EXPERIMENTAL INVESTIGATION OF THE RAM ACCELERATOR PRINCIPLE: INSTRUMENTATION AND DATA ACQUISITION

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Abstract

EXPERIMENTAL INVESTIGATION OF THE RAM ACCELERATOR PRINCIPLE: INSTRUMENTATION AND DATA ACQUISITION

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This thesis is presented to lay the groundwork for continuing research on the University of Washington Ram Accelerator project. A streamlined projectile is used to simulate the converging diverging section of a ramjet engine. The projectile, when fired into a tube containing a combustible gas, is to be accelerated by combustion processes. The gas is compressed and burned in the recirculating zone behind the projectile in a ramjet mode. Thermal choking results and forward thrust is generated. A detailed explanation of the experimental apparatus and instrumentation developed during the research is presented. Interpretation of results from some of the experiments is included. The operating procedure is outlined and some of the experience gained to date is discussed. Techniques required for the maintenance and for the preparation of each experiment and the basic procedure followed for a test firing are also included.

Table of Contents

Page

List of Illustrations

List of Plates

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The author would like to take this opportunity to express his sincere gratitude and appreciation to his graduate faculty advisor Professor Adam P. Bruckner, to Professor Abraham Hertzberg who had enough faith in me to offer me the job and to Dr. David W. Bogdanoff for his valuable assistance.

The author would also like to thank his fellow research assistants: Carl Engelbrecht, Carl Knowlen, Dean Brackett, Keith McFall and Dale Barr. A special thanks also to his dear friend Deanna Hough for her magic fingers and toes.

CHAPTER I

INTRODUCTION

Achieving high velocities for a projectile fired from a gun is limited by the energy available in the driving gas. Specifically, the velocity of a projectile in a gun is limited by the acoustic velocity of the expanding driving gas. The efficiency of converting the internal energy of the gas into kinetic energy decreases rapidly as the projectile velocity is increased. A new concept of achieving velocities significantly greater than the acoustic velocity of the propellant gas is being developed at the University of Washington. This concept, called the Ram Accelerator, involves utilizing chemical energy in such a way that the energy release process travels with the vehicle. This concept is unlike the rocket in that no fuel or oxidizer is carried on board the vehicle.

The gasdynamic principle involved in the Ram Accelerator is similar to that used in airbreathing ramjet engines (Ref. 2). Four principal components make up a ramjet: the diffuser, the fuel injection, the combustor and the exhaust nozzle (Fig. 1). Forward motion is needed to initialy drive the gas through the engine. The engine itself contains no moving parts; this leads to simplicity, low weight, and high thermal efficiency. The gas is compressed in the diffuser through shock waves and also through subsonic diffusion to a higher pressure. Fuel is added at a location behind the normal shock and ignited. A flame holder is used to stablize the combustion zone. The burned gases are expanded through a nozzle and ejected rearward at high velocity.

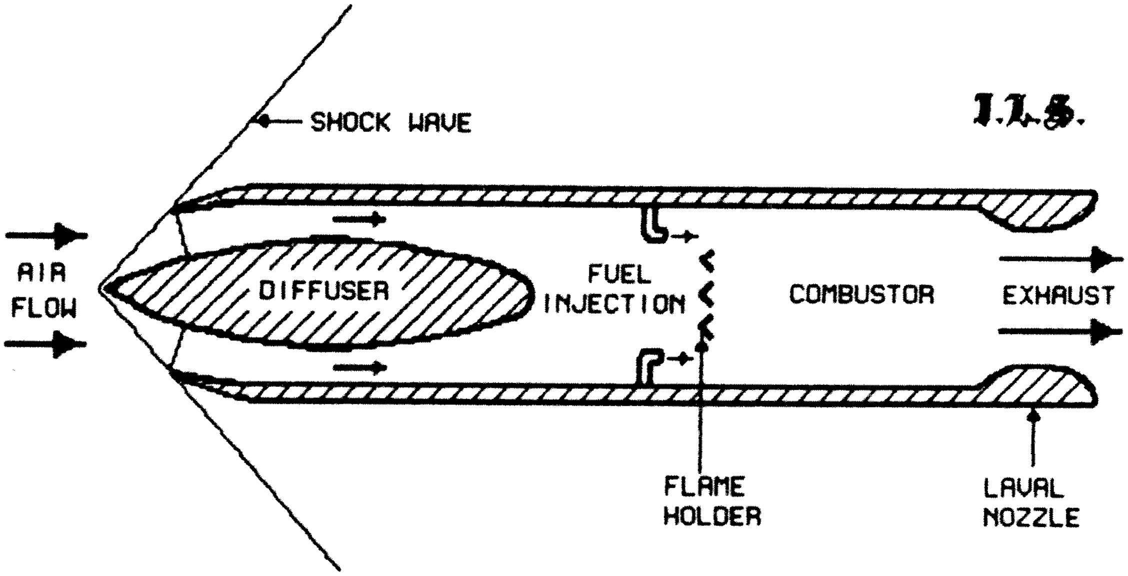


Fig. 1 Ramjet Flow Diagram

The Ram Accelerator however, is operated in a slightly different manner. Two modes of combustion are used, subsonic combustion and overdriven detonation. In the subsonic combustion mode the projectile is initially accelerated to approximately 1,000 m/s by conventional means whereupon it enters a tube filled with a combustible gas mixture whose pressure and composition (and hence, chemical energy, and acoustic velocity) can be controlled. The projectile enters at a Mach number greater than or equal to 2.5 to start the ramjet mode of operation. An oblique shock wave system is established in the diffuser section of the projectile. As the projectile travels through the combustible mixture in the tube the gas is first compressed in the oblique wave system and then through a normal shock wave. Combustion occurs in the region behind the projectile and thermally chokes the flow. The chemical heat release results in forward thrust. This mode of operation can accelerate the projectile to the 2,000 to 3,000 m/s range.

In the overdriven detonation mode, the projectile travels at a velocity greater than the detonation speed of the combustible gas mixture. An overdriven detonation wave forms on the vehicle aft of the diffuser throat. Combustion occurs in a thin layer adjacent to the shock front and the heated gas is expanded through a convergent-divergent nozzle, providing thrust. This mode of operation can accelerate the projectile to velocities in excess of 5,000 m/s.

CHAPTER II

RAM ACCELERATOR FACILITY

The Ram Accelerator facility, located in the Aerospace and Energetics Research Building, is composed of twelve principal components.

1. High Pressure Driver
2. Double Diaphragm Section
3. Launch Tube Section
4. Driver Gas Dump Tank
5. Sabot Stripper Section
6. Sabot Stripper Dump Tank
7. Start Section
8. Ram Accelerator Section
9. Final Dump Tank
10. Decelerator Section
11. Gas Handling System
12. Data Acquisition System

A schematic of the Ram Accelerator facility is shown in Fig. 2 and photographs of the same are shown in Plates I-IV. Each component is described below in order of progression along the apparatus.

