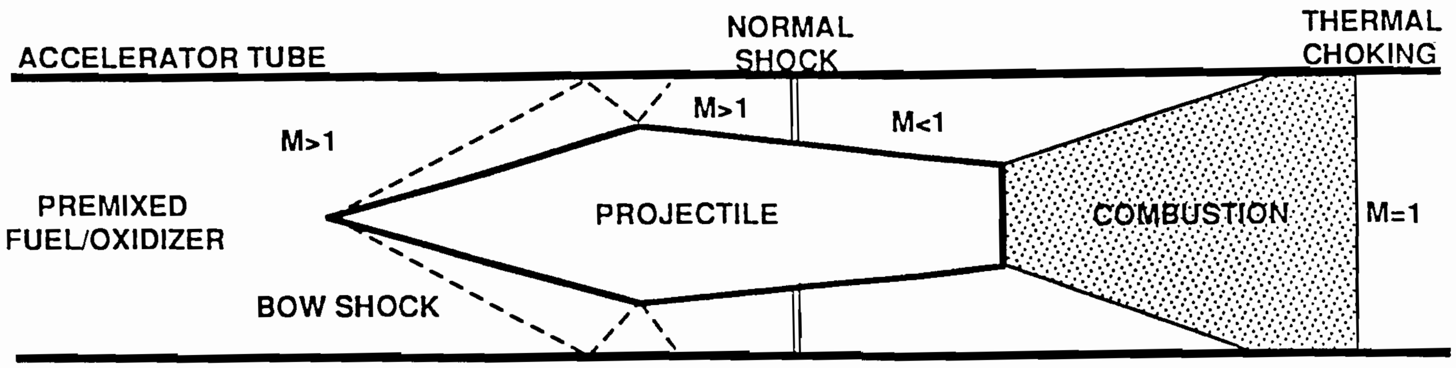


Fig. 1 Schematic of thermally choked ram accelerator propulsive mode.

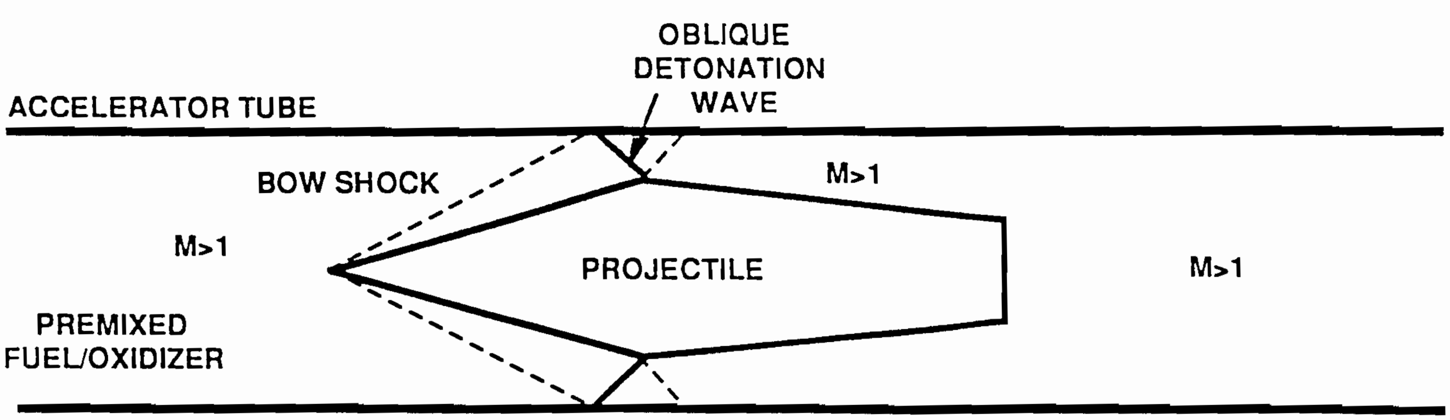


Fig. 2 Schematic of oblique detonation ram accelerator propulsive mode.

