PROGRESS REPORT

OBTAINING HYPERVELOCITY ACCELERATION USING PROPELLANT-LINED LAUNCH TUBES

May, 1969

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Prepared under Contract No. NAS 9-6812

for

Manned Spacecraft Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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CHAPTER I

INTRODUCTION

The purpose of this research is to develop a propellant lined launch tube to accelerate a projectile to hypervelocity. This report summarized the results that have been obtained since the first report[1] submitted in March 1968.

The major developments of the researc during this period were: The development of strain gage instrumentation that indicated the slow burning rate of the propellant; the subsequent bench testing that found nitrocellulose prevented the rapid burning of all fuel oxidizer propellant mixtures; and the development of mathematical solutions that will result in a better understanding of the concept.

Two new methods of obtaining hypervelocities have been given serious consideration in the last several years. One is the method proposed by Physics International to accelerate a reservoir behind the projectile through the mechanism of explosively collapsing a thin tube. This method has met with some success but also contains many technical difficulties related to the physical construction and operation. One of the primary problems is that the tube must be thin enough to collapse. When it is this thin, the pressure of the gas behind the projectile expands the tube and allows blow by around the projectile. Another problem is controlling the velocity of the detonation of the explosive charge. Even with these limitations the concept shows promise of exceeding current light gas gun velocities.

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[1] Superscripted numbers refer to References

The propellant lined launch tube concept is somewhat comparable in operation. The internal propellant lining forms the walls of a tube through which the projectile travels. The lining is fired and the resulting gas forms a piston driving a reservoir with the projectile. A thick walled launch tube restrains the propellant and holds the internal diameter relatively constant. The high pressure behind the projectile is beneficial in igniting and accelerating the burning rate of the lining. The key elements to the successful operation of the concept are that the ignition of the propellant be timed by the projectile passage and that the reaction rate of the propellant be rapid enough to maintain the piston containing the base pressure. The study of the critical parameters requires both theoretical and experimental evaluation. The original calculations indicated the need for microsecond ignition and a burning rate in the order of 250 meters per second (10,000 inches per second). While this burning rate is well below the detonation velocity of most secondary explosives, it is faster than most propellant burning rates, which are typically 1 to 3 inches per second. However some new fuel mixtures, recently developed by the McCormick Selph Company of Hollister, Calfornia, have indicated burning rates of 7,500-12,000 inches per second. These mixtures were suspended in a nitrocellulose filmogen and used for a number of test shots. When increases in velocity were not forth-coming, further tests were made to determine if the problem was ignition delay or burning rate. The strain gage output could be interpreted to show that the burning rate was the problem. New tests were initiated to measure burning rate and a change from nitrocellulose to a vinyl filmogen gave order of magnitude changes in burning rate.

Considerable effort was expended to develop a ratic al mathematical model of the gas flow in the launch tube. It was desired to predict the projectile motion and launch tube pressures as accurately as possible. It was also desired to be able to determine the effect of the many possible variations in propellant and projectile parameters. Compromises were made to allow the study of the parameter variations by sacrificing the accuracy of the physical modeling. Hopefully, this will lead to the selection of a few configurations that can then be studied more exactly.

The future research will use the theory to establish desired propellant projectile configurations in conjunction with tests to develop the desired characteristics of the propellant.

CHAPTER II

THEORY

The primary objective of the theoretical studies is to develop a rational theory of the operation of this new concept for the purpose of directing the experimental program. A considerable expenditure of time and thought has gone into the development of a mathematical theory that would accurately model the processes taking place. Because of the complexity of the problem, a unified theory was not satisfactorily postulated. It was decided that, for development purposes at this time, it would be more desirable to develop a tractable model. The advantage of this approach is to provide parametric studies and determine the gross effect of the variation of a large number of parameters. Two basic approaches have been taken. The first is the assumption of ideal conditions to obtain an upper limit on performance and the second is the assumption of a simplified model that would provide lower bounds to the solution with a knowledge that gun performances should fall between these two theories. Future developments of the theory would be to refine and improve the solutions to bring them closer to the actual physical characteristics of the concept.