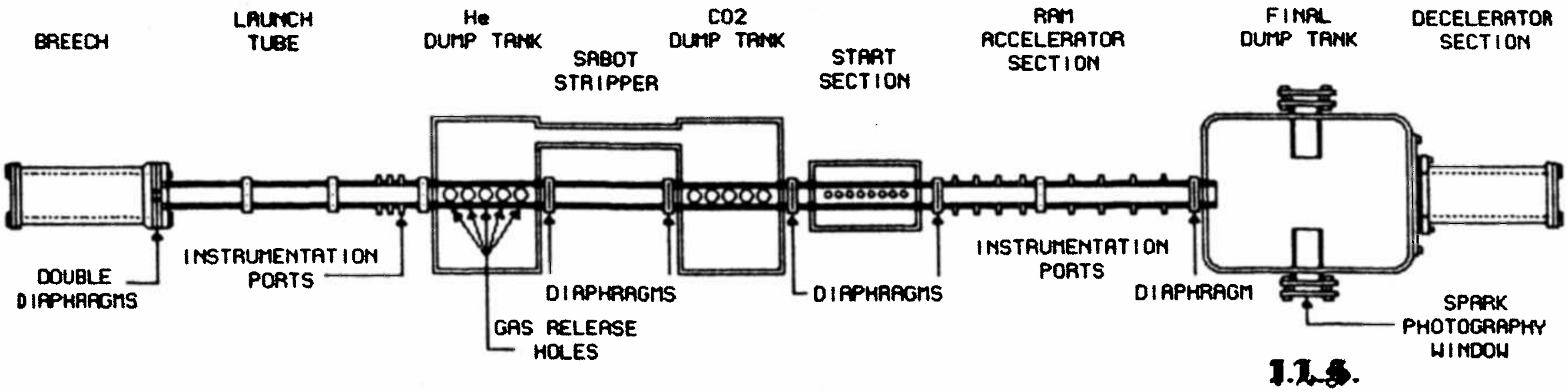


Fig. 2 Schematic of the Ram Accelerator Facility

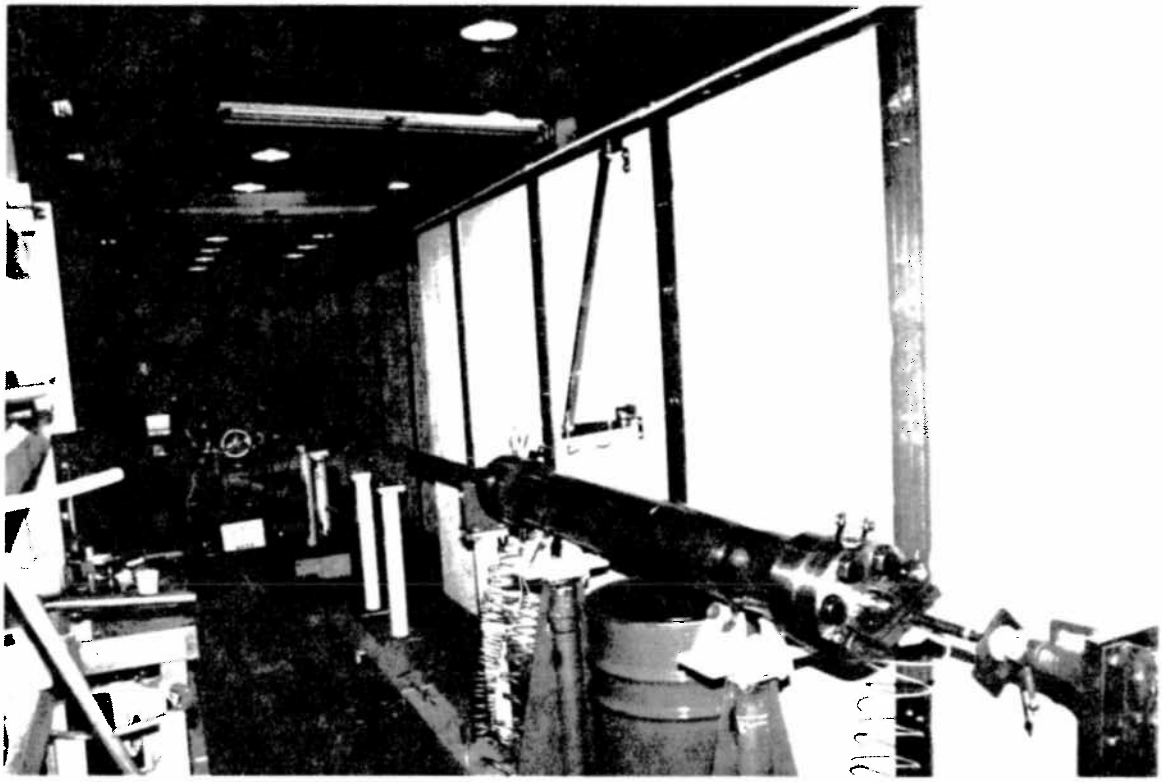


Plate I. Breech and Launch Tube

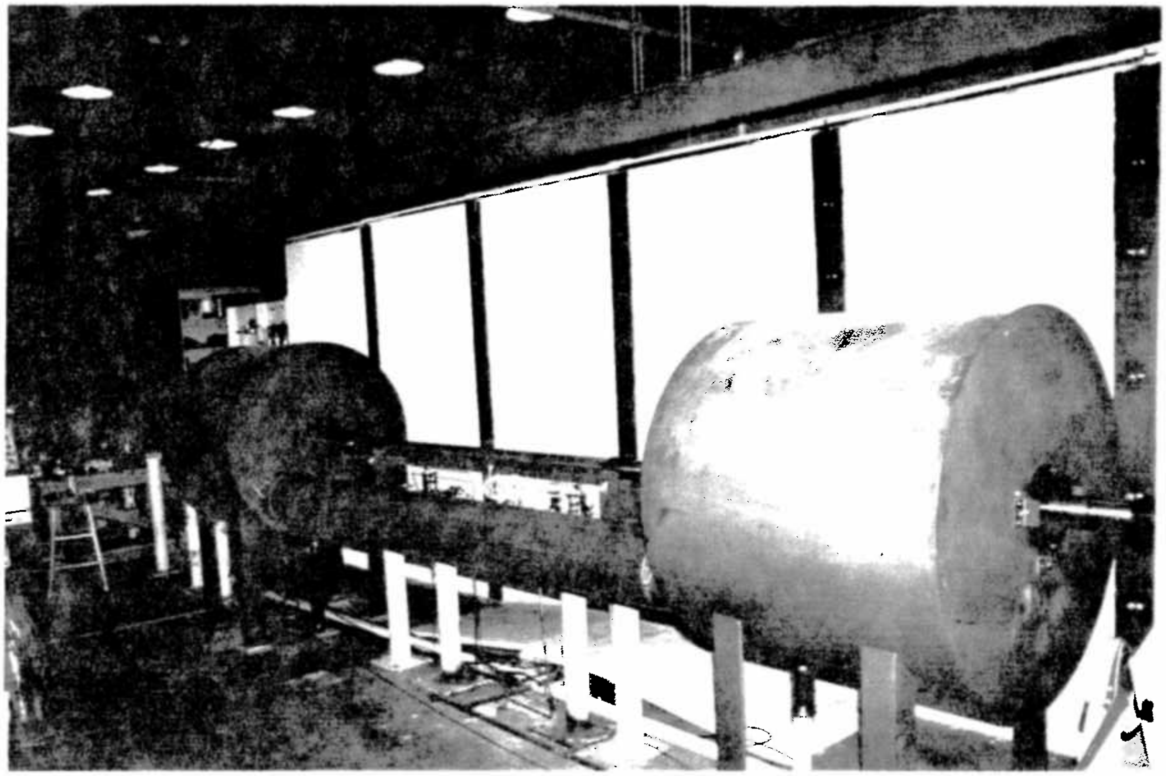


Plate II. Driver Gas and Sabot Stripper Dump Tanks

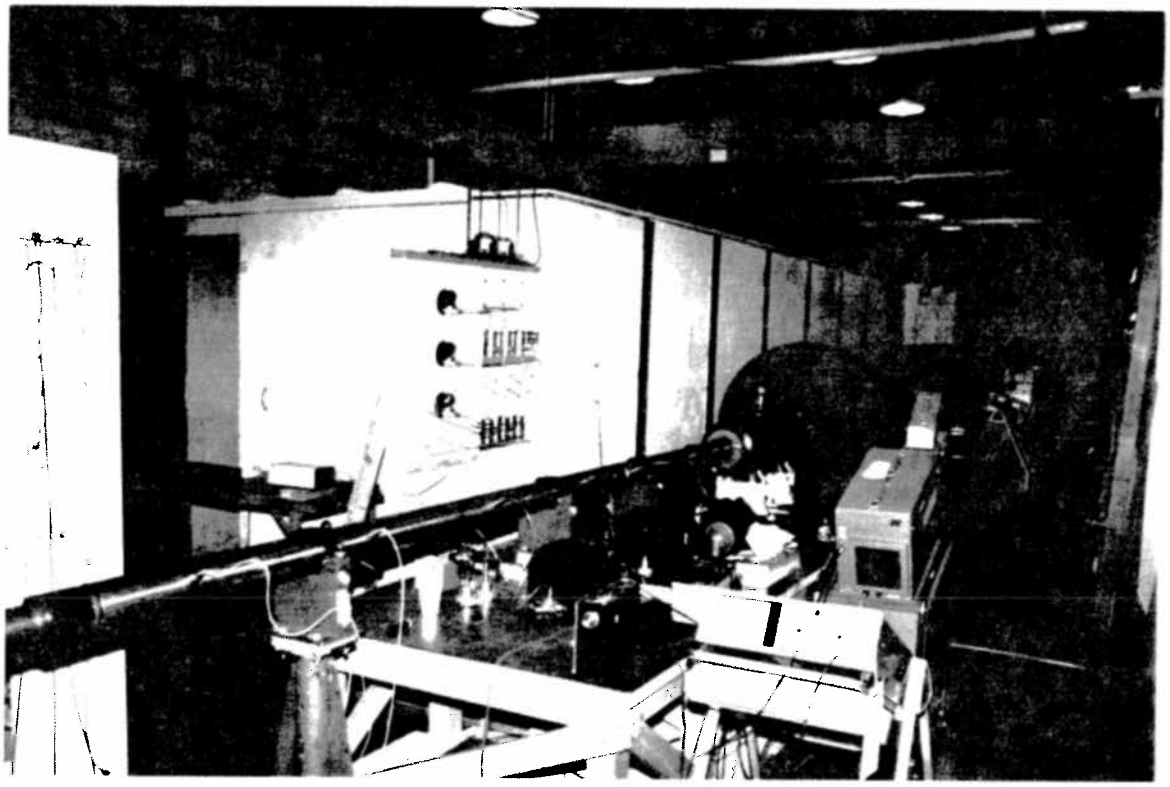


Plate III. Start Section and Ram Accelerator Section

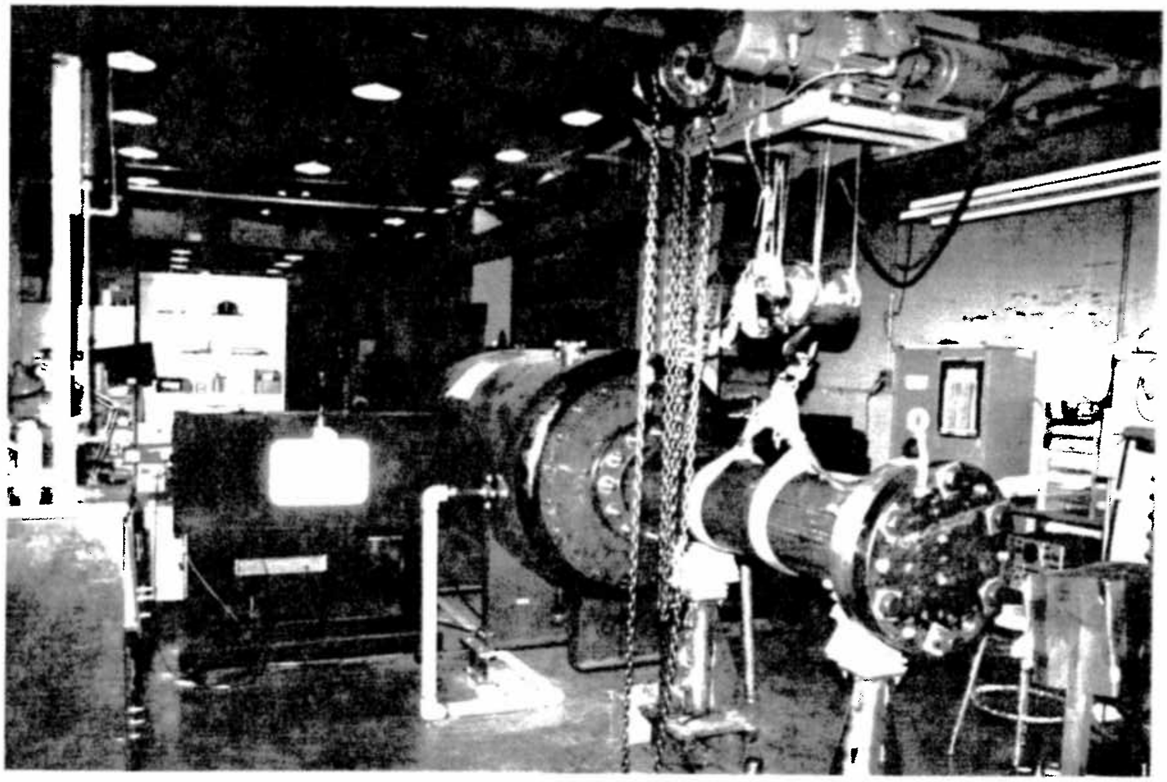


Plate IV. Final Dump Tank and Decelerator Section

1. High Pressure Driver

The high pressure driver was designed and fabricated at the University of Washington. It consists of a cylindrical 4142 steel flanged tube heat-treated to Rockwell C 28-32, with the following principal dimensions: 4 in. inside diameter, 8 in. outside diameter and 6 ft. length . It is located at the south end of the Ram Accelerator facility. The driver is supported on two ball bearing support stands. This permits horizontal movement necessary for maintenance and recoil. To dampen the recoil a Taylor " Fluidshoks " shock absorber is utilized. This device is placed between the driver and a screw jack attached to a brace mounted against the south wall. A 3 in. thick steel plate seals the upstream end of the driver tube. To this plate is attached a high pressure gas line from the pressure control panel (Plate V).

2. Double Diaphragm Section

A triple flange connects the driver section to the adjacent launch tube (Fig. 3). Each flange incorporates a high pressure O-ring seal and dowel pins to support and align the two diaphragms. The flanges are bolted to the driver section and the launch tube is threaded into the last flange. A high pressure gas line is connected to the first flange. This line is used to pressurize the space between the two diaphragms, and is connected to the pressure control panel. The interdiaphragm space is pressurized to about 2/3 of the breaking pressure (P1) of the metal diaphragm. The driver is filled to about 4/3 of the breaking pressure (P2). Thus, when the gas in the interdiaphragm space is released both diaphragms rupture. A vacuum line is attached from the second flange to the vacuum control panel (Plate VI) in order to evacuate the space between the downstream diaphraghm and the vehicle sabot.

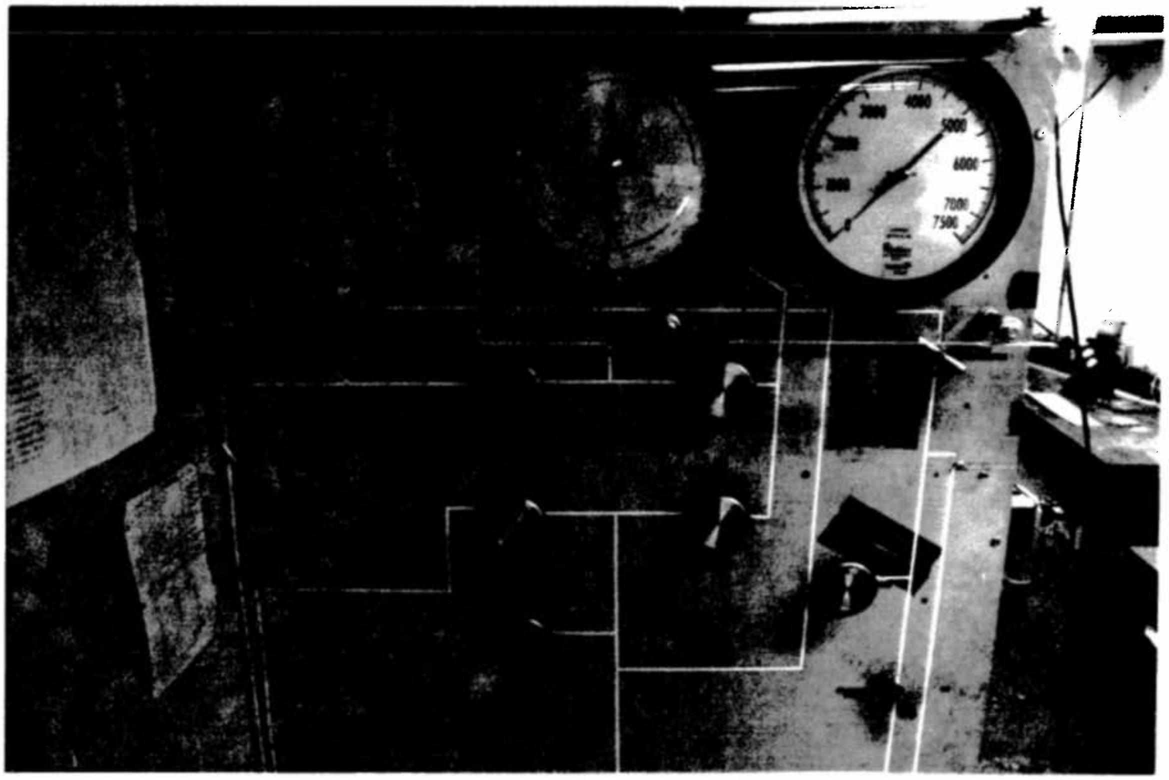


Plate V. Pressure Control Panel

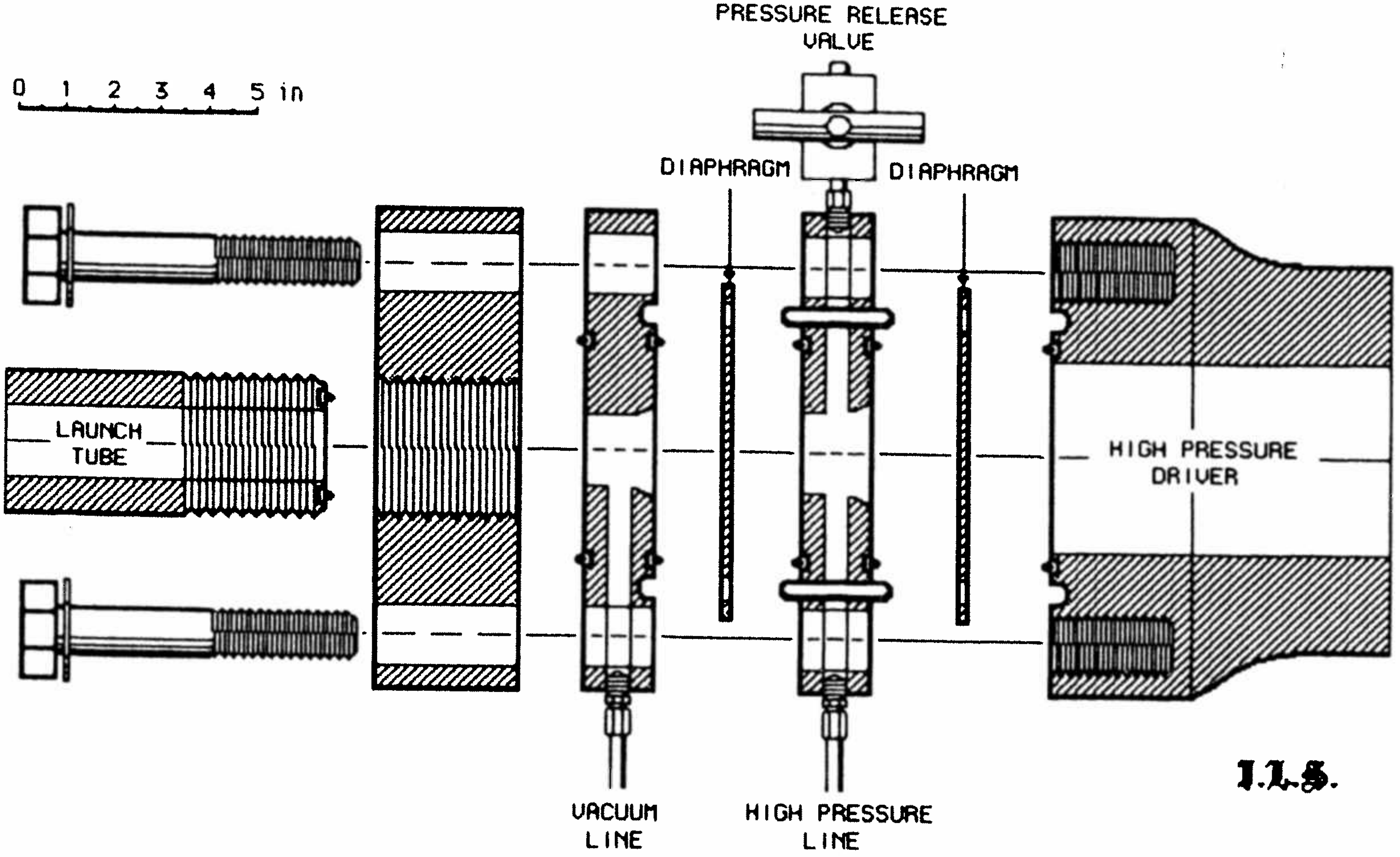


Fig. 3 Schematic of the Double Diaphraghm Section

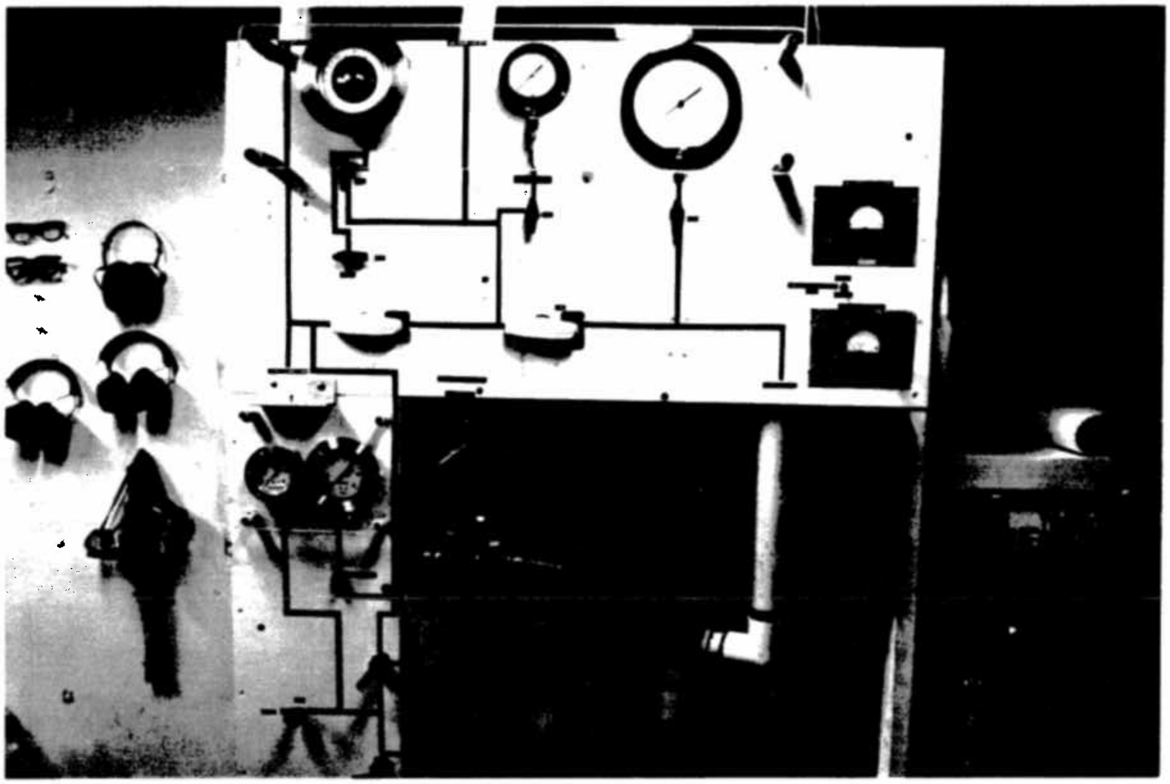


Plate VI. Vacuum Control Panel

The diaphragms are made from 1100-0 (dead soft) aluminum sheets 0.032", 0.064", 0.096", or 0.125" thick. Two knife edge scores, 90 degrees apart, are made in each diaphragm. The scores are oriented 45 degrees to the rolling grain of the aluminum. The force needed to generate the score is supplied by a hydraulic press. From rupture tests, the force needed to properly score the various diaphragms to give a good operating range of burst pressures has been determined. The diaphragms must be inserted with the scribed face downstream (toward the launch tube) for proper rupture. This helps to prevent pieces of the diaphragm from breaking off and being thrown down the launch tube.

3. Launch Tube Section

The launch tube section is composed of three 8 ft. long, 1.5 in. I.D., 3 in. O.D. tubes made of 4150 steel heat treated to Rockwell C 28-32. Each tube section has a double O-ring seal at both ends. The tube joints are held together by threaded collars. Each tube rests on ball bearing support stands, which allows axial movement of each tube for periodic maintenance and inspection. At the end of the last launch tube, three pairs of " generic " instrumention ports have been tapped into the sidewall. These are diametrically opposed and spaced at 6 in. intervals. One pair of opposed instrumentation ports contains light fiber probes and is used to trigger the data acquisition system. One fiber illuminates the other with light from a He-Ne laser. The other two pairs of ports contain two Kistler pressure transducers mounted on the same side of the tube. Opposing these are one blank plug and one vacuum line attachment, respectively.

The vehicle/sabot combination (Plate VII), initially at the driver end of the launch tube is forced down the evacuated launch tube upon the bursting of the double diaphragms. The sabot has a hollowed out cavity in the rear which provides a Bridgeman high pressure seal against the tube wall. The expansion of the high pressure gas drives the sabot/projectile combination down the launch tube to speeds up to approximately 1200 m/sec. As the projectile passes the light fiber instrumentation port, the He-Ne laser light that emanates from one of the fiber light guides is obscured. The change in output from the opposing fiber probe is detected by a photodiode which generates a trigger signal for the data acquisition system.

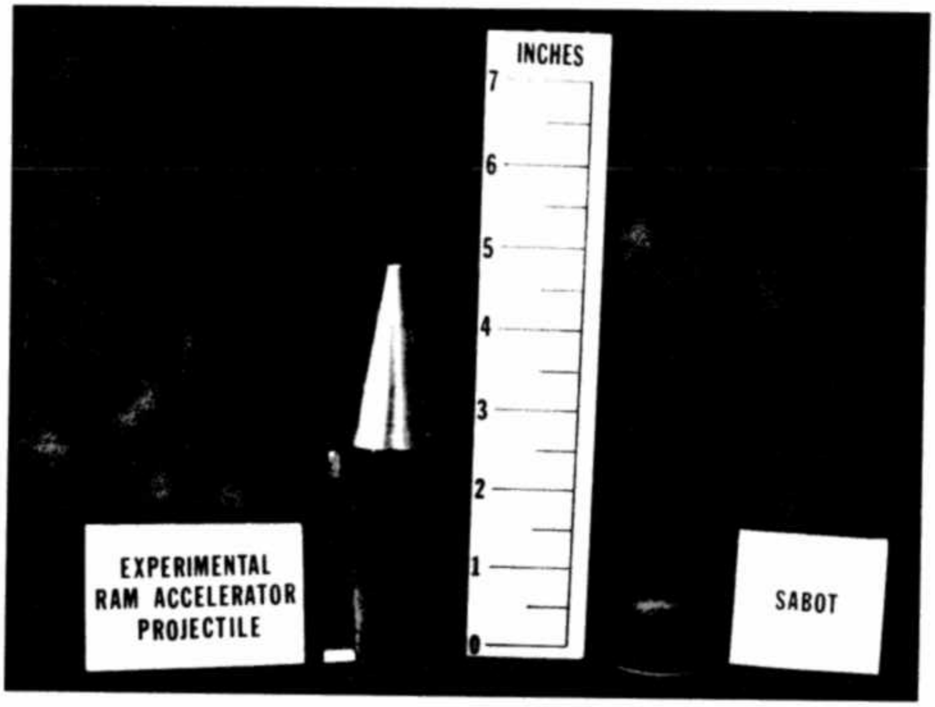


Plate VII. Projectile and Sabot

4. Driver Gas Dump Tank

The end of the launch tube is connected to a 5 foot long perforated tube inside a large cylindrical tank which serves as a dump for the helium driver gas. This tank is evacuated through a 2 in. I.D. PVC vacuum line connected to the vacuum control panel. The tank has adjustable O-ring seal collars on both ends to allow axial movement of the tube.

5. Sabot Stripper Section

Upon leaving the dump tank, the projectile/sabot combination traverses a 0.002 in. thick Mylar diaphragm and enters the sabot stripper section which is a single 8 ft. long tube, similar to the launch tubes. A single gas line branches off from the tube to two valves. the two lines from these valves are used to evacuate and pressurize the tube.