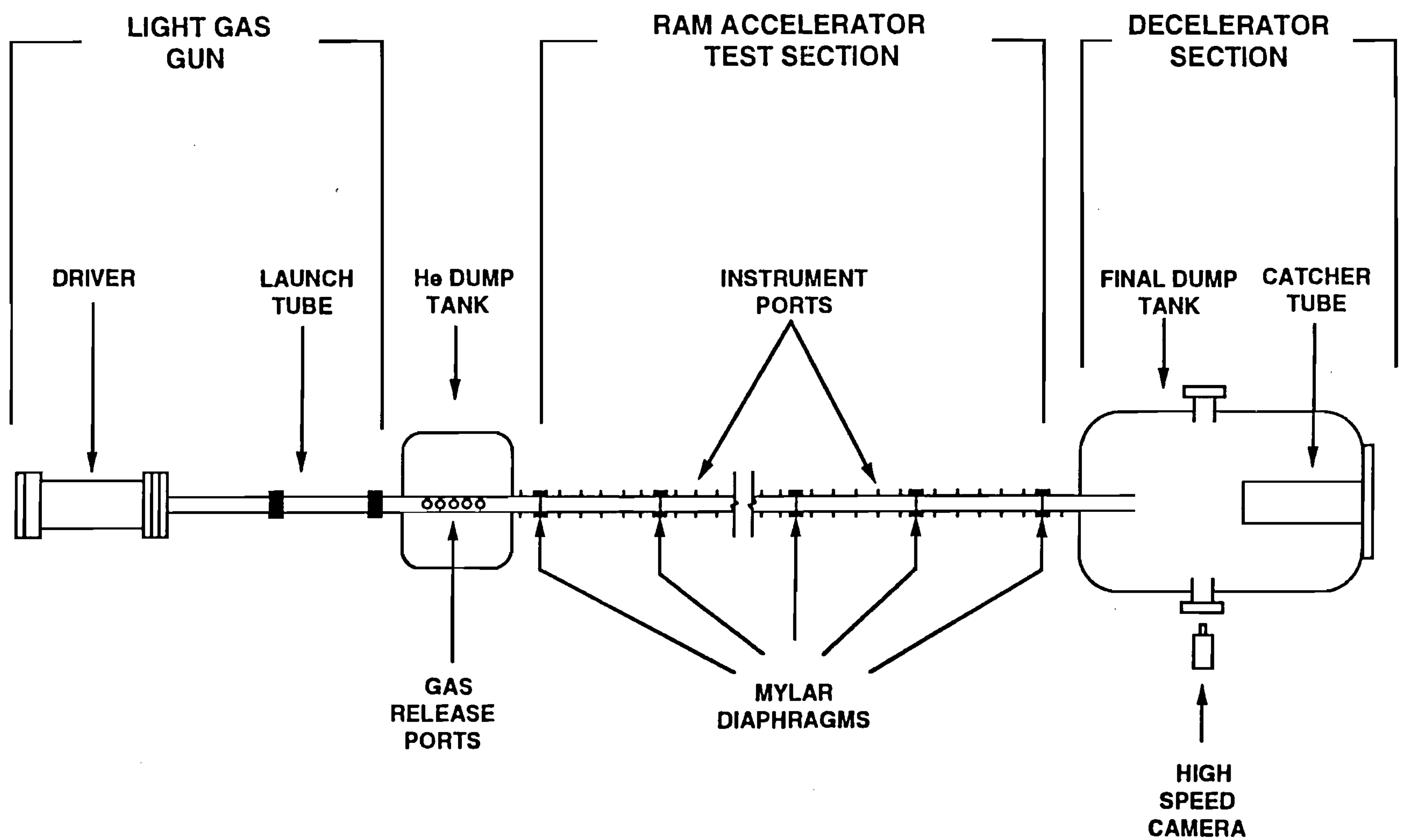


Fig. 3 Schematic of experimental ram accelerator facility.