The first approach was to assume that the internal propellant lining ignited as a function of the projectile location and that the released gases expanded forming a solid wall which acted as a conically shaped piston. Initial parameter variations were reported in the March 1968 report[1] and examined the effect of igntion delay time and the effect of the distance of the virtual piston behind the projectile. An analysis was performed by Watson, Gill, and Steel[2] of Physics International to investigate the projectile velocities that could be obtained that if it were assumed that the cone formed by the propellant gases was constrained to a cone angle determined by a constant velocity of the propellant gases and the increasing velocity of the projectile. Their analysis indicated that if mass could be added to the cone on the projectile, from either a traveling charge or due to jetting of the gases, that hypervelocities would be achieved.

Another approach was developed that would use a high speed computer to calculate the gas dynamic characteristics for an entire run of the projectile through the launch tube. In order to obtain reasonable computing times a one dimensional code has been developed which is based on the assumption that the gases developed by the burning propellant completely mix with the gas in the tube without forming a piston. The advantage of this program is that it allows the study of the parameters of various propellant characteristics and projectile configurations. The effect of burning rate, burning temperature, delay time, and traveling charge can all be incorporated into the model. It does not account for any jetting or any two dimensional effect that may be present. A two dimensional code was initiated but could not be used to obtain a complete launch run because of the large amount of core storage and computing time required. It is planned to use a one dimensional code to make studies of the effects of various parameters. The two dimensional code will then be refined to study the two dimensional effects of the more promising propellant configuration at selected intervals along the launch tube.

CHAPTER III

LAUNCH TUBE PRESSURE STUDIES

Strain gages were mounted on the outer surface of the hypervelocity launch tube to obtain a relationship between the pressure development and time due to the gas released by the rapid burning propellant on the inner surface of the launch tube. With the tube behaving as a transducer, the effects of pressure, heat addition, and dynamics were measured. Through correct interpretation of the data, the strain due to heat addition and dynamics were separated from the data and the pressure was measured as a function of time.

INSTRUMENTATION

In order to measure the internal pressure, strain gages were mounted on the launch tube in the hoop direction. The launch tube acted as a transducer, with the strain resistance changes producing signal changes proportional to the pressure. The strain gage signal was inherently weak, requiring the development of an amplification system. The signal was amplified and displayed with an oscilloscope. The voltage changes were recorded on a storage type cathode ray screen and a photograph was taken of the trace for permanent data recording. Circuits for the instrumentation are presented in Appendix I.

Two types of strain gages were employed on the launch tube: A foil type, SR-4, Type FAE-03G-12S9 and a semiconductor type, SPB2-12-100C6. The strain gages were mounted in the circumferential or hoop direction. Two strain gages were mounted at each station to multiply the strain readings by a factor of two for a greater amplification of the reading. The first data station is twelve inches down the tube and designated gage #12. A semiconductor strain gage is mounted five inches in front of gage #12 to trigger the sweep of the oscilloscopes. The second station of the five foot tube is forty-eight inches downstream and designated gage #48.

To amplify the voltage change out of the wheatstone bridge, a μA702A Resistance Bridge Amplifier is used. The amplifier has desirable characteristics for measuring the strain on the launch tube. The gain of the amplifier is 470:1.

For data recording, three Hewlett-Packard 141A dual trace storage Osciiloscopes were used. Three scopes were needed. One for each of the two strain gage stations and another scope was used to relate velocity and position of the projectile. The scopes were generally set using chopped mode to obtain dual traces. Sweep speed was set for 0.2 cm/millisecond. The sensitivity generally was set at 0.2 volts/cm.

The strain gage circuit was calibrated both statically and electrically. The system was statically calibrated by pressurizing a tube. The electrical calibration was performed by paralleling resistors across the strain gages, thus simulating the resistance change due to strain.