A high molecular weight gas, such as CO2, is used to separate the sabot from the projectile. When the projectile/sabot combination enters the pressurized gas region a normal shock wave is generated ahead of the sabot. The high pressure region behind the shockwave produces a large drag force on the sabot. The projectile, which does not fill the tube diameter and is heavier and streamlined experiences a much lower drag force and thus moves ahead of the sabot. A detailed investigation of sabot separation phenomena can be found in Reference 3.

6. Sabot Stripper Dump Tank

After the sabot is separated from the projectile, the projectile travels through another 0.002 in. thick Mylar diaphragm into a 5 ft. long perforated tube inside the sabot stripper gas dump tank. This tank is identical to the driver gas dump tank and is evacuated via a 10 in. diameter interconnecting tube. Sabot stripping gas and any residual driver gas escapes into this dump tank.

The shock waves that are generated in the sabot stripper section are diffused by the perforated tube. This prevents a Kantrowitz unstart condition from occuring before the projectile enters the Ram Accelerator section. In a Kantrowitz unstart, the flow at the throat of the projectile is choked. When this occurs a shock wave is propagated ahead of the projectile and the flow on the projectile goes subsonic, greatly increasing the drag.

7. Start Section

The start section is composed of a 4 ft. long, 3.5 in. O.D. 1.5 in. I.D., thick walled perforated tube that fits inside a pressure containment tube. A line is connected to the combustible gas mixing panel (Plate VIII) which can evacuate or fill the start section with an inert gas or a combustible gas mixture. When the start section is left evacuated it can serve as an extension of the second dump tank. In another application a thin Mylar diaphragm is inserted at the joint after the second dump tank and the start section is filled with an inert gas. This provides a pressurized gas region which the projectile can travel through before reaching the combustible gas mixture in the Ram Accelerator section. A variation of this application is to use a combustible gas mixture in the start section. The combustible mixture in the start section may differ from that in the Ram Accelerator tube and its pressure may also be different.

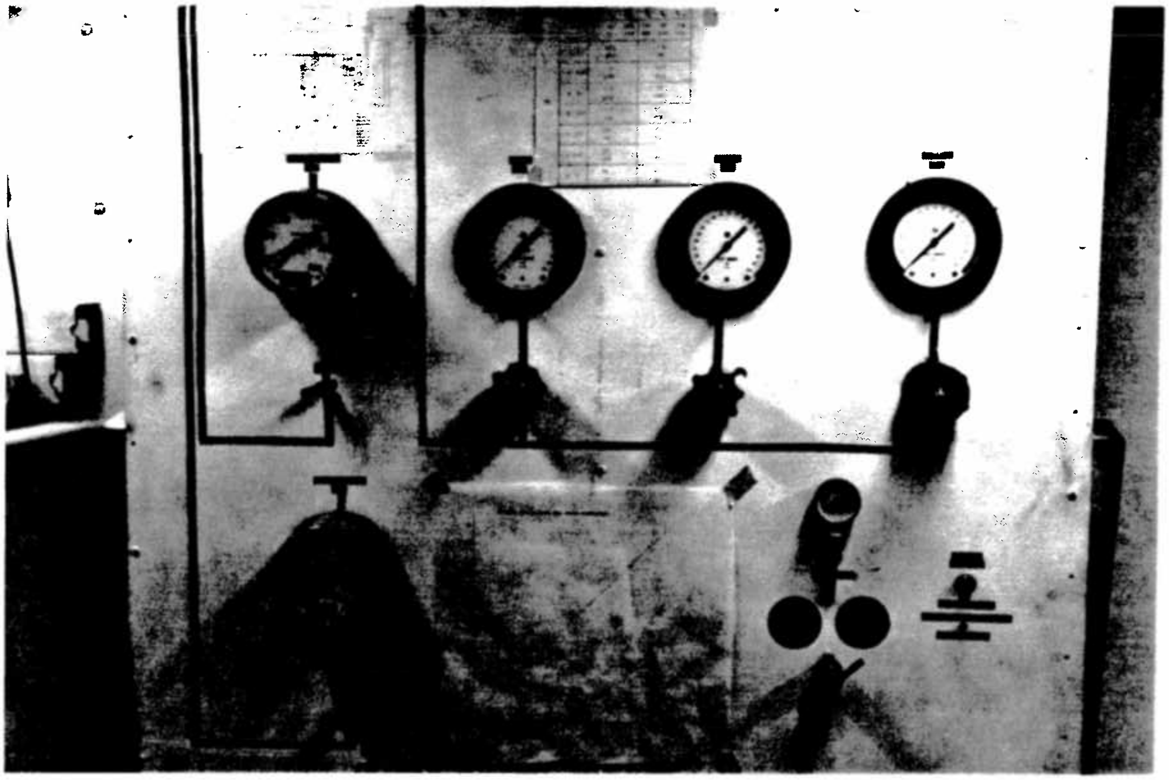


Plate VIII. Combustible Gas Mixing Panel

The start section is used to eliminate the possibility of a projectile diffuser starting problem (Kantrowitz unstart). If when the projectile enters the perforated tube, a shock wave is propagated ahead of the projectile, the high porosity of the perforated tube serves to dissipate the shock. This assumes the establishment of supersonic flow over the projectile before it enters the Ram Accelerator section.

The start section is removable and a 4 ft. long instrumentated tube can be inserted in its place. This provides an additional eight instrumentation ports and can be used as an extention to the Ram Accelerator section.

8. Ram Accelerator Section

The Ram Accelerator section consists of 2 tubes: tube # 1 is 4 ft. long, has a 1.5 in. I.D., a 4 in. O.D., and has four pairs of diametrically opposed instrumentation ports tapped at 12 in. intervals. Tube # 2 is 8 ft. long, has a 1.5 in. I.D., a 4 in. O.D., and it also has 4 pairs of diametrically opposed instrumentation ports tapped at 24 inch intervals. Both tubes are made from 4150 steel heat treated to Rockwell C 36-40. This provides 16 instrumentation ports from which to observe the progress of the projectile and sabot. The 8 ports that are located on the same side of the tubes are used to house Kistler pressure transducers. On the other side are found blank plugs, light fiber probes, and a line that is connected to the combustible gas mixing panel. This line is used to evacuate and then fill the Ram Accelerator with the combustible gas mixture.

Upon entering the Ram Accelerator section, the projectile pierces a 0.005 in. thick Mylar diaphragm. This diaphragm is the one that is used to set off the ignitor in the projectile. A small magnesium pellet, 0.060 in. dia. X 0.070 in. long is glued to the center of the diaphragm. The pellet is scooped up by the projectile in flight, travels through a tube in the prjectile and activates the primer of the ignitor shell which is filled with 1.5 gm. of black powder. Upon ignition, the hot reaction gases escape through four ports in the shell, enter an annular plenum and exit through eight exhaust ports at the base of the projectile. The hot gases (> 1500 deg. C.) enter the recirculation region behind the base of the projectile and ignite the combustible gas in the Ram Accelerator section.

9. Final Dump Tank

When the accelerated projectile leaves the Ram Accelerator section it travels through a 0.003 in. thick Mylar diaphragm and into the final dump tank, where it flies free. The final dump tank is evacuated by a 2 inch PVC vacuum line. This dump tank is the largest of the three that are used, with dimensions of 4 ft. dia. and 8 ft. length. A pair of diametrically opposed 10 in. dia. Plexiglas viewing portholes have been added to each side of this tank. These portholes provide the means to observe the projectile in flight and to verify the survival of the projectile after the high stresses encountered during the initial launch process. Since the projectile is largely destroyed when it is decelerated in the catcher tube, the projectile integrity must be verified. A high speed spark shadowgraph photography system (exposure time aproximately 300 ns.) was installed to take a photograph of the vehicle as it flies through the final dump tank (Ref. 4). The shadowgraph equipment setup is shown in Fig. 4 and a photograph of a projectile in flight is shown in Plate IX . The photographs show that the projectile does survive the initial launch acceleration of up to 25,000 g's .

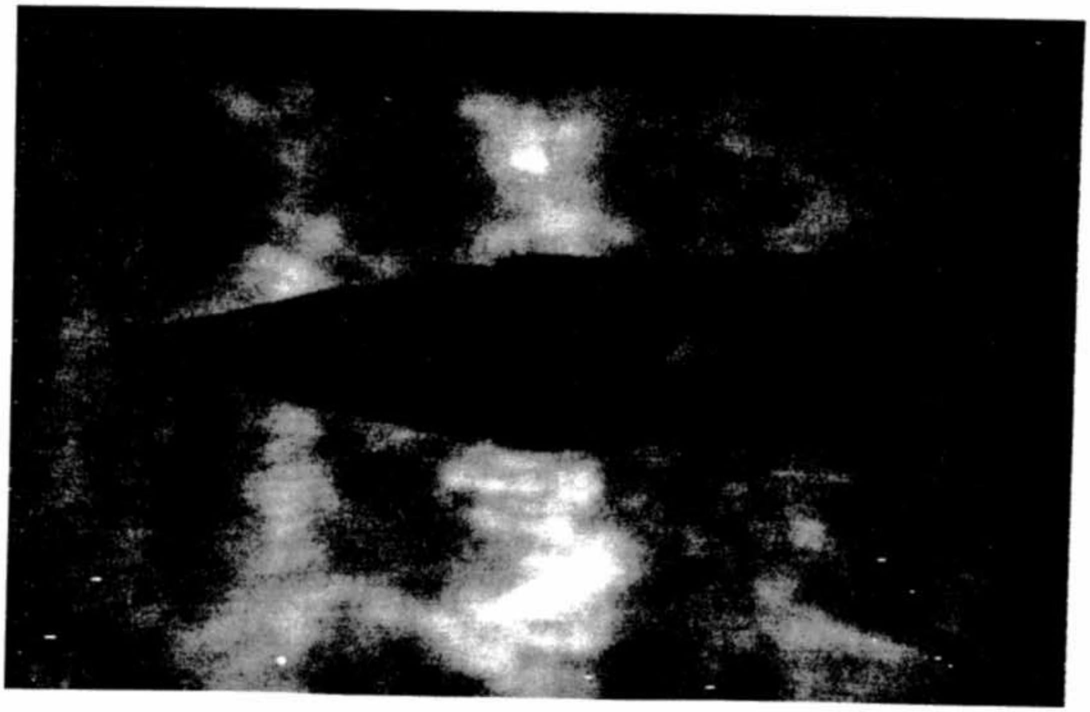


Plate IX. Spark Photograph of the Projectile in Flight (V=940 m/sec.)

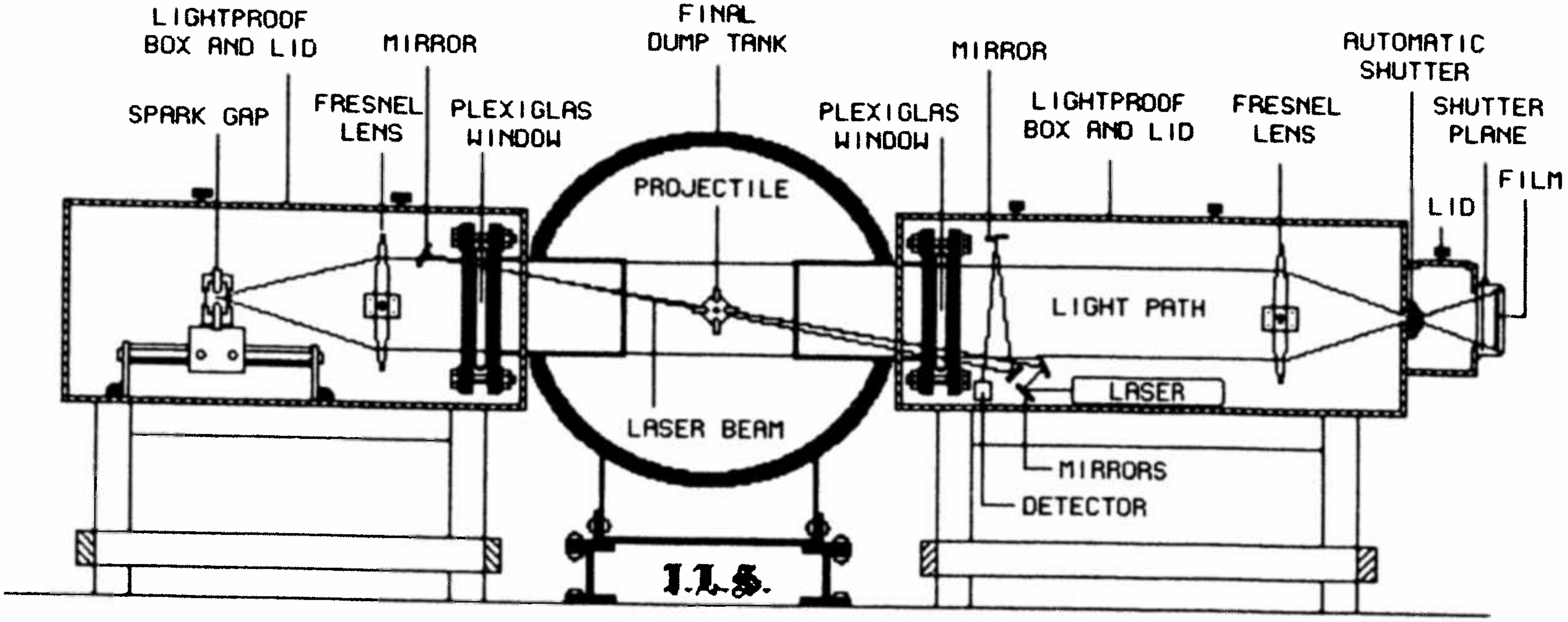


Fig. 4 Spark Shadowgraph Set-Up

A two-beam laser velocity measuring system has also been incorporated across the Plexiglas observation windows for a final velocity check before the projectile is stopped in the decelerator section.

10. Decelerator Section

The decelerator section is the last section of the Ram Accelerator apparatus. It has the following dimensions: 6 ft. length X 7 in. I.D. X 14 in O.D.. A 3 in. thick cover plate closes the rear of the tube. The catcher tube is separated from the final dump tank by a thin aluminum sheet having perforations to equalize the pressure between the two volumes. The end plate and the final dump tank joints are O-ring sealed. The catcher tube rests upon two ball bearing support stands, which permits horizontal movement necessary for the repacking of the decelerating materials (carpet remnants and steel lathe turnings) and for the removal of any projectile/sabot debris.

11. Gas Handling System

A schematic of the total gas handling system is shown in Fig. 5 . Commercial bottled helium at a pressure of 1,700-2,400 psi provides the gun gas supply and is kept in the gas bottle bunker. A high pressure line links this to the pressure control panel. To attain higher pressures, a Corblin pump (Plate X) capable of reaching 6,000 psi is also connected to this panel. The complete high pressure system has been hydrostatically tested to 7,500 psi., using a special test rig was designed to use hydraulic fluid to displace water. Operating pressures at present range up to 3,000 psi.

Two Welch vacuum pumps (Plate XII) are connected with 2 inch PVC lines to the vacuum control panel. The main pump, Welch model 1398 (0.0001 torr, 1500 liter/min.), serves to evacuate the launch tube and the three gas dump tanks. The second, Welch model 1397 (0.0001 Torr, 500 liter/min.), serves as a back-up should the first pump fail. High pressure lines from the gas bottles in the gas bottle bunker are connected to the gas mixing control panel (Plate XIII). From this panel, the combustible gas mixture can be controlled. By adjusting the dome regulators to the proper mixture ratio and by using the automatic valves (also found on the same panel), the various gases can be sent through filters and sonic orifi (for a constant flow rate) to a flow mixer and then on to the Ram Accelerator section. The regulator for pressurizing the spark gap and the controls for the spark photography shutter are also found on this panel.