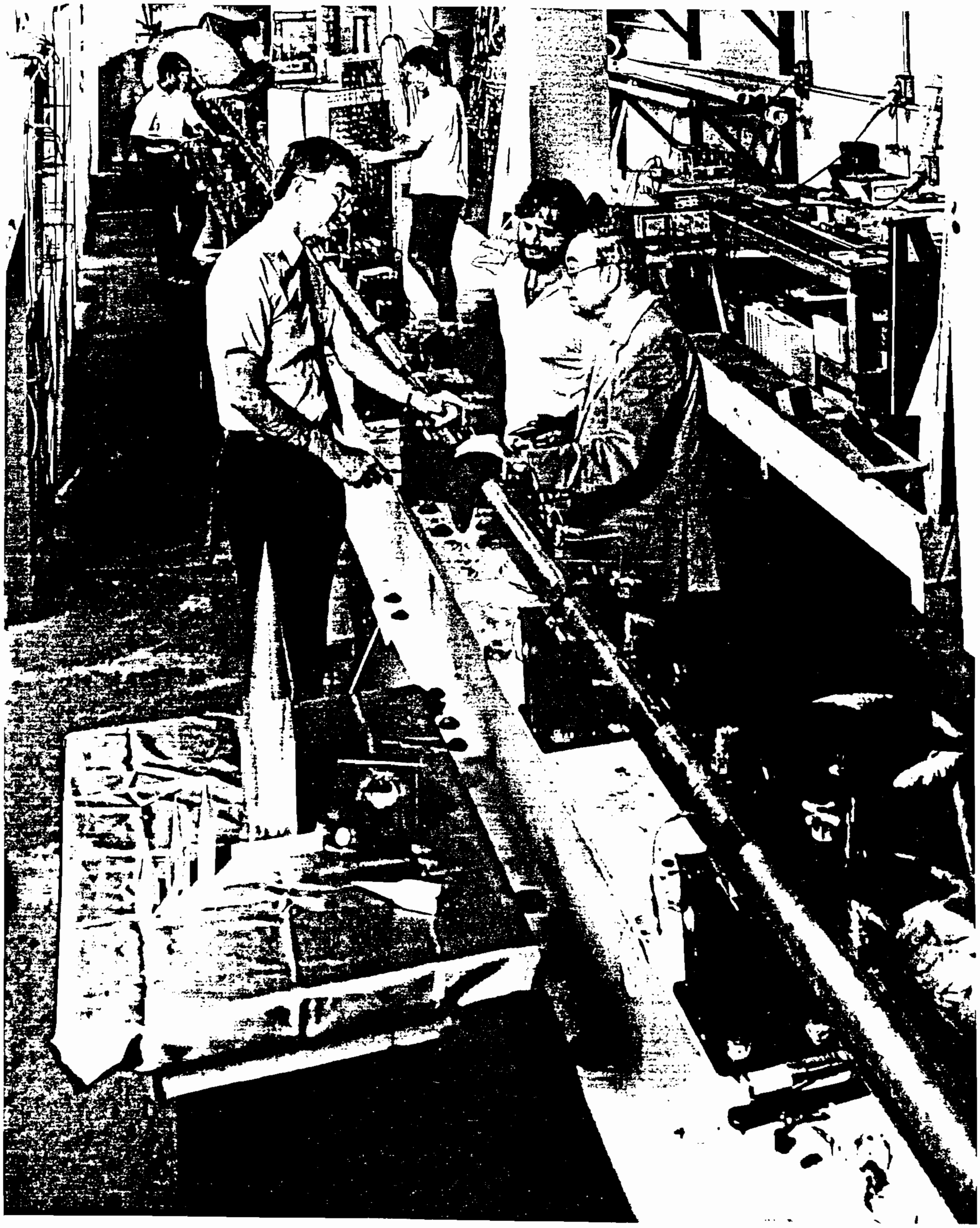
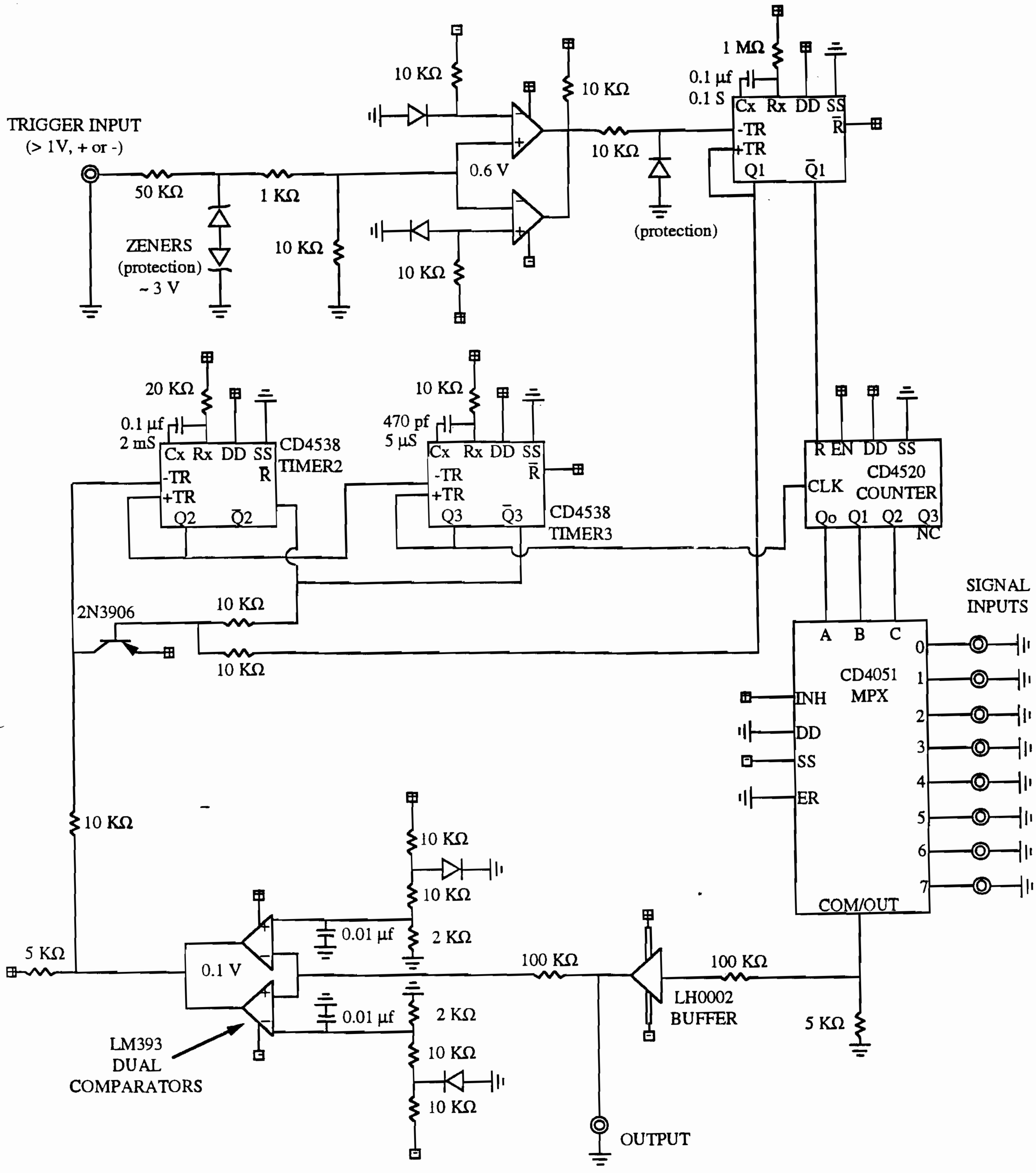


Fig. 4. Photograph of ram accelerator facility.