EXPERIMENTAL TESTS

Tests were run using various propellants, ignition charges, projectiles, and propellant thicknesses. A typical trace is illustrated in Figure III.1. The trace of gage #12 is the upper trace and begins on the reference line with zero strain. It remains zero for 120 microseconds. At this point the projectile passes gage #12 and the strain gages react by deflecting

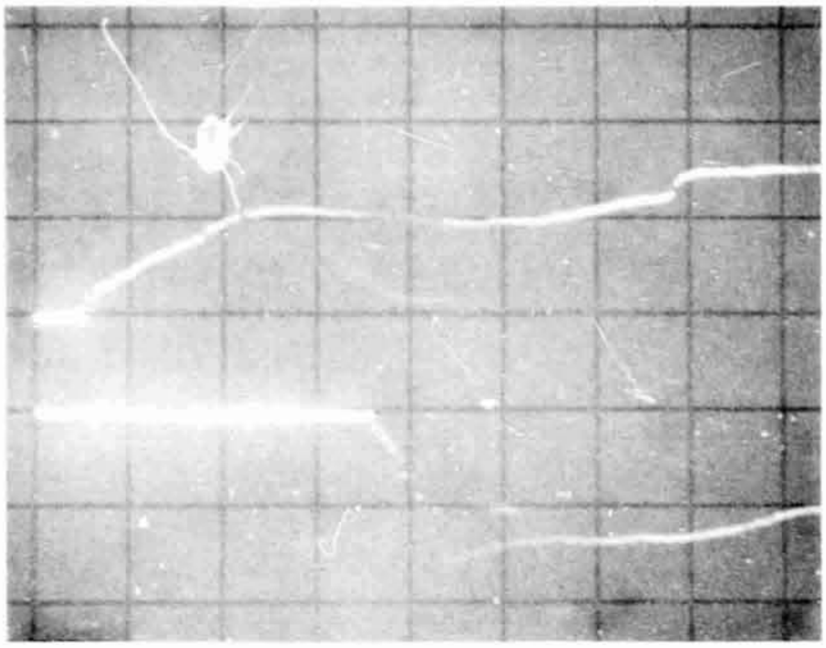


Figure III.1: Gage # 12 and 48 trace with 3 in/sec. burning rate propellant.

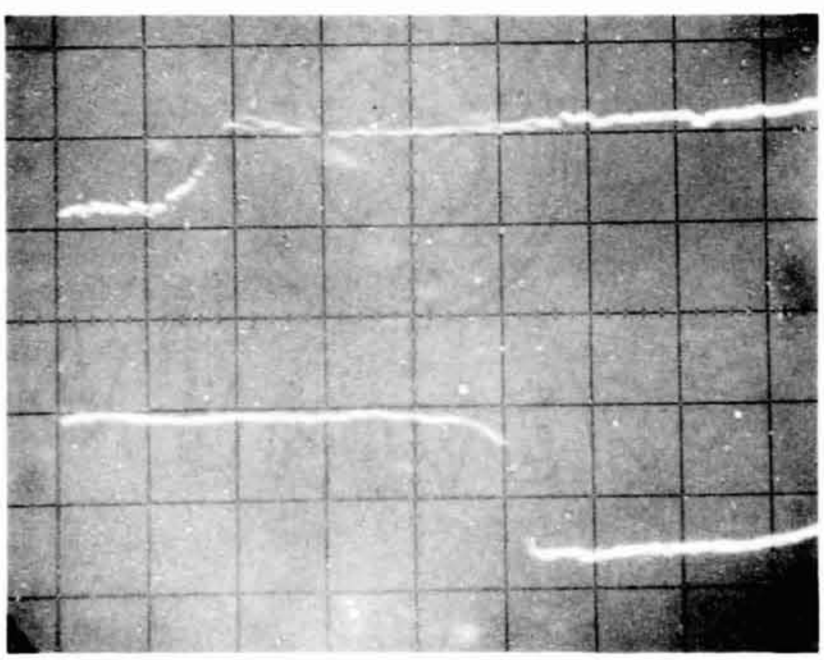


Figure III.2: Gage #12 and #48 trace with 30 in/sec. burning rate propellant.

upward 0.1cm, which is the strain caused by the base pressure on the projectile. With time the strain continues to increase with increasing pressure within the tube. After 1.2 milliseconds the thermal strain appears on the exterior surface of the tube. This is the time that the propellant serves as an insulator between the hot gases and the launch tube wall. The thermal strain is seen as another deflection in the trace. The lower trace on the figure is gage #48. The strain remains at the zero level until the passage of the projectile, at which time the strain gages react by deflecting downward since the trace on the oscilloscope was inverted for convenience. The oscilloscope sensitivity was set at 0.2 volts/cm, therefore one centimeter deflection represents 100 in/in microstrain.