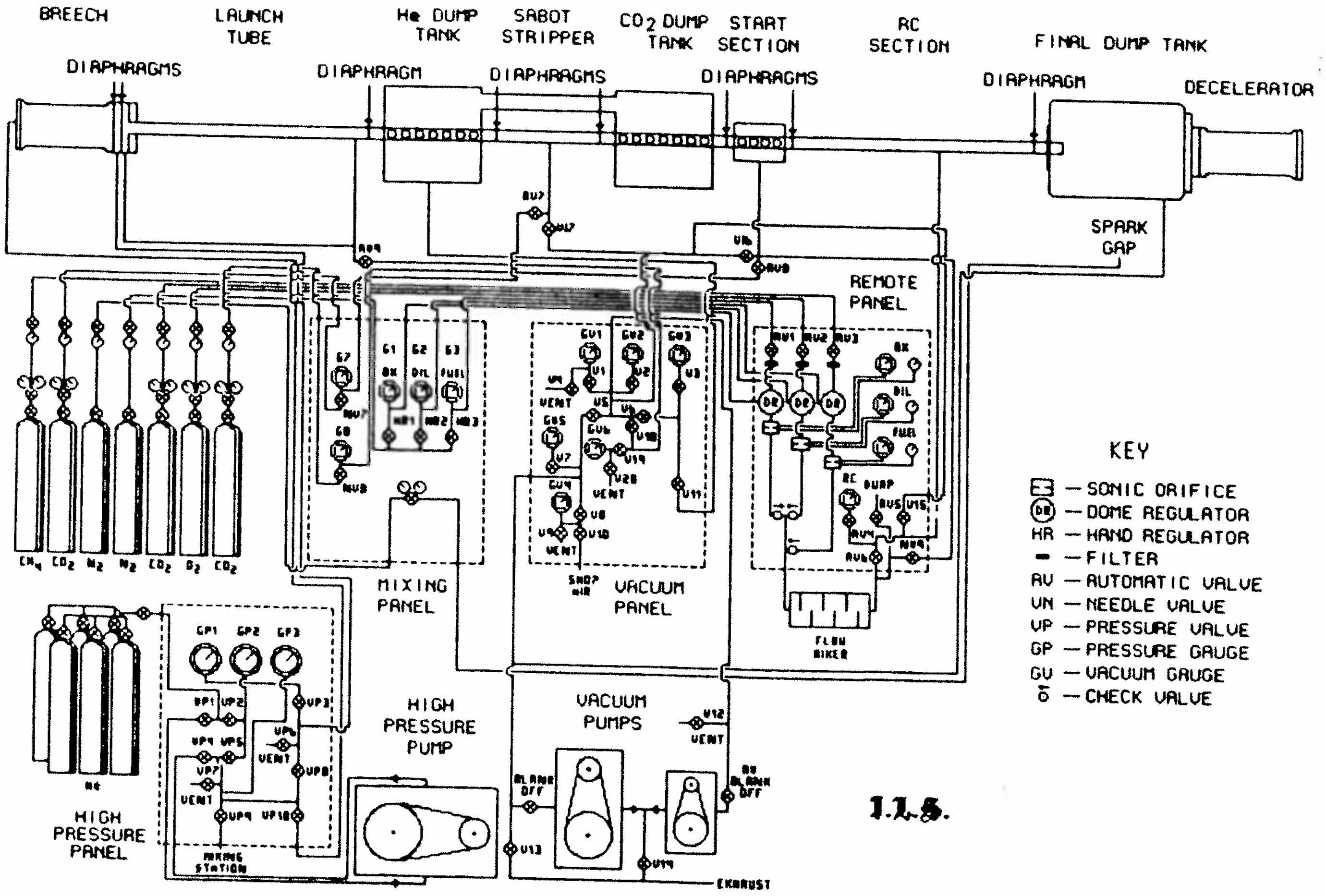


Fig. 5 Schematic of the Gas Handling System

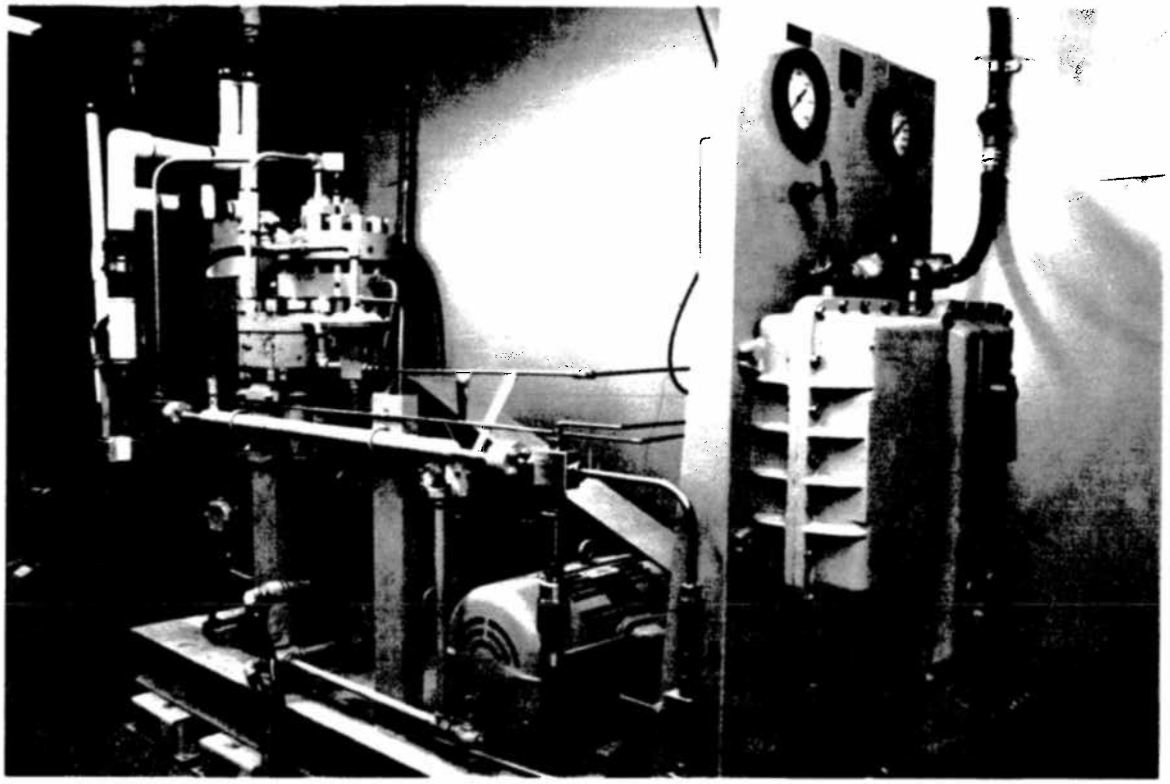


Plate X. High Pressure Corblin Pump

Plate XI. Model 1398 and Model 1397
Welch Vacuum Pumps

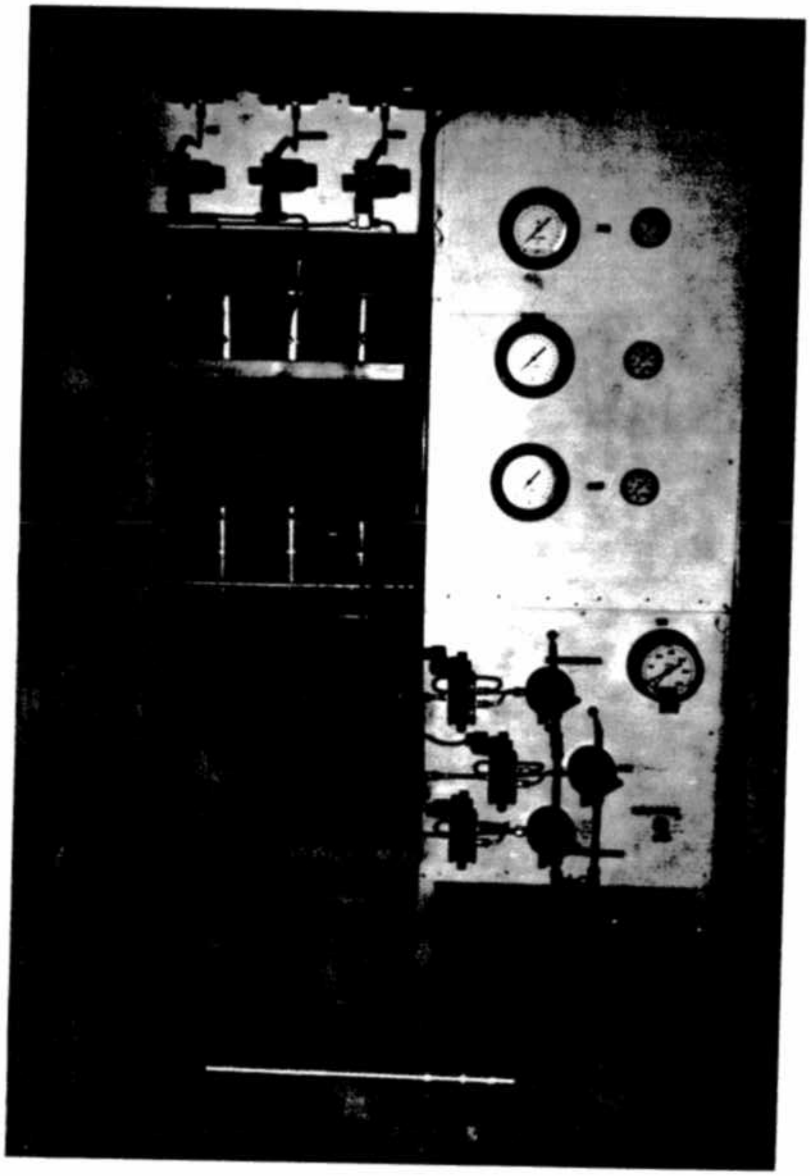


Plate XII. Gas Mixing Control Panel

12. Data Acquisition System

A 16-channel LeCroy Research Systems Corp. data acquisition system (Plate XIV) is used. All the light fiber and pressure transducer signals travel through coaxial cables to LeCroy model 8210 Quad 10-bit transient digitizers. These digitizers use track and hold cicuits, capable of handling four analog inputs per module. These analog input signals are digitized and stored in LeCroy model 8800A memory modules which have a capacity of 32k 12-bit words. The data are read out through the memory control cicuit in the 8210 unit and each of the four channels can be separately addressed. These modules, along with the LeCroy model 8252, 32 channel data logger and the LeCroy model 8910A CAMAC to GPIB interface are contained within the LeCroy model 1434 CAMAC crate. The crate employs a model 1034P CAMAC power supply. The 8910A CAMAC to GPIB interface connects to an IBM PC-XT microcomputer with 128kB random access memory, 40kB of read-only memory, a 10MB hard disk drive, and a 360kB floppy disk drive. A LeCroy Wave-Form Catalyst software program is used to manipulate and to display the data. To obtain a hard copy of the results a Hewlett-Packard HP2225C Think Jet printer is used.

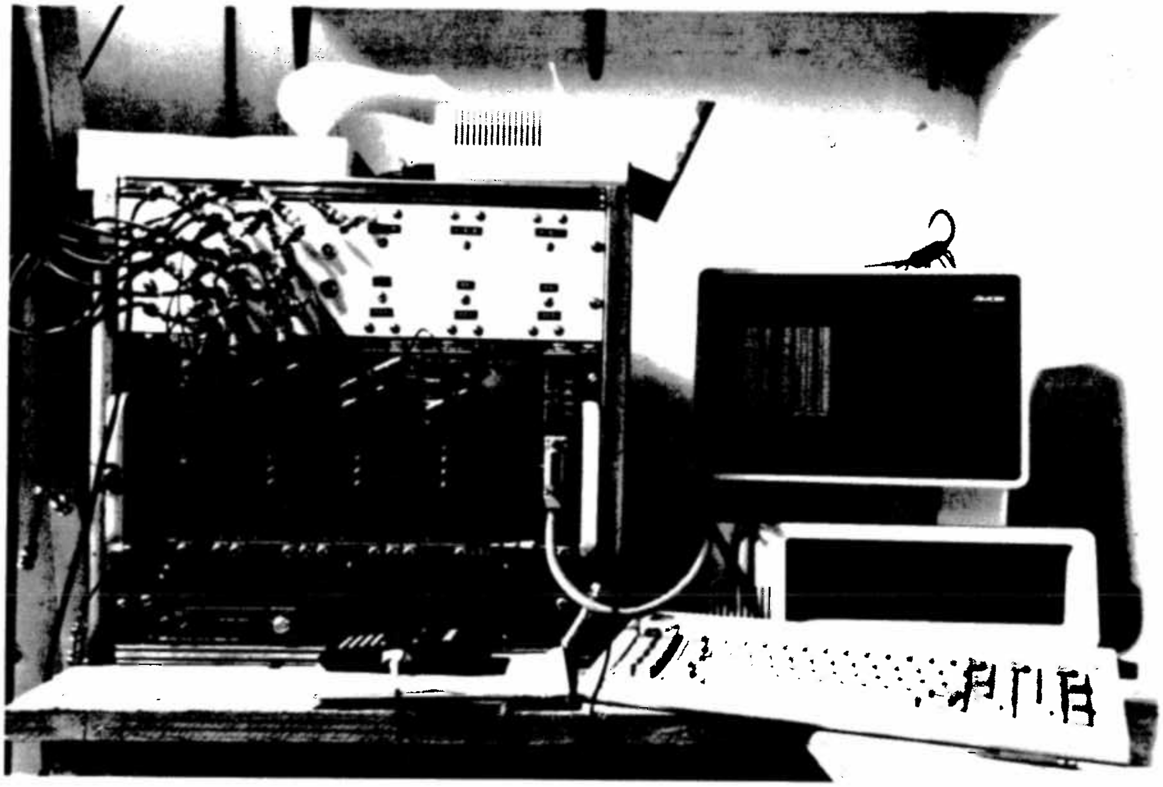


Plate XIII. LeCroy Data Acquisition System

Personnel and Gas Bottle Bunkers

Two bunkers are used for the protection of personnel and high pressure gas cylinders. Each bunker has a frame of 2" x 6" studs faced on the inside with 1 in. sheets of plywood. The outside face is armored with 1/4 in. steel plates covered with 1 in. sheets of plywood. The spaces between the studs are filled with sand. The roof is of similar construction with 1/4 inch steel plates sandwiched between two 3/4 inch sheets of plywood supported on double 2" x 6" stud rafters. The personnel bunker houses the pressure, vacuum and gas mixing control panels, the high pressure Corblin pump, the two Welch vacuum pumps and the

LeCroy data acquisition system. Photographs of the inside of both bunkers are found in Plates XIV and XV, the outsides can be seen in Plates I,II and III. The gas bunker houses the high pressure gas bottles used in the experiments. Also found within the laboratory are electronic instrumentation tables at several locations along the apparatus and the combustible gas mixing panel.

Plate XIV. Interior of Personnel Bunker

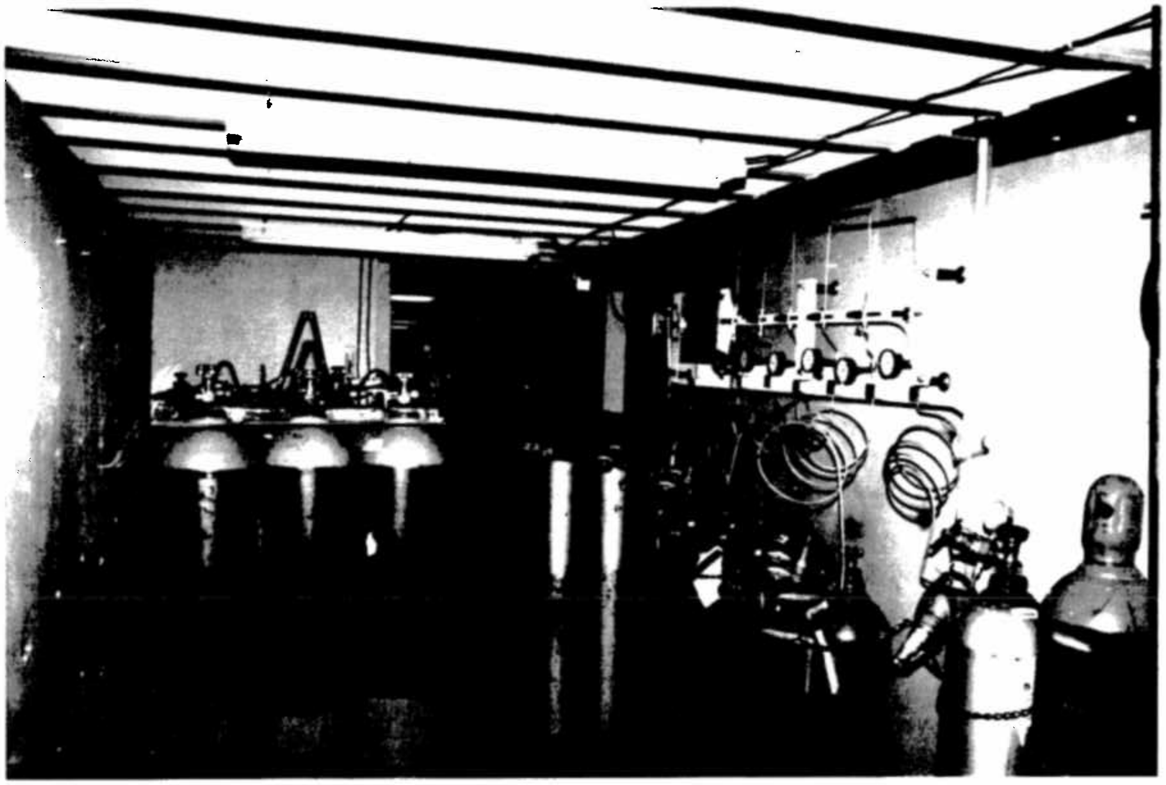


Plate XV. Interior of Gas Bottle Bunker

CHAPTER III

INSTRUMENTATION

Results from the Ram Accelerator experiments are only as good as the instrumentation used to record them. Pressures range from 6000 psi. in the driver section to 1 Torr in the launch tube and dump tanks and the dynamic testing times are of the order of a few milliseconds. This provides severe requirements for devices used to measure these pressures.

The short test times require the use of high speed instrumentation. The two basic requirements for dynamic sensing instrumentation are a high sensitivity and a rapid response time. To date the only types of instrumentation that have been used are laser velocity measuring systems, fiber optic light detectors and Kistler pressure transducers.

Laser velocity measuring system:

Initially the laser velocity measuring system was designed to determine the velocity of the projectile and sabot as they traveled down the launch tube and Ram Accelerator section.

The original design of the laser velocity measurement system (Ref. 3) involves using laser fiber probes shown in Fig. 6. A 0.059 in. diameter plastic light fiber is epoxied into the inner plug. This provides an internal pressure seal while an external O-ring provides the pressure seal with the outer ' generic ' plug. To ensure against thread failure high strength, type 4150 steel is used. The polished end of a light fiber is protected with a small glass window and is supported on a Lexan holder which in turn rests on a Lexan washer.

Light supplied by a 2.5 mw. He-Ne laser travels through the plastic light fiber to the fiber probe in a instrumentation port, across the tube barrel and is received by a second fiber probe directly opposite the first. The collected light continues to travel through the second plastic light fiber to a PIN photodiode. When the projectile and/or sabot blocks the laser light, a change in voltage across the photodiode results. This voltage must be amplified to between 3 to 5 volts to be usable by the data acquisition system. A two-stage amplifier with a frequency response of over 1 MHz was constructed. This circuit is shown schematically in Fig. 7.

It was found that the PIN photodiode detectors could be saturated by the radiation from sparking of the projectile as it traveled down the tube and from the shock heated gas. This made the data difficult to interpret. It is for this reason that the velocity measuring system was replaced for the time being by pressure transducers in the instrumentation section of the Ram Accelerator.