NOTE: All diodes are 1N4148 unless otherwise noted.
Power supply leads on all IC's must be decoupled by 0.1 µf capacitors (not shown).
All signal inputs are connected to ground by 10 KΩ resistor (not shown).
+ and - refers to +12 V and -12 V.

Fig. 5 Schematic of signal multiplexer circuit.

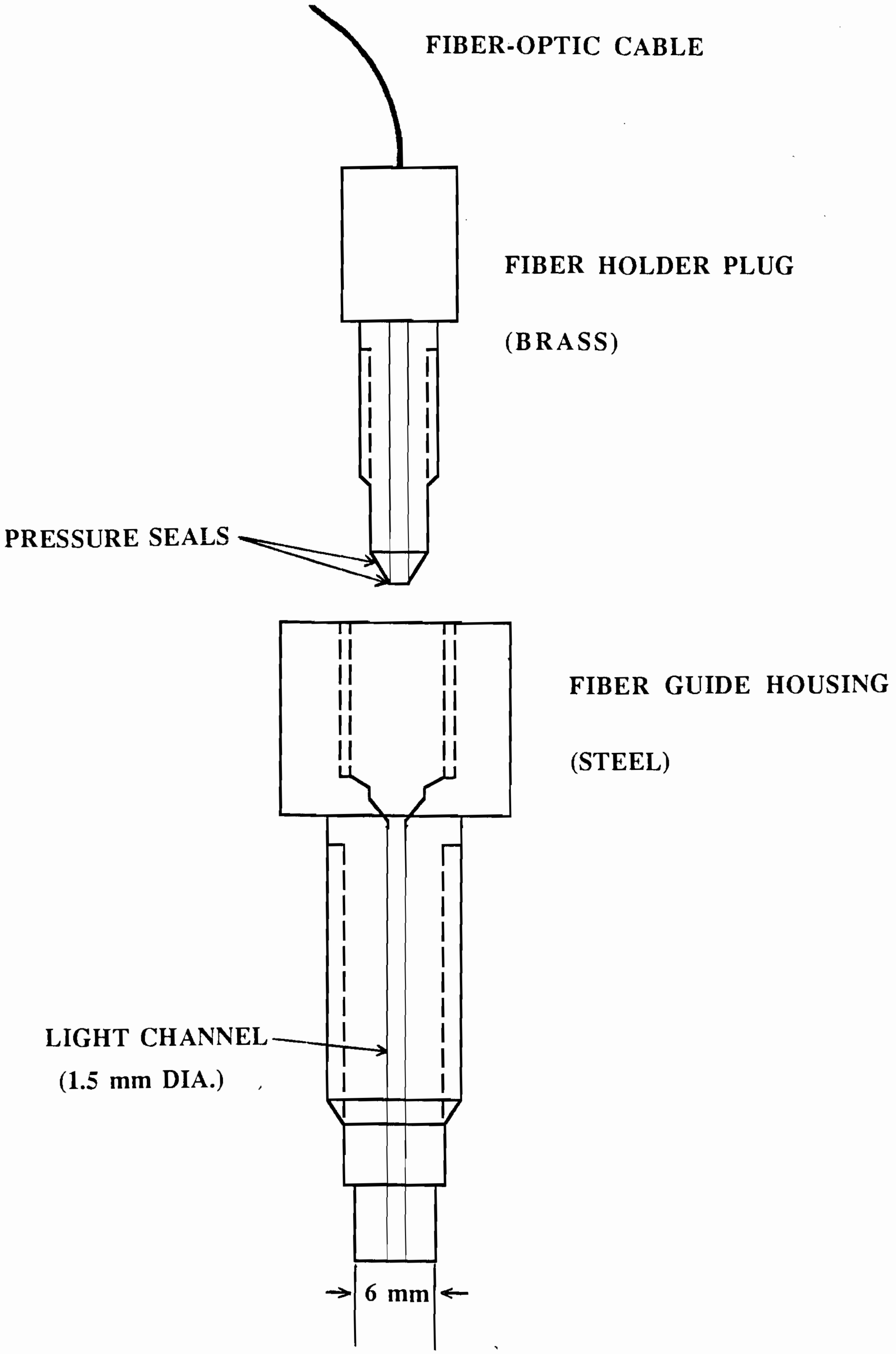
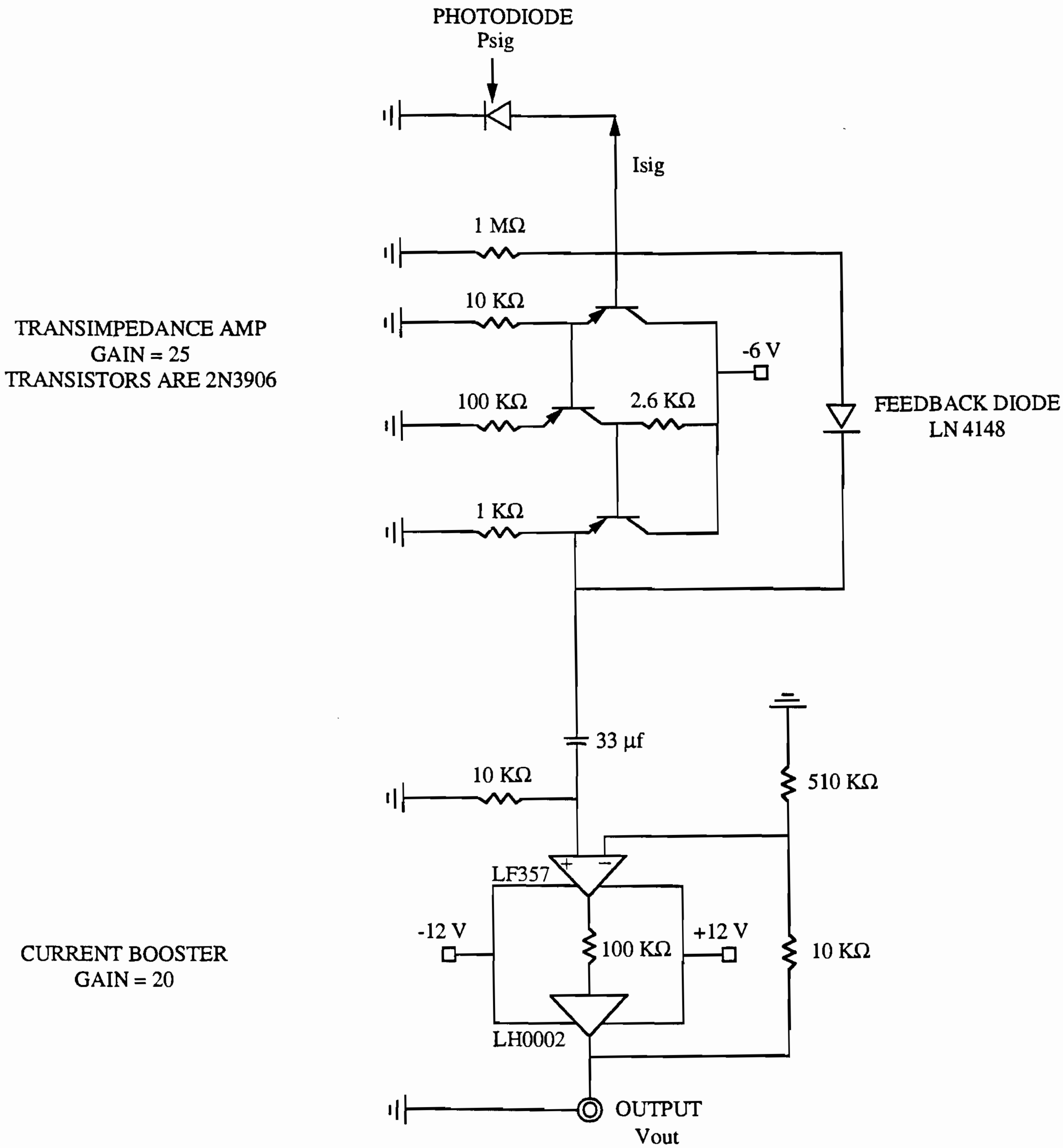


Fig. 6 Schematic of fiber-optic probe.



RESPONSE:	Vout (volts) ~ ln[1 + 1/2 Isig(μA)]
PHOTODIODE:	Isig(μA) ~ 0.5Psig(μW)
BANDWIDTH:	1 Hz to 1 MHz
NOISE:	Vout(noise) ~ 1 MV (rms)
DYNAMIC RANGE:	10-8 W < Psig < 10-2 W (S/N > 1)

Fig. 7 Schematic of logarithmic amplifier circuit for photodiodes.

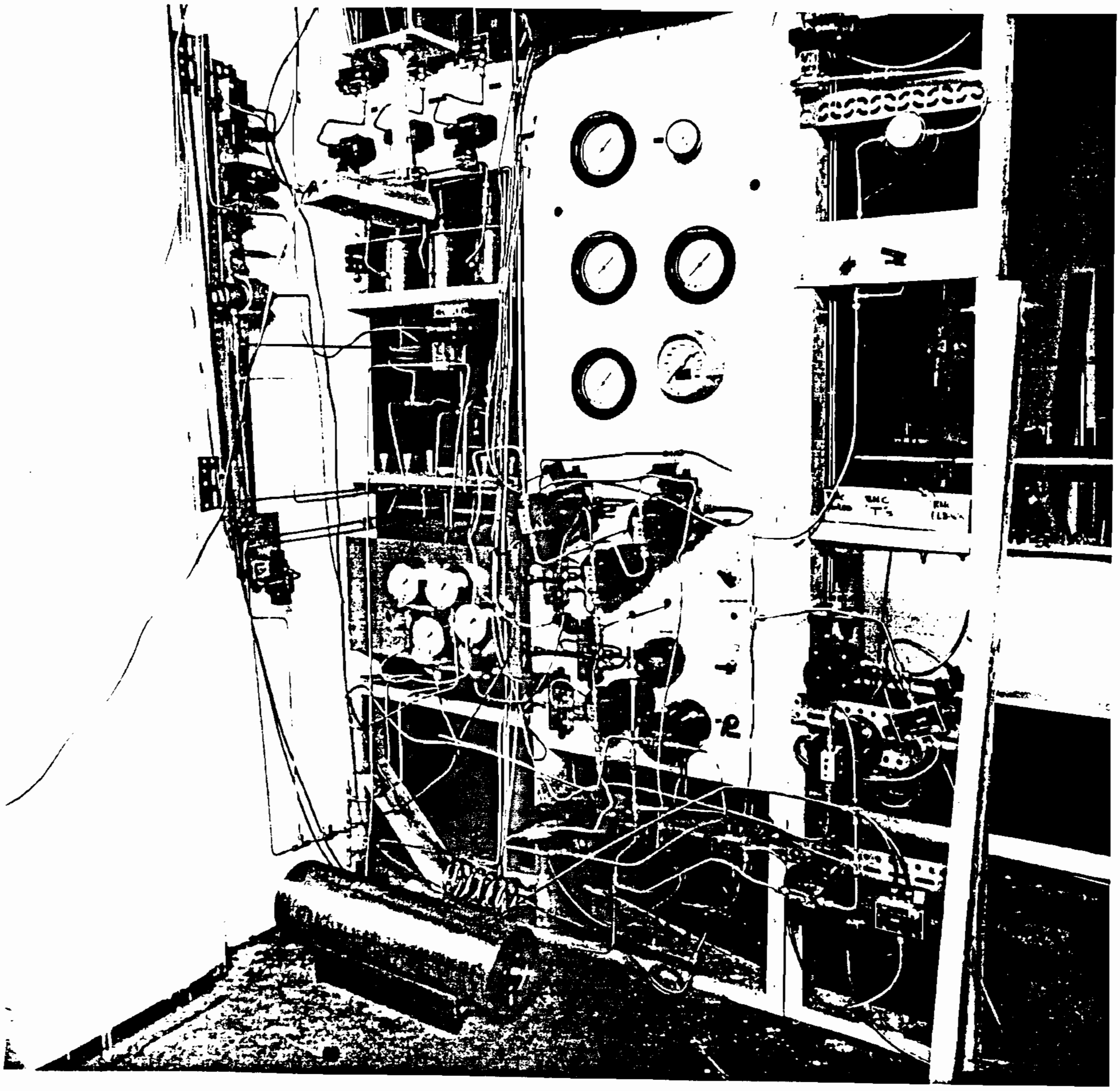


Fig. 8 Photograph of propellant mixing system.