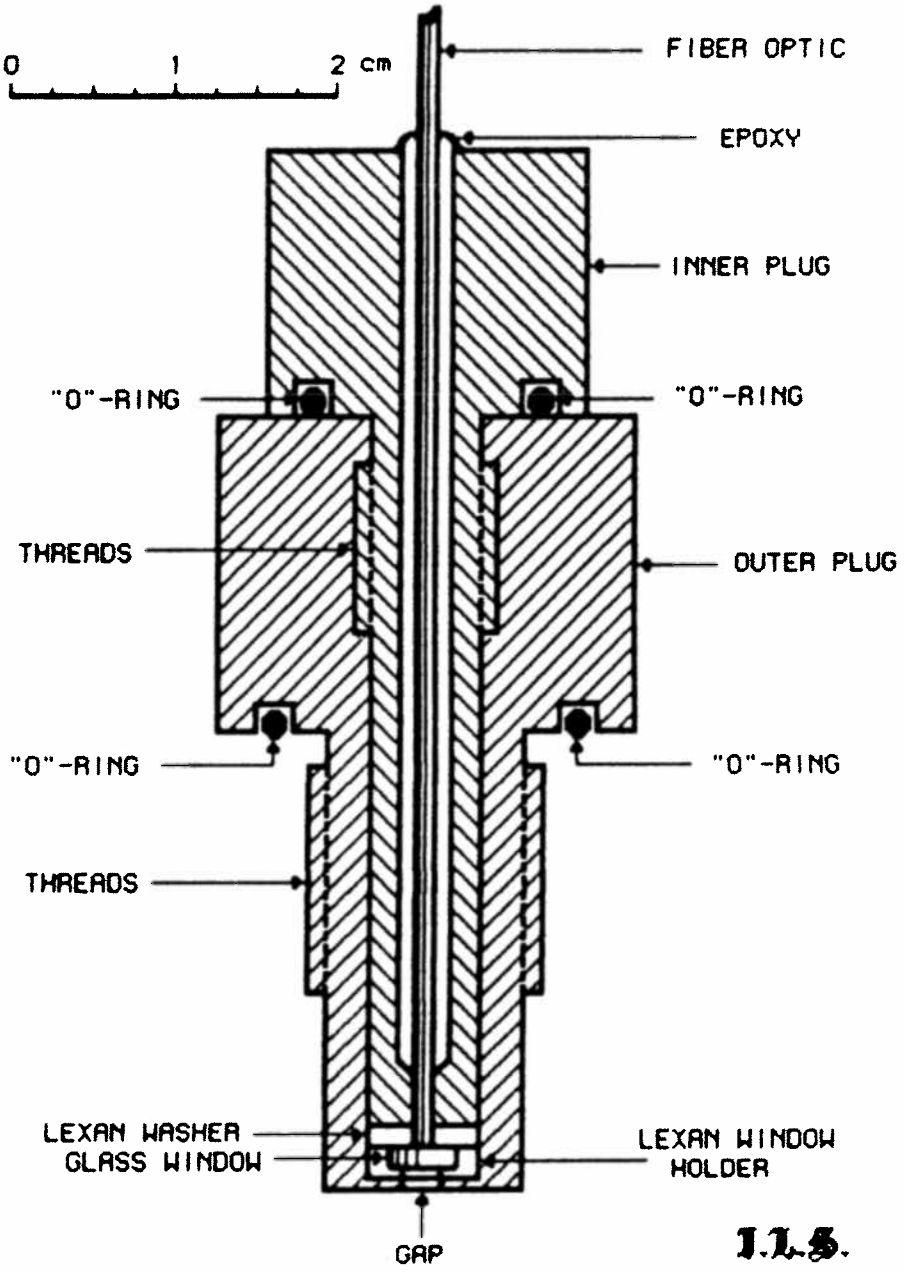


Fig. 6 Light Fiber Probe

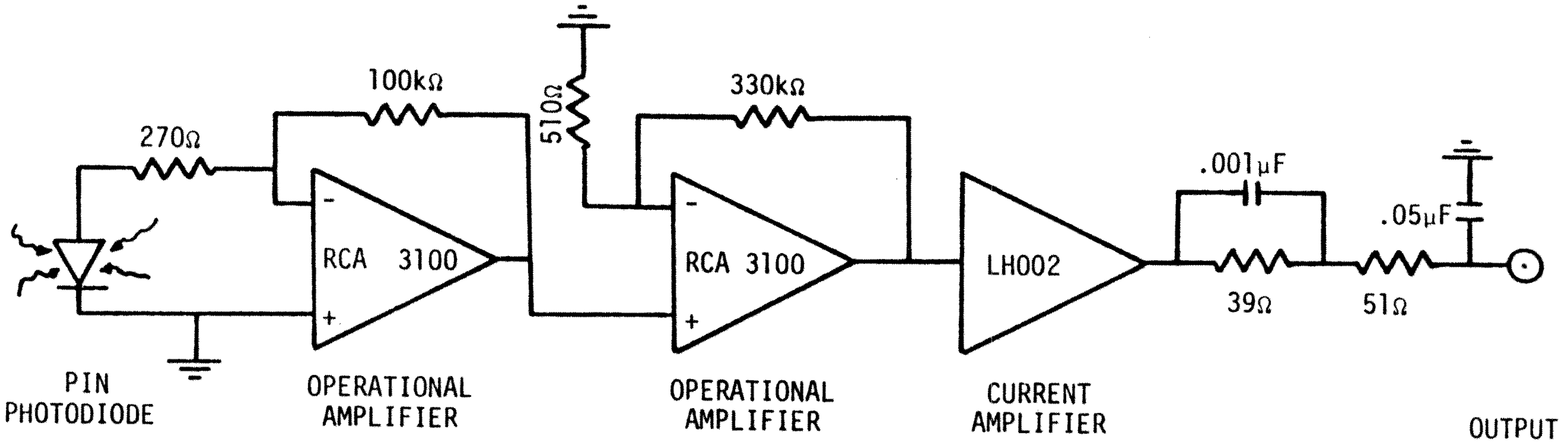


Fig. 7 Schematic of Photodiode Amplifier Circuit

Only one pair of light fiber probes, located in the first pair of instrumentation ports of the last section of the launch tube, is currently being used to trigger the data acquisition system. A modified laser velocity measuring system is currently being incorporated within the spark photography boxes. Two parallel laser beams travel through the evacuated tank via the Plexiglas observation windows and are detected by two optically filtered PIN photodiodes in the same amplifiers as described before.

The light fiber probes are also used as passive light detectors. A light fiber probe is placed into an instrumentation port opposite a Kistler pressure transducer plug. The other end of the plastic light fiber goes to a optically filtered PIN photodiode amplifiers. Any light created by the ignitor, gas combustion, shock waves, etc. is recorded by the passive light detector system.

Kistler Pressure Transducers:

Kistler high-level, low impedance Type 211B(X) Piezotron pressure transducers are used for the pressure measurements. These transducers produce a signal that is the voltage analog of the dynamic pressure input with a resolution on the order of one part per 20,000 of the full scale range. The transducer consists of a crystalline quartz sensing element and a solid-state impedance converter (Ref. 5). The sensing element consists of stacked quartz plates, interlaced with gold electrodes. When pressure is applied to the stainless steel diaphragm that covers the cavity containing the sensing element, a proportional high impedance electrostatic charge output is produced. The integral converter matches the high impedance and produces a linear voltage output with an impedance of less than 100 ohms. A single coaxial cable is connected to a Microdot connector at the top of the transducer. This coaxial cable simultaneously carries operating power to the transducer and transmits the return signal back to the multichannel Kistler power supply and signal conditioner, a Kistler Piezotron Coupler, Model 5126.

Twelve Kistler pressure transducers and twelve channels of signal conditioning equipment are available for the Ram Accelerator project. The pressure transducers are mounted in instrumentation plugs shown in Fig. 8. These plugs fit in to the " generic " ports in the instrumentated sections of the Ram Accelerator.

Heat Transfer Gauges:

Currently there are no heat transfer gauges in the instrumentation system of the Ram Accelerator,however such devices will be used in the future. Appendix 'A' discusses the theory and construction of heat transfer gauges.

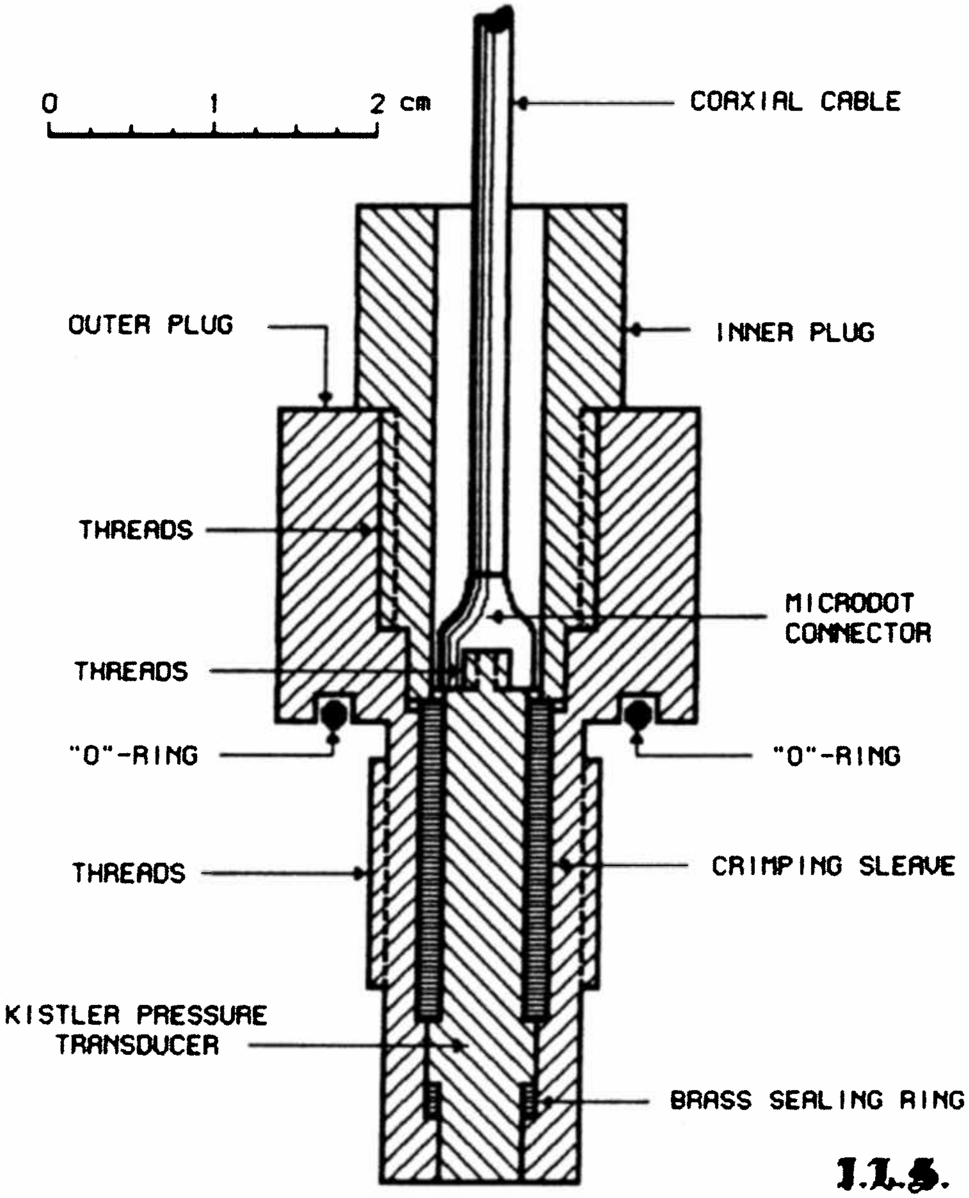


Fig. 8 Kistler Pressure Transducer Probe

CHAPTER IV

OPERATIONAL PROCEDURE

Before each experimental run, The apparatus must first be prepared, and the instrumentation set up and checked for proper operation. The procedure starts with the removal of the projectile decelerator tube from the final dump tank. This is done with the use of a five ton crane. The tube is completely removed from the support stands and placed off to one side. The catcher tube is packed with suitable materials to slow the projectile to a stop. A typical pack consists of lathe turnings in the rear 1/4 of the tube, carpet scraps in the next 1/2 of the tube, and aircraft construction honeycomb and/or carpet scraps in the forward 1/4 of the tube.

With the rear of the final dump tank now exposed, the barrel of the apparatus can be cleaned. This is accomplished by swabbing the full length of the inside of the barrel using a multi-sectioned rod. Cheesecloth is rolled and tied to the multi-sectioned rod and is wet with isopropyl alchohol. The rod is then stroked back and forth along the full length of all the tubes until most of the products of combustion and other contamination are removed. The discoloration of the cheesecloth is a measure of the tube cleanliness. The insides of the Plexiglas observation windows can also cleaned at this time. When this is completed, the catcher tube can then be replaced upon its support stands. An aluminum sheet with two small off-center holes is placed between the O-rings of the catcher tube and the final dump tank. The projectile decelerator is then rolled forward and bolted to the final dump tank.

The next step in the setup procedure is to place the various Mylar diaphragms at their appropriate locations. A 0.003 inch thick Mylar diaphragm is placed in the last joint of the barrel at the end of the Ram Accelerator section. At the joint at the beginning of the Ram Accelerator section a 0.005 inch thick Mylar diaphragm with the firing pill cemented at the center is installed. Finally two 0.002 inch thick Mylar diaphragms are inserted at the first and second joints of the sabot stripper section.

The projectile is prepared by first loading the pyrotechnic ignitor. This consists of a 0.357 magnum small arms cartridge with two pairs of diametrically opposed holes drilled into the lower 1/4 length of the shell. A rolled thin paper insert is then placed into the shell to cover the holes. A Winchester primer is pressed into the primer hole at the base of the shell with the use of a hand-held cartridge primer reloader. The shell is first filled with 0.11 gm. of fine magnesium powder (a 75% fill), then filled with 1.5 gm. of coarse black powder and finally capped with a thin cardboard disc. The powder is compressed by using an arbor press which produces approximately 88 pounds of force (A value greater than the compressive force experienced by the powder upon the initial acceleration of the projectile/sabot). To fill the void that is generated by the compaction process, modeling clay is used. The loaded pyrotechnic ignitor is then inserted into the projectile and affixed with a threaded retainer plug, and the projectile nose is subsequantly threaded into the body (Fig. 9). The base of the projectile is coated with a thin film of vacuum grease and is placed upon the sabot. The projectile/sabot combination is inserted into the launch tube, projectile in first. The two aluminum diaphragms are placed in position and the double diaphragm section bolted into place. All rotating collars are rechecked and the shock absorber put into place. Following these procedures the Ram Accelerator apparatus is ready to be evacuated and loaded with the various gases.

The complete procedure for set-up and checkout of the instrumentation is discussed in Appendix B. Also included are the complete operational procedures for the vacuum and pressure systems, and the procedure for storing data from the data acquisition system. Appendix C describes the manipulation and presentation of the experimental data.

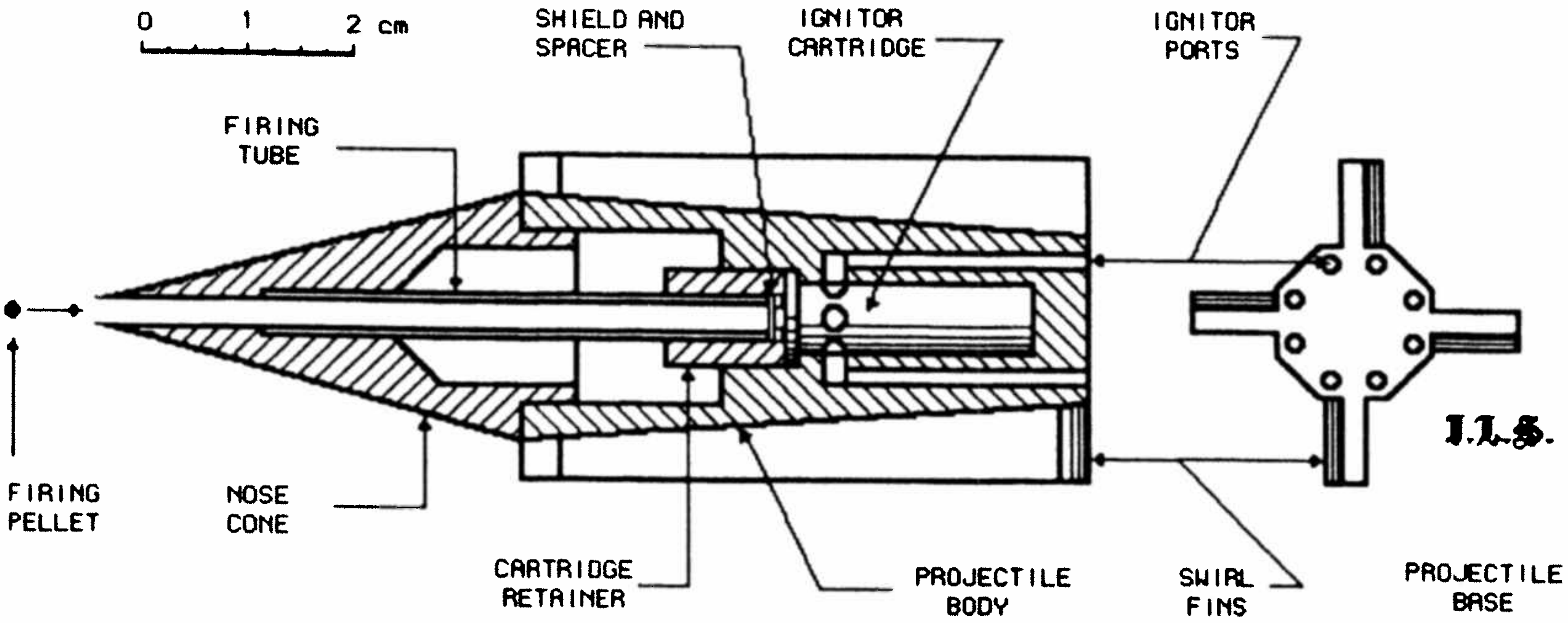


Fig. 9 Cross-Section of Ram Accelerator Projectile

CHAPTER V

RESULTS AND CONCLUSIONS

An apparatus for achieving projectile velocities greater than the acoustic velocity of the propellant gas was built, tested and is currently being used in continued research. The instrumentation used for physical measurements, with the exception of the laser velocity measuring system, has proved to be adequate. The data acquisition system is also an invaluable aid in presenting data from the experiments.

Results from the instrumentation used in the Ram Accelerator experiment are presented in this section and basic interpretation or conclusions from some of the sample data outputs will be included.

The primary instrumentation used to obtain data are the Kistler pressure transducers. With the use of the data acquisition system's "Catalyst" software program, a pressure (mV) verses time (ms) can be displayed. A typical output from one of these transducers is shown in Fig. 10 with an expanded portion containing the projectile pressure data shown in Fig. 11. From these curves, the shockwave generated ahead of the projectile and sabot and their subsequent pressure drop afterwards are readilly apparent. When compared with the next downstream Kistler pressure transducer, a velocity measurement can be obtained. Also, as shown in Figs. 12,13 and 14, a combustion wave can be followed from its beginning formation to when it generates

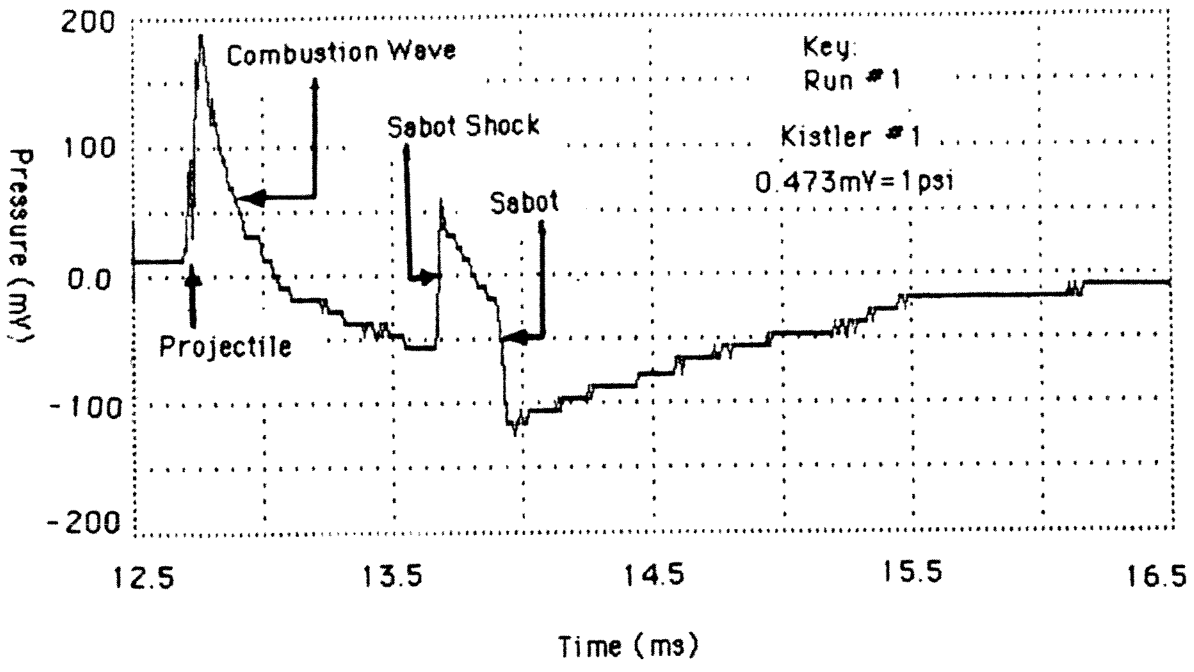


Fig. 10 Kistler Pressure Transducer Output

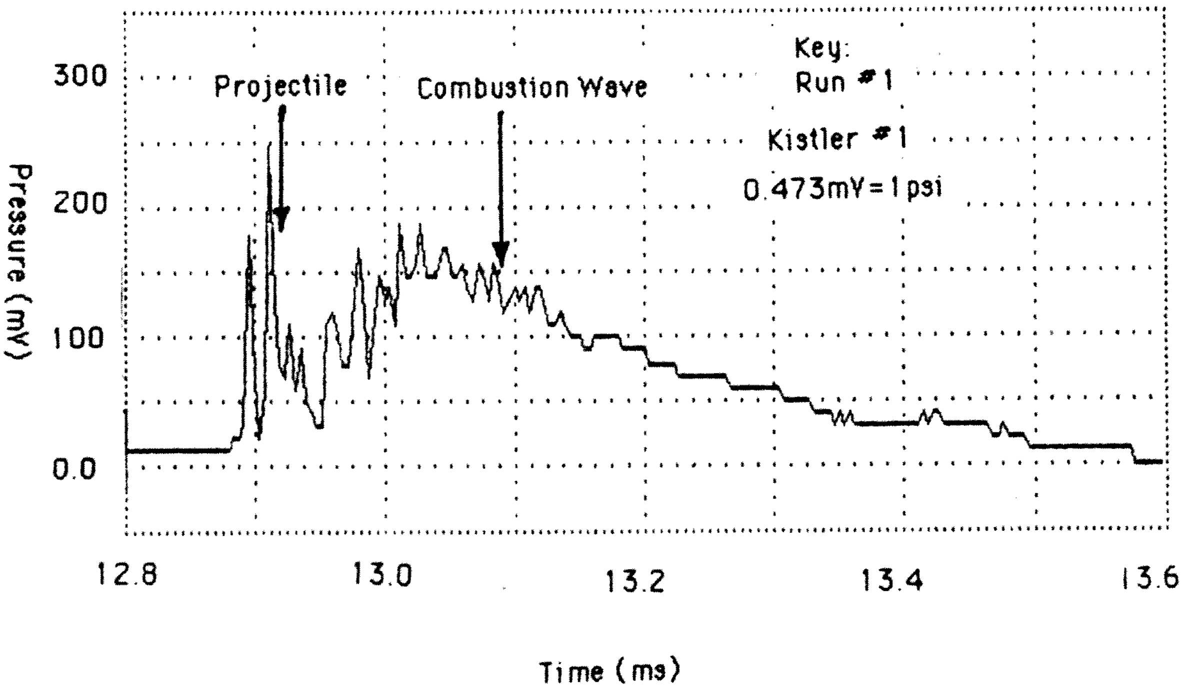


Fig. 11 Pressure Transducer Output Expanded Trace

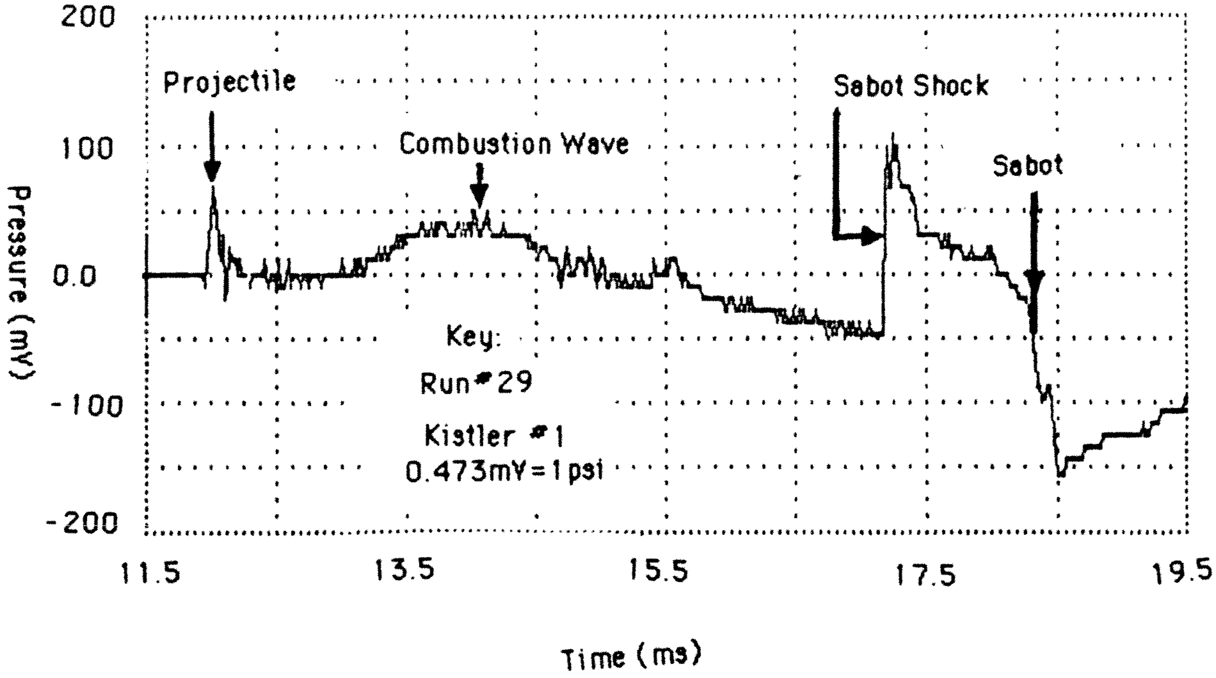


Fig. 12 Combustion Wave Formation

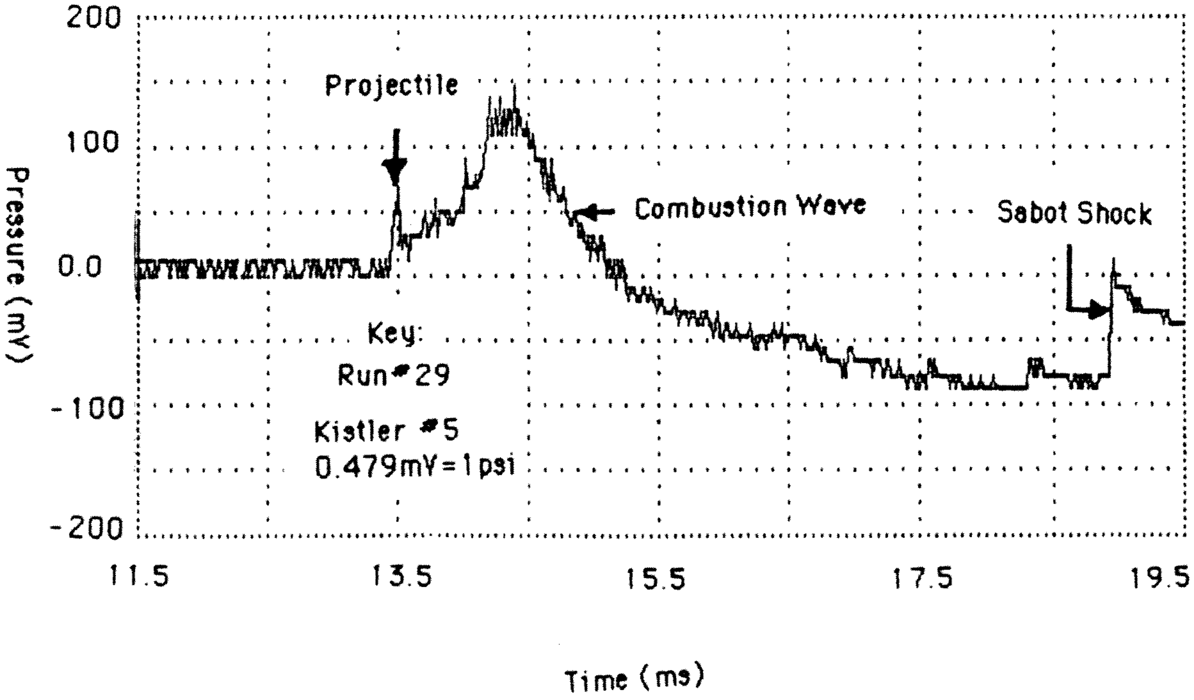


Fig. 13 Combustion Wave

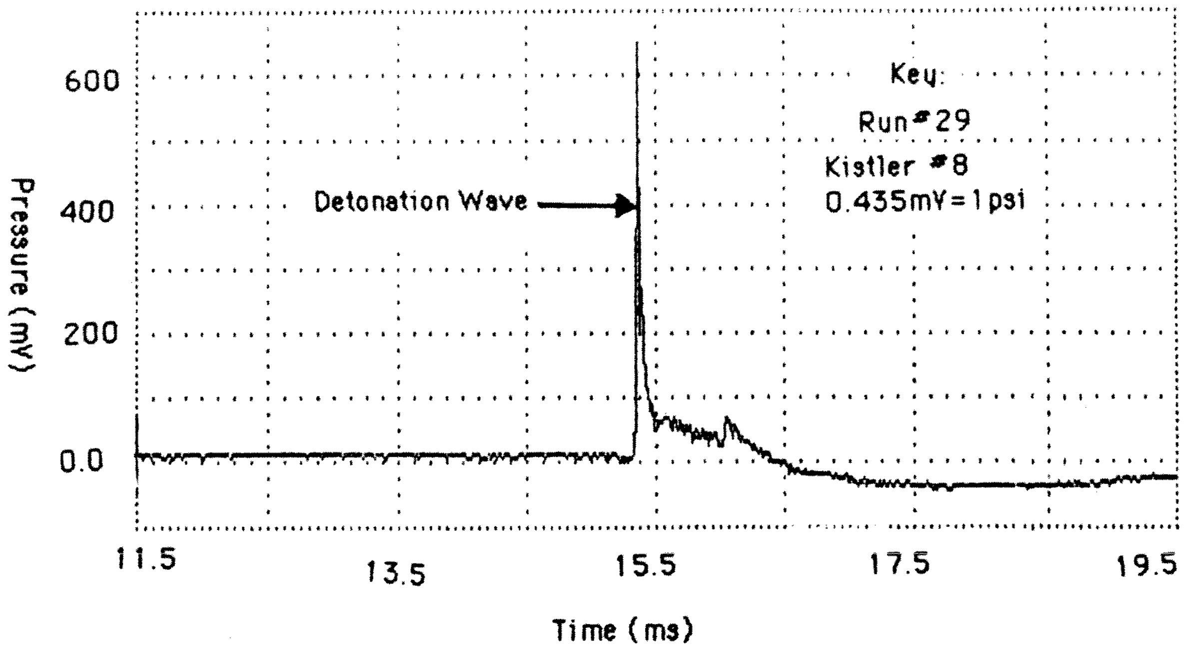


Fig. 14 Detonation Wave

into a detonation wave and propagates ahead of the projectile. Problems arise when the detonation wave passes ahead of the projectile. The pressure rise that is associated with the wave is of such high magnitude that the pressure rise from the projectile is no longer observed.

The Kistler pressure transducer output can also be displayed together with an ignitor light output. This combined output is shown in Fig. 15 with a separate expanded igniter light output shown in Fig. 16. Since both curves have the same trigger point they will also share a common origin. The location of the combustion zone and

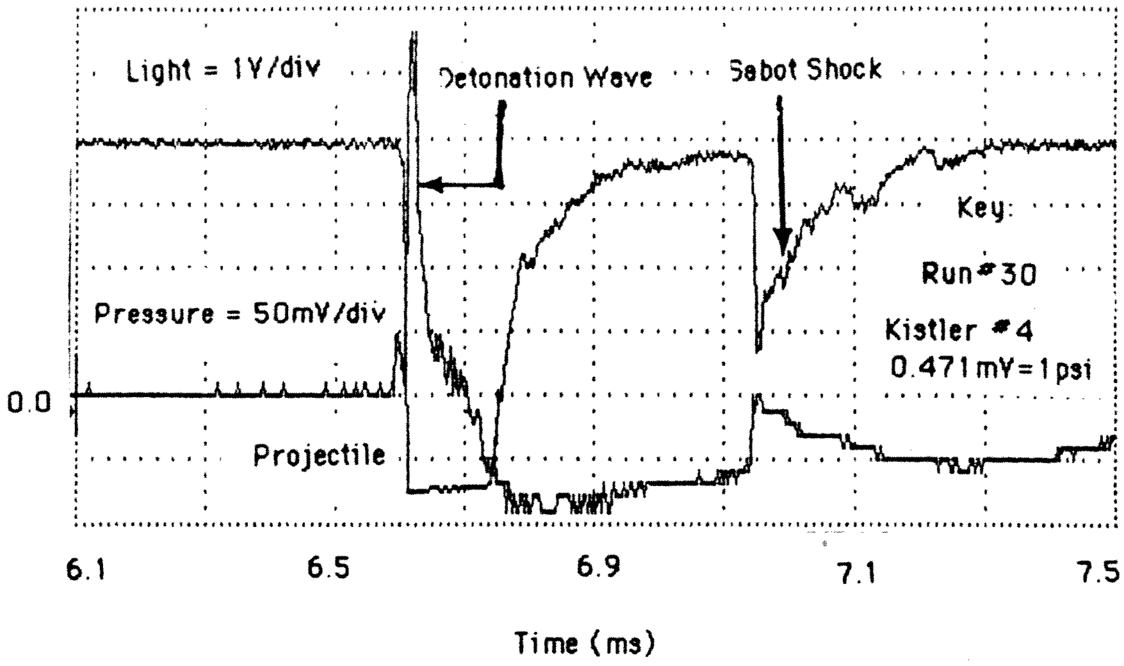


Fig. 15 Ignitor Light/Pressure Transducer Output

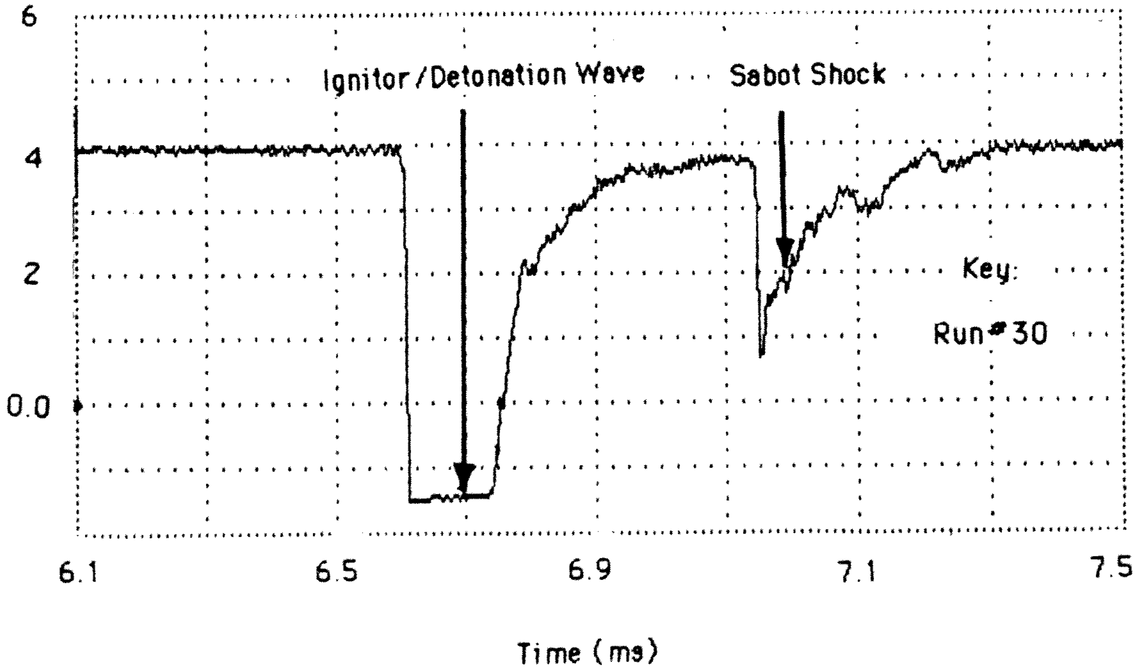


Fig. 16 Ignitor Light Expanded Trace

ignitor discharge region behind the projectile can thus be determined. It can be seen from the figures that light is generated from the detonation wave and/or ignitor discharge is located at the rear of the projectile, also light generated from the sabot shock.