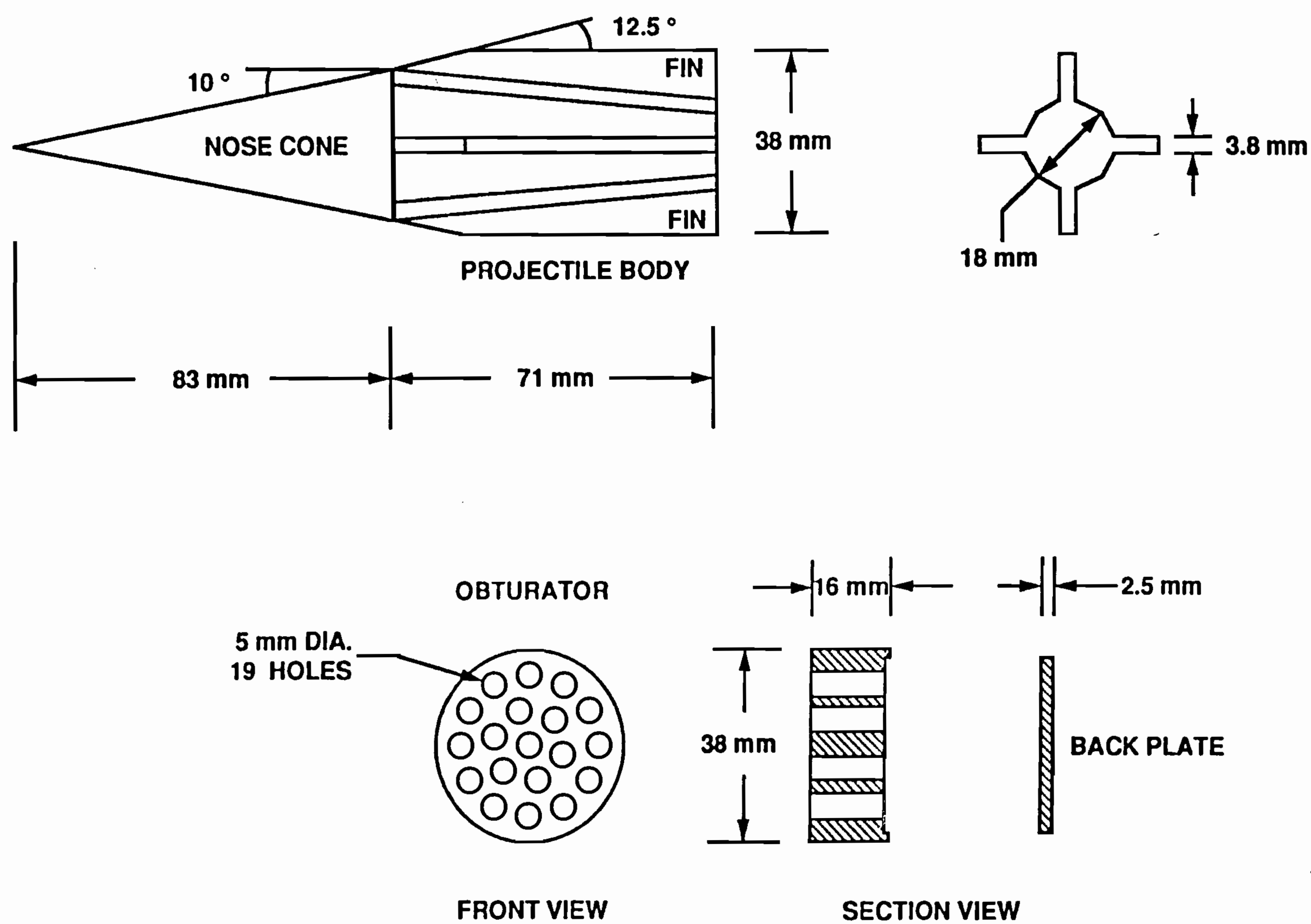


Fig. 9 Typical experimental projectile and obturator.