As stated earlier, the laser velocity measuring system does not clearly define the location of the projectile or sabot and is not used to determine their velocities. Although the projectile is hidden within the signal output, it can still serve as a trigger source for the data acquisition system. From Fig. 17 and from the known location of the trigger point, one is able to locate the projectile and sabot. This was not the case for the other downstream systems and were thus replaced with Kistler pressure transducers.

A variation of the velocity measuring system is used to determine a final velocity of the projectile before reaching the catcher tube. As can be seen in Fig. 18 , the projectile is clearly defined and time measurements can be taken from the trailing edges of the recorded curves. Projectile sparking and heated gas radiation problems and detonation wave effects are absent since the projectile is flying freely through a vacuum.

Experience has been gained in developing theory and operation of the Ram Accelerator. However, many problems still exist, including developing a new more reliable velocity measuring system and a more dependable triggering method.

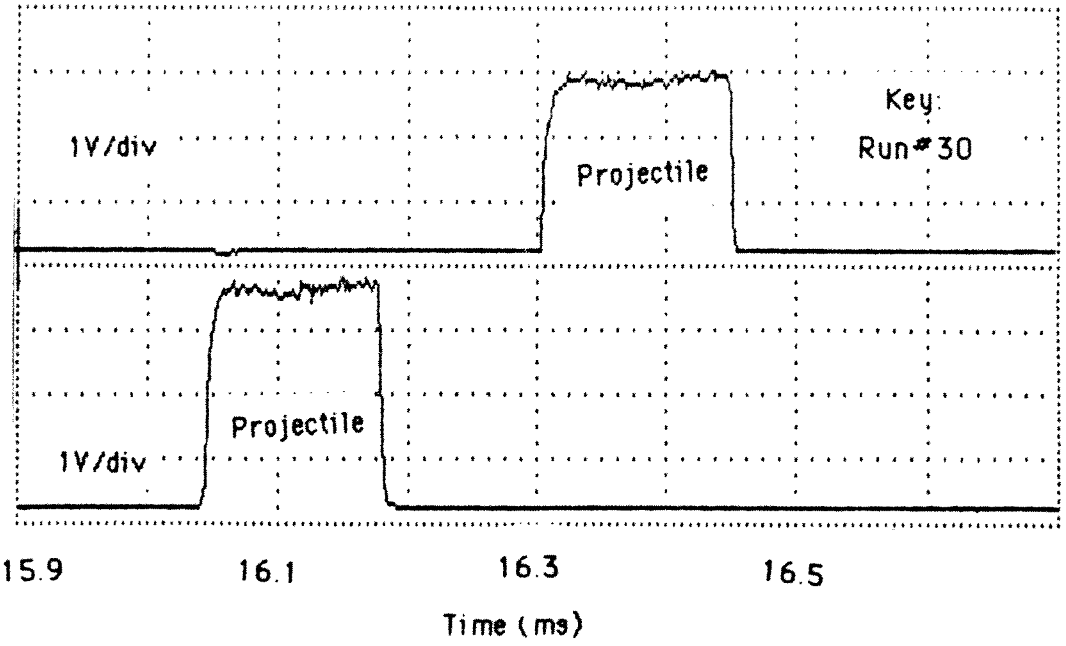


Fig. 17 Velocity Measuring System Output

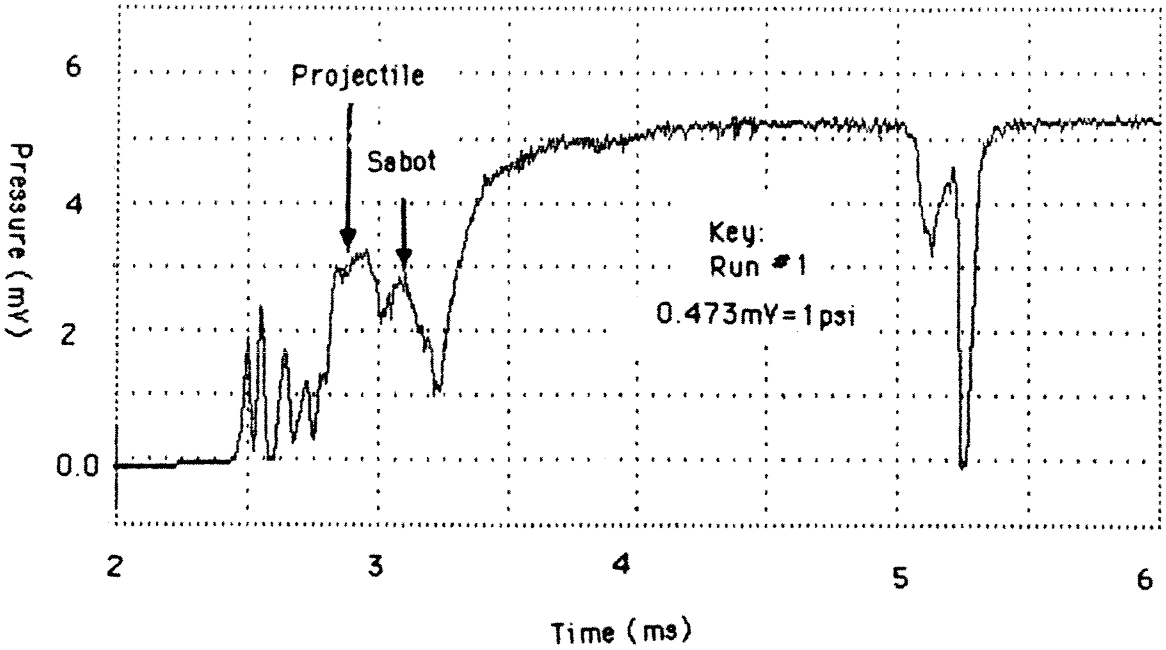


Fig. 18 Tank Velocity Laser Outputs

List of References:

1) A. Hertzberg, A.P. Bruckner and D.W. Bogdanoff. "Apparatus and Methods For the Acceleration of Projectiles to Hyper Velocities" U S patent application #623,829, June 22, 1984.
2) G.L. Dugger, ed. "Ramjets" AIAA selected reprints series Vol VI, 1969.
3) C.S. Engelbrecht, "A Study of Sabot Deceleration Behind an Aerodynamic Vehicle In a Gas-Filled Tube", Master's Thesis in Aeronautics and Astronautics, University of Washington, 1986.
4) P. Kano, "The Design of a High Speed Spark Shadowgraph System", Aeronautics and Astronautics AA 322 class report, University of Washington, June 7, 1985.
5) Kistler Instrument Corp., "Instruction Manual, Model 211B(x)/60(x)b1, Univeral Pressure Transducers", Version 3.0, February 1980.
6) R.J. Vidal, "Model Instrumentation Techniques For Heat Transfer and Force Measurements In a Hypersonic Shock Tunnel", Cornell Aeronautical Labratory Report No. AD-917-A-1, February 1956.
7) LeCroy, "Waveform-Catalyst Multichannel Digital Oscilloscope and Instrument Control System Users Manual", Version 1.0, Jan. 1985.

APPENDIX A

HEAT TRANSFER GAUGES

Heat Transfer Gauge:

A heat transfer gauge is a thin-film resistance thermometer which operates on the principle that the electrical resistance of a metal varies with the temperature. A small constant current is passed through the element; the voltage across the resistance then changes with temperature. The output voltage from a thin-film gauge cannot be interpreted as the change in temperature of the gas surrounding the element; it will only indicate the change in surface temperature. Using a one-dimensional transient heat transfer analysis, combined with the output from the thin-film gauge, the heat transfer from the gas to the element can be obtained (Ref. 6).

Thin film heat transfer gauges have been supplied by the Calspan Corp. (formerly Cornell Aeronautical Laboratory), Buffalo, New York. Two additional thin film gauges used in past research at the University of Washington are also available. These gauges are similar to the ones developed by Calspan for use in their shock tunnels.

A thin-film gauge consists of a thin film of a good conducting metal (0.01 micron thick platinum) on a Pyrex glass backing. Leads (printed circuit silver paint) are then connected from the metallic film through a fixed resistance to a power supply. The power supply used in conjunction with these gauges provides an output of 300 volts. This voltage together with 12,000 Ohms resistance in series with the gauge element provides a constant current of 25 milliamps. A schematic of the required circuit is shown in Fig. 19.

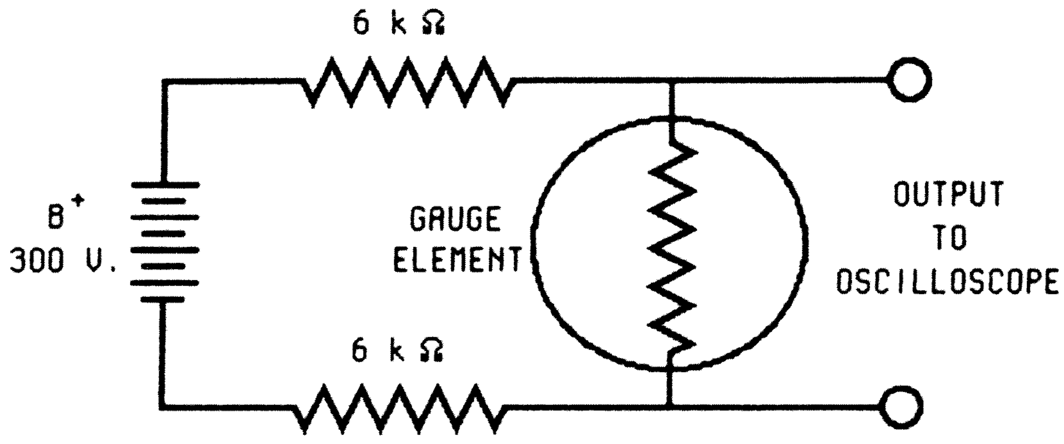


Fig. 19 Schematic of Heat Transfer Gauge Circuit

The instrument can be applied to a wide range of heat transfer measurements because of its ability to vary the degree of sensitivity. The sensitivity is mathematically stated in Ref. 6 as :

$$dE/dT = I*Ro*Alpha$$

where

dE/dT= time rate of change of energy

I= current passing through the element

Ro= element resistance at room temperature

Alpha= resistance temperature coefficient of the metal

By changing any one of the three quantities the sensitivity can be increased or decreased.

For non-quantitative uses, the thin-film resistance gauge serves as an excellent shock wave detector. Since the gauge is temperature sensitive and the temperature changes dramatically across a shock wave, the output from such a gauge could be used to determine the location of a shock or be used as a trigger source for an oscilloscope or data acquisition system. Problems with this type of gauge can result from the contamination of the film surface. Although temperature readings may then become inconsistent, its ability to determine a shock location should not change substantially.

APPENDIX B

INSTRUMENTATION SET-UP AND GAS HANDLING PROCEDURE

Laser Velocity Measuring and Spark-Photography System:

1. Turn on all photoamplifier power supplies located above the data acquisition system (DAS).
2. Turn on tank laser, spark trigger power supply and main switch to the spark gap power supplies (located outside of the spark-photography camera box).
3. Remove the covers from both spark photography boxes.
4. Align spark trigger laser beam (check to see if the green light goes out on the spark trigger power supply).
5. Connect the Nitrogen gas bottle to the spark-photography gas line and open the valve/regulator found on the gas mixing panel to 300 psi.
6. Purge a small amount of gas from the spark gap by opening the valve found below the spark gap box.
7. Turn on both power supplies to spark gap.

DANGER

DO NOT REACH INTO THE REGION BETWEEN THE FRESNEL LENS AND THE REAR OF THE SPARK GAP BOX. THE VERY HIGH VOLTAGE IN THIS REGION CAN KILL !

8. Break the spark trigger laser beam and check for a spark
9. Align both velocity laser beams to a parallel 7" (use centering rings on the Plexiglas windows)
10. Turn on the oscilloscope and check for proper operation by breaking the velocity laser beams.

11. Shut off the oscilloscope.
12. Replace the spark photography box lids (recheck if the green light on the spark trigger power supply is off).
13. Arm the automatic camera shutter by cocking the release lever found in the shutter box.
14. Check for proper operation by twice pressing the shutter button located on the gas mixing panel, with a 2 sec. pause in between.
15. Rearm the automatic camera shutter.

Kistler Pressure Transducers:

1. Turn on the Kistler Piezotron Transducer Couplers located under the Ram Accelerator Section.
2. Check for any 'Opens' or 'Shorts' by pressing the test buttons for each transducer.

Ignitor Light Detectors:

1. Remove, check and clean light fiber probes with alcohol.
2. Check to see if the detector ends of the light fibers are centered against the filtered PIN photodiodes.
3. Cover with a black cloth to eliminate room light.

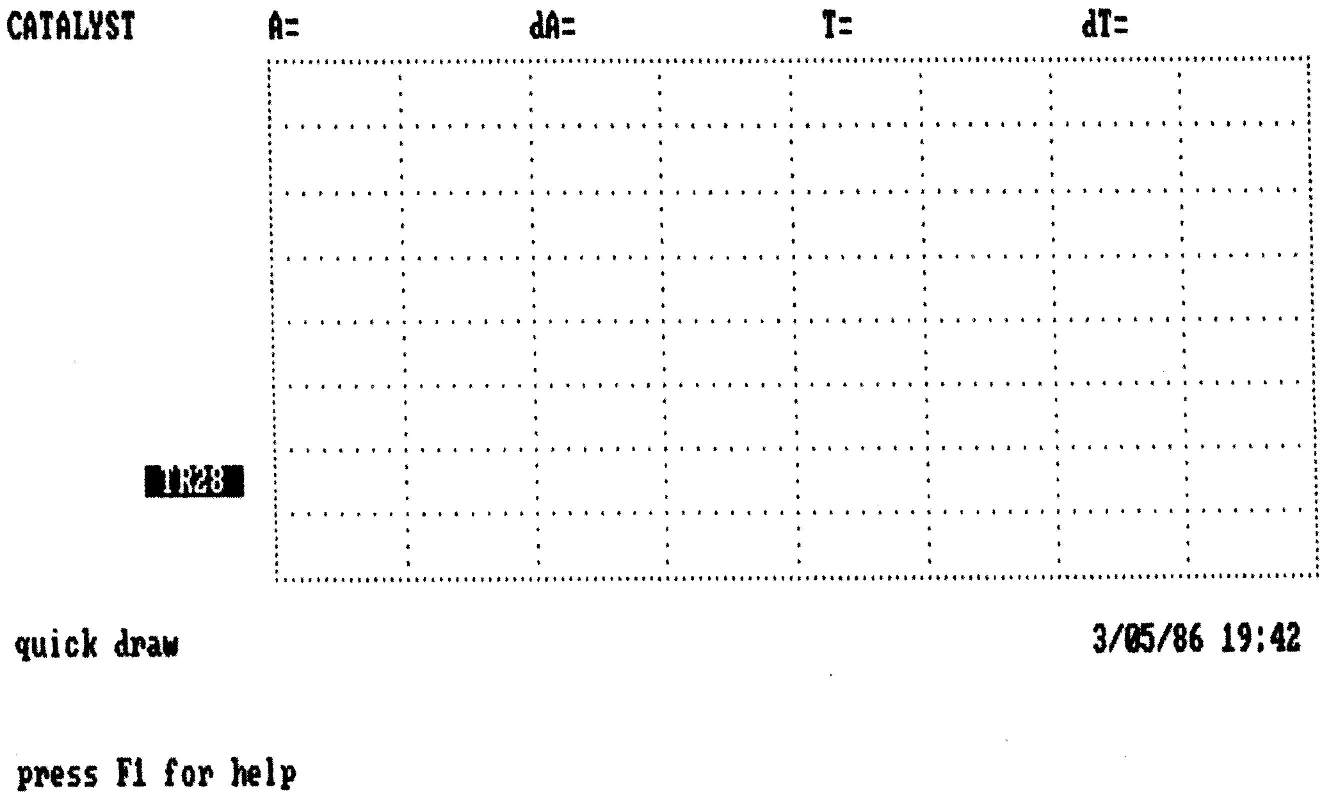
DAS Light Fiber Trigger:

1. Turn on the oscilloscope.
2. Turn on the laser and chopper wheel.
3. Place the chopper wheel in the laser beam path.
4. Turn on the trigger pulse generator box.

5. Watch the output on the oscilloscope, check to see if a trigger pulse of 3 volts or greater and a noise-free signal is generated. If not, remove the probes from the tube barrel and clean the glass lens with alchohol or replace with a new lens.
6. Shut off and remove chopper wheel from laser beam path.
7. Shut off oscilloscope.

DAS Initial Set-Up:

1. Turn on the LeCroy power supply switch located at the lower left on the CAMAC crate.
2. Turn on the switch to the Amdek Video-300A monitor.
3. Turn on the HP Thinkjet printer.
4. Turn on the IBM PC-XT computer. The computer automaticaly loads the catalyst program.
5. Upon loading the internal "Catalyst" program (Fig. 20), insert any comments that are necessary for the experiment by first pressing 'I' on the computer key board (Fig. 21).
6. Enter comment and finish by pressing the return key.
7. Press the 'S' key to set the single trigger.
8. To insure the proper operation of the trigger system break the laser beam at the end of the launch tube.
9. Monitor the LeCroy 8800A memory module, memory enable lights to see if they stop flashing. (This will show that the data have been sampled.)



CATALYST A= dA= T= dT=

TR28

quick draw 3/05/86 19:42

press F1 for help

Fig. 20 DAS Initial Display

```
---------------------------------------------------------------------------------
|   1   |   2   |   3   |   4   |   5   |   6   |   7   |   8   |   9   |   0   |
|Trace  |Trace  |Trace  |Trace  |       |       |       |       |       | Reset |
|   1   |   2   |   3   |   4   |       |       |       |       |       |counter|
---------------------------------------------------------------------------------
    ---------------------------------------------------------------------------------
    |   Q   |   W   |   E   |   R   |   T   |   Y   |   U   |   I   |   O   |   P   |
    | Quick | Write | Edit  | Read  | Trace |       | User  |Insert |On/Off | Print |
    | draw  | data  | setup | data  | Reset |       | camac |comment| grid  |screen |
    ---------------------------------------------------------------------------------
        -------------------------------------------------------------------------
        |   A   |   S   |   D   |   F   |   G   |   H   |   J   |   K   |   L   |
        | Auto  |Single |Define |Freeze | Grid  |       | Join  |       | List  |
        |trigger|trigger|origin |trigger|format |       |Blocks |       |modules|
        -------------------------------------------------------------------------
            -------------------------------------------------------------------------
            |   Z   |   X   |   C   |   V   |   B   |   N   |   M   |   <   |   >   |
            | Zero  |eXpand |Connect|Version|       |Normal |Manual | Page  | Page  |
            | trace | home  |points |  id   |       |trigger|trigger| left  | right |
            -------------------------------------------------------------------------
```

```
-----------------------
|   f1     |    f2    |
|          |   Disk   |
|  Help    |Utilities |
-----------------------
|   f3     |    f4    |
|          |          |
-----------------------
|   f5     |    f6    |
|          |          |
-----------------------
|   f7     |    f8    |
|          |          |
-----------------------
|   f9     |   f10    |
|Reprogram |   Exit   |
| modules  |  to DOS  |
-----------------------
```

```
---------------------------
|    7    |  8   |   9    |
|Primary  | /|\  | Second |
| cursor  |  |   | cursor |
---------------------------
|    4    |  5   |   6    |
|         |      |        |
|   <--   |      |  -->   |
---------------------------
|    1    |  2   |   3    |
| eXpand  |  |   |Position|
|  trace  | \|/  | trace  |
---------------------------
```

Fig. 21 Keyboard Set-Up Commands

10. Repeat steps 8 & 9 until satisfied with the systems reliability.
11. Press the 'S' key to reset the single trigger.
12. Turn off the room lights.
13. Remove the camera shutter plane from spark-photography camera without removing the black cloth used to prevent light leaks.
14. Secure the bunkers by closing all sliding doors.
15. Warn and check with the High Beta Q machine next door (If High Beta Q is in operation during these experiments, its large transient currents can cause spurious triggering of the DAS.).
16. One is now ready to load the gases for the experiment.

Gas Handling Procedure

Vacuum System:

All valves and gauges referred to can be found in the schematic of the gas handling system, Fig. 5 in the main text.

1. Close up the system by:

Closing Valves : V4, V8, V10, V12, V13, V20,
AV6, AV9,
VN7, VN8

Opening Valves : V5, V6, V9, V11, V14, V15, V16, V17,
AV4, AV7, AV8

2. To display the pressures,

   Open valves : V1, V2, V3, V7, V18, V19

3. Turn on the Ram Accelerator pressure gauge video camera and monitor.

4. The pressures are shown on:

   Gauges : GV1, GV2, GV3, GV5, GV6

5. Operate pump with gas ballast valve open one turn to minimize the condensation of water vapor in the pump.

6. Close Blankoff Valve.

7. Start the pump.

8. Open Blankoff Valve.

9. Pump down to vacuum by observing the following pressures on gauges:

   G1 - 3 torr
   G2 - 29 in. Hg.
   G3 - 0 psi.
   G5 - 30 in. Hg.
   G6 - 30 in. Hg.

10. Shut off the pump.

11. Close Blankoff Valve.

12. Blank off the vacuum gauges by:

    Closing Valves : V1, V2, V3, V7, V18, V19

13. Before loading the gun, sabot-stripper, start section or Ram Accelerator section check to ascertain;

    Valves Closed : V11, V15, V16, V17
    Valves Open : V4, V20

Connect the gas bottle to its appropriate gas line and open the gas bottle valve/regulator.

Sabot Stripper:

1. Close Valve : V17
2. Open Valve : AV7
3. Load gas by adjusting valve VN7 to the desired pressure shown on gauge G7.

Start Section:

A) Non-combustible gas

1. Close Valve : V16
2. Open Valve : AV8
3. Load gas by adjusting valve VN8 to desired pressure shown on gauge G8.
4. Close Valve : AV8

B) Combustible gas

1. Close Valve : AV6
2. Open Valves : AV5, AV1, AV2, AV3
3. Adjust the mixture ratio (by using the hand regulators) to the desired value by observing gauges G1, G2, G3 (Take a gas sample as needed, after running for 1-2 minutes).
4. Using two people; one person,

   Opens Valve : VN9

   at the same time the other person,

   Closes valve : AV5

5. Load the mixed gas until the desired pressure is reached on gauge G8 .
6. Close Valve : VN9, AV1, AV2, AV3, AV8

Ram Accelerator Section:

1. Close Valve : AV6
2. Open Valves : AV5, AV1, AV2, AV3
3. Adjust the mixture ratio (by using the hand regulators) to the desired value by observing gauges G1, G2, G3 (Take a gas sample as needed, after running for 1-2 minutes).
4. When the desired mixture has been reached,

   Close Valve : AV6

   Open Valve : AV5
5. Repeat as necessary, by observing the pressure on the Ram Accelerator video monitor.

   Close Valves : AV1, AV2, AV3,
6. Blank off the Ram Accelerator gauge by:

   Closing Valve : AV4

Gun Loading:

1. Close up the high pressure system by;

   Closing Valves : V1, V4, V5, V6, V7, V8, V9

   Open Valves : V2, V3, V10
2. Attach a 6-bottle bank of helium gas to its appropriate gas line.

3. Open the gas bottle valves and monitor the pressure on gauge G2 .
4. Close Valve : V2
5. Load the breech to 1/2 the inter-diaphragm pressure by
   Fully Opening Valve : V5
   and Adjusting Valve : V2,
   until the desired pressure is reached on gauge G2 .
6. Then, to equalize the pressure between the breech and interdiaphragm,
   Open Valve : V8
7. Read the pressures on gauges : G1, G2 .
8. Repeat driver load / pressure equalizing until desired pressure P2 is reached.
9. Isolate the interdiaphragm space by;
   Closing Valve : V8
10. Monitor the inter-diaphragm for pressure leaks on Gauge G1.
11. Load the breech to its final pressure P1 by;
    Adjusting Valve : V2
12. Monitor the pressure on gauges : G2, G3 .
13. Wait for the gas to cool before reading final pressure.
14. If the final breech pressure is lower than the available bottle pressure the Corblin pump is needed.
15. Open the valves for the cooling water.
    Close Valves : V2, V5
    Open Valves : V1, V4

16. Turn on the main power switch to the Corblin and push the ON button.
17. Pump to the desired pressure, and by cracking Valve V5 monitor the pressure on gauge G2 .
18. Push the OFF button and shut off the main switch on the Corblin pump.
19. Safety the gauges by;

    Closing Valve : V3, V10
20. Press the camera shutter button on the gas mixing panel.
21. FIRE by;

    Opening Valve : V6,

    for a duration of 2-3 seconds.
22. Close Valve : V6
23. Repress the camera shutter button on the gas mixing panel.
24. Replace the camera shutter film plane on the spark-photography camera.
25. Develop and label the Polaroid picture.
26. Turn on the room lights.

Shut Down Procedure:

1. Close all the gas cylinder bottle valves.
2. Open Valves : AV1, AV2, AV3, AV5, AV7, AV8, V7, V11
3. Re-evacuate the system as shown in the "Vacuum System" section found above.

4. Open Valves : V12,
   VN7, VN8
5. Bleed the gas cylinder regulators.
6. Close Valves : AV1, AV2, AV3, AV5, AV7, AV8,
   V2, V3, V5 (on pressure panel)
7. Shut off tank velocity laser, Kistler power supplies, spark photography power supplies, spark trigger power supply, main switch to the spark gap power supplies, photodetector power supplies, video camera/monitor, trigger pulse generator box, trigger laser, shop air, and cooling water to the Corblin pump (letting the water run through the pump for 30 minutes before shutting it off).
8. Remove the catcher tube from the final dump tank.
9. Remove the projectile/sabot remains and place in a labeled body bag.

To Save the Data from the DAS to Hard Disk:

1. To save the data that were obtained press 'W' on the computer key board.
2. Enter the file name (such as H19.1) and press the return key.
3. Enter the module name M1, M2, M3 or M4 and press the return key.
4. Repeat for all the modules.

To Save the Data from the DAS to Floppy Disk:

1. Press 'F2' on the function keys.
2. Type 'C' to change drives.

3. Enter 'A:' (to get back to the hard disk, enter 'C:/data').
4. Press the space bar to return to main menu.
5. Insert a blank formated disk in deck A.
6. To save the data that were obtained press 'W' on the computer keyboard.
7. Enter the file name (such as H19.1) and press the return key.
8. Enter the module name M1, M2, M3 or M4 and press the return key.
9. Repeat for all the modules (only up to two Modules can be saved per disk).

Procedures for manipulation and presentation of the data are discribed in Appendix C.

APPENDIX C

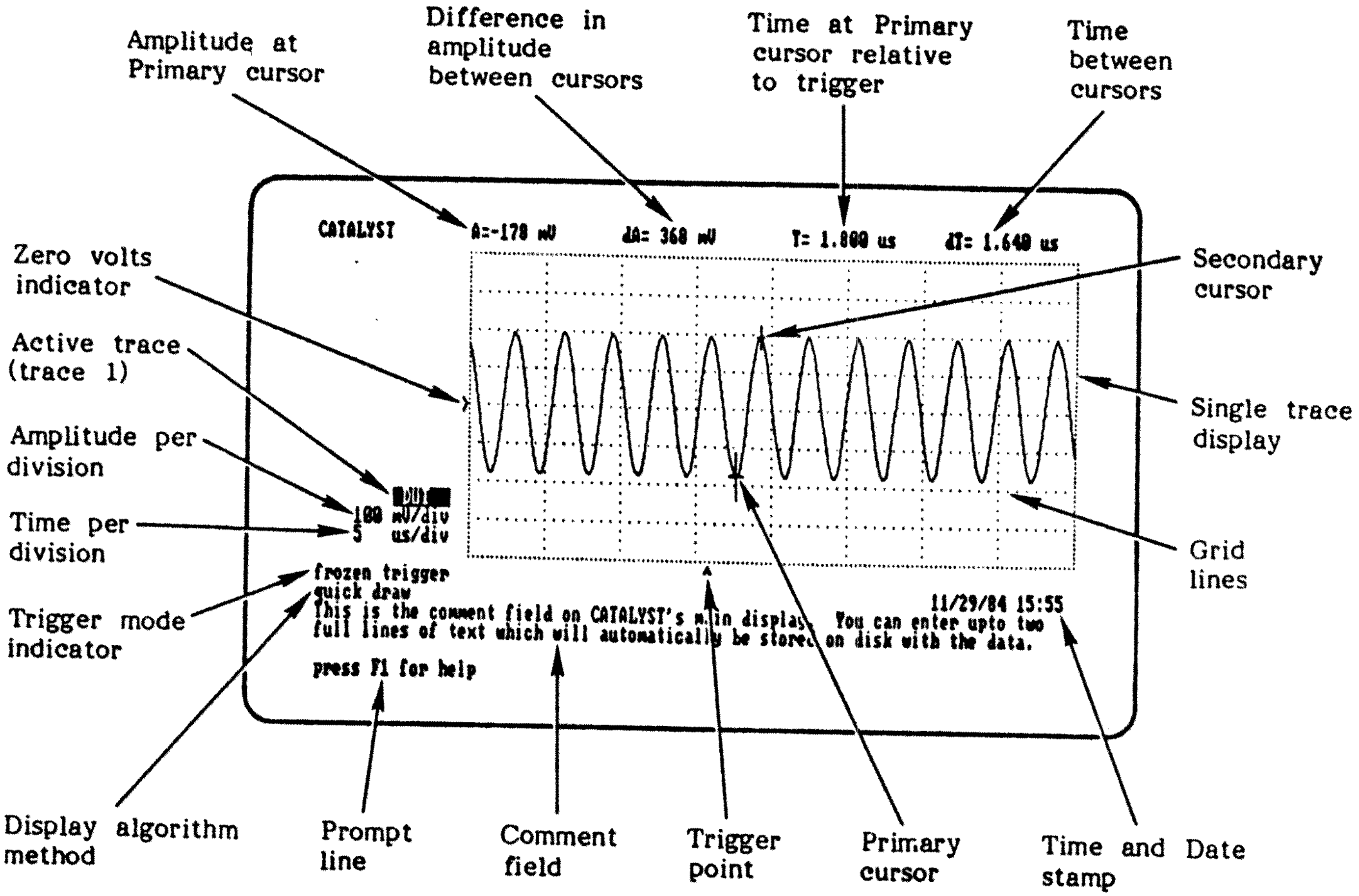
DATA MANIPULATION AND PRESENTATION

To be able to display data that have been saved on a floppy disk, or on a hard disk or data that are still contained within the memory modules, must first be retrieved. All keyboard inputs can be referred to Fig. 21 in Appendix B.

The simplest and fastest method of data retrieval is right from the memory modules themselves, immediately after an experimental run. There are four curves or channels for each of the four memory modules, one for each signal input. Each curve can be displayed on the CRT screen by typing the module name that contains the curve after specifing which of the four traces it is desired to represent (One first types '1','2','3'or'4' then enters M1,M2,M3 or M4). The grid at present is set to display the four traces from a common origin. To change the display type 'G' , 'S' is entered for single (1,2,3 and 4 on one graph), 'D' for dual (1,2 ; 3,4 on two graphs), and 'Q' for quad (1;2;3;4 on four seperate graphs), and the space bar is pressed to continue. The traces that are read from a module all start at the first curve or channel of that module. To obtain the other channels that are found in the memory, one must page through each of the four blocks of data for each channel. To page right or left through to the appropriate channel type '>' or '<', once for each block of data. One can not page to the right past the 4th block of data on channel 4, and one cannot page to the left past the 1st block of data on channel 1. To display a different curve from a different module on a trace previously defined to another, one must do a trace reset by typing a 'T' after entering the module name. To remove a trace from the screen, type the trace number and then press the return key.

To retrieve data from a floppy disk , first insert the disk that contains the data into deck 'A', type 'R', then enter '1','2','3' or '4' to specify the trace, then enter the file/module name (example: H40.1 for hot shot 40, module 1) and finally enter a name for the trace. It is assumed here that the disk drive has been specified (see Appendix B, page 63), otherwise data will try to be read directly from the hard disk. The trace can now be paged to the proper channel.

At this point the desired traces are dispayed on the CRT screen. Fig. 22 gives a quick description of the various parts found on the display. It can be seen that the primary and secondary cursors can be used to display the values at any point or between any two points. To move these cursors, press '7' or '9' on the keypad and use '4' and '6' to move them right or left. To be able to work on a different trace, press '7' on the keypad, then use '8' and '2' to move to the upper or lower trace. The active trace will have its name inverted within a small box to the left of the screen.



CATALYST A=-178 mV dA= 368 mV T= 1.800 us dT= 1.640 us

100 mV/div
5 us/div
frozen trigger
quick draw
This is the comment field on CATALYST's main display. You can enter upto two full lines of text which will automatically be stored on disk with the data.

11/29/84 15:55

press F1 for help

Fig.22 Parts of the Waveform-Catalyst Display

One can manipulate the desired trace by expanding it horizontally and vertically or by moving its position on the display. To expand a trace, first press '1' on the keypad, then '8' or '2' to increase or decrease its amplitude, or '6' or '4' to extend or shrink its time scale. Each expansion is of a factor of two from the origin or from the zero line. To help in expanding about a particular part of the trace, use the define origin key to move the trace to the left. This is done by first moving the primary cursor to the point that one wants to be defined as the new origin. Then press the 'D' key and the trace will move over and can be expanded further. The define origin key should not be pressed without first expanding the trace horizontally at least once (faulty time errors will result). If the trace is expanded to the point where the trace becomes points, the latter can be reconnected by pressing the 'C' key. To expand the trace further vertically, the position trace key must be used. To move the zero line up or down, press '3' on the keypad then '8' or '2'. There are times when two traces need to be joined together. One such case is when the data needed are found on two separate blocks of data from the same channel. Pressing '3' on the keypad and then '6' or '4' will enable one to move the beginning of second trace and splice it to the end of the first. Two additional keys that are helpful are the zero trace key and the expand home key. Pressing

'Z' will restore the zero line to its original location. Pressing 'X' will unexpand the trace and pressing it a second time will bring it back to its expanded form. This is helpful if a mistake has been made and one wants to start over again. Also one must first unexpand the trace before paging to the next block of data.

There are two different methods used in obtaining a hard copy of the data dispayed upon the CRT screen. One method is to type 'P' on the keyboard. This will result in a smaller but faster printout as shown in Fig. 23. The other is to press the 'Ctrl' and the 'PrSc' keys simultaniously. This will produce a large but slower printout which were shown in Figs. 10 thru 18 and fig. 20.

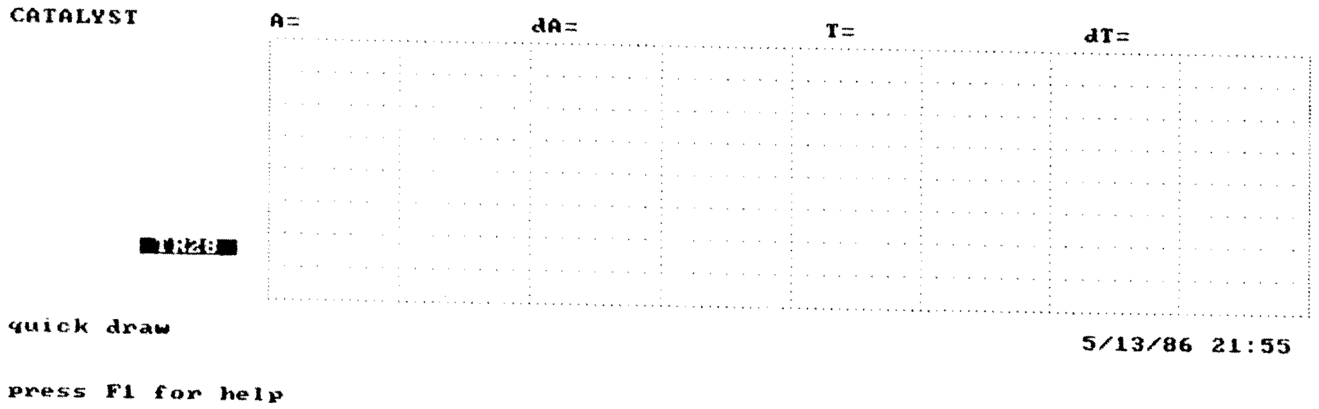


Fig. 23 Example of a Quick Printout