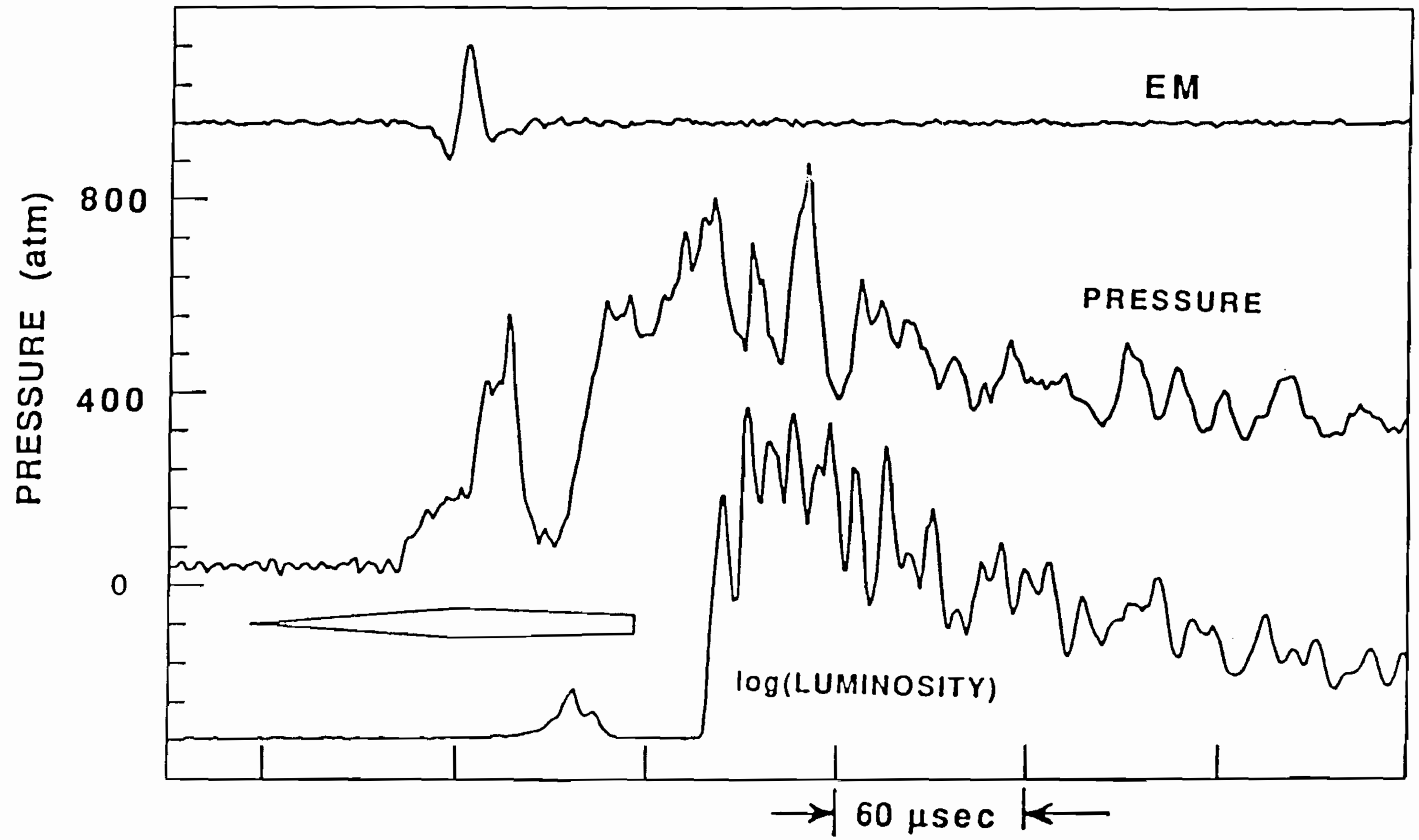


Fig. 10 Typical electromagnetic (EM), pressure, and broadband luminosity signals in thermally choked ram accelerator.

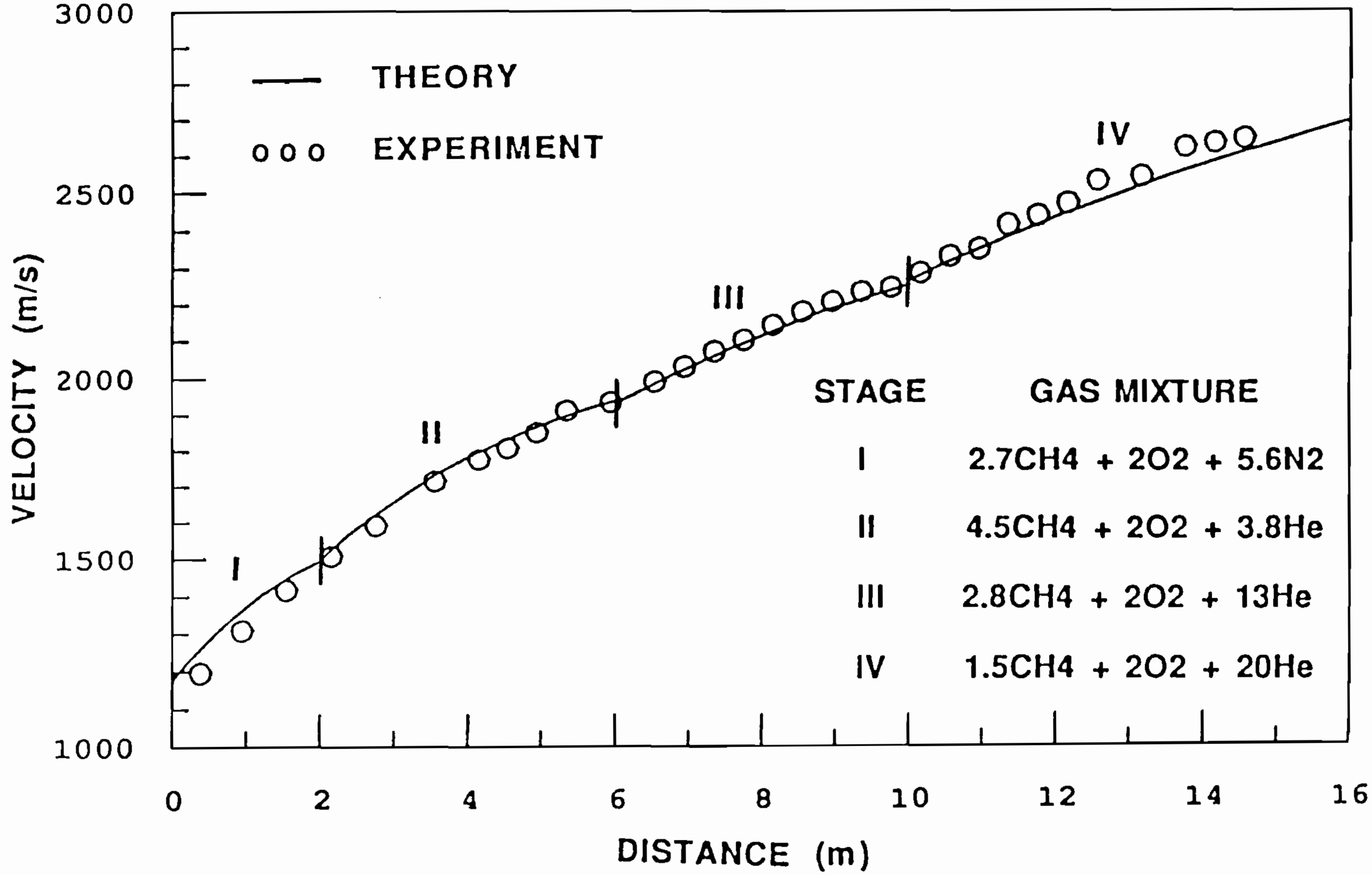


Fig. 11 Velocity-distance profile of four-stage thermally choked ram accelerator experiment.