Figure 1 is a pressure trace of a propellant burning in the hypervelocity launch tube with a longitudinal burning rate of approximately 3 in/sec. Figure III.2 depicts a pressure trace of a propellant with a burning rate of approximately 30 in/sec, or ten times that of the propellant used in the test of Figure III.1. The pressure development is a function of the burning rate, therefore the time required to reach maximum pressure is longer for the slower burning propellant. The required time for pressure development can be found by considering the slopes of the strain traces. Figure III.1 shows a jump in trace as previously discussed, whereas in Figure III.2, the initial deflection has a curved deflection. The curved deflection is due to the propellant igniting in front of the projectile, thus the jump in trace due to base pressure is not seen. Considering the slopes after the initial deflection in Figures III.1 and III.2, the results confirm the burning rate data. Figure III.1 shows a smaller slope with the slower burning propellant and Figure III.2 shows a larger slope with a faster burning propellant.

DISCUSSION OF PRESSURE DETERMINATION BY USING STRAIN GAGES

It is feasible to use strain gages mounted on the external surface of the launch tube to measure the internal pressure behind the projectile. The strain recorded on the external surface is produced by pressure, heat addition and dynamic response. With correct interpretation the strain produced by each effect can be found. The frequency of the dynamic strain waves will cancel themselves at projectile velocities less than the sonic speed of the launch tube. At greater velocities the dynamic strain must be considered. For the current data, the dynamic strain does not appear on the strain trace. The magnitude of the thermal strain was found to be negligible during the first 1000 microseconds after the passage of the projectile where there is a slow burning rate of the propellant. With the effects of heat addition and dyanmics eliminated from the oscilloscope data trace, the strain was assumed to be due only to internal pressure for the first 1000 microseconds of data recording.

The pressure data has two regions. The first is in the area of initial strain recording. In this area the strain is produced by the pressure directly behind the projectile. The initial deflection will produce a jump in the trace for high base pressures and jump will be larger for greater pressures. A correlation has not been established between the jump in the data trace and the velocity of the shot due to limited test results. However, the jump in the data trace is related to the base pressure. The second area begins at the point where the strain trace assumes a definite slope. It has been found that when the slope is large it is accompanied by a jump in trace, indicating a large base pressure. The maximum deflection of the strain trace in this area defines the value of ultimate pressure. The ultimate pressure data can be used to find the gas volume produced by the thin film propellant.

As stated, the initial deflection is produced by the pressure directly behind the projectile. With this knowledge strain gages mounted to the external surface can relate the position of the projectile at various times within the launch tube. Average velocities of the projectile can be obtained between strain gage stations.

CHAPTER IV

PROPELLANT STUDIES

An intensive propellant study has begun over the past six months. Three areas of investigation are being considered while studying thin film propellants. These area are: Ignition time, longitudinal burning rate and normal burning rate. Instrumentation to study the area of longitudinal burning rate has been built. Instrumentation to study the other two areas is being designed. Preliminary longitudinal burning rate tests were conducted with several variables being introduced in the propellant. The variables found to most effect the burning rate are: filmogen material, fuel/oxidizer ratios and materials, friction material, and propellant thickness.

INSTRUMENTATION

To test the longitudinal burning rate of the propellant, two different types of test apparatus were developed. The first measured velocity of the burning was made by the use of ionization gages. The ionization gages were made of two straight needles placed parallel and insulated from each other. The needles were .125 inches apart and at an elevation of .125 inches above the surface of the propellant. The propellant was coated on a steel coupon in a straight strip by the use of masking tape. The strips of propellant were .25 inches wide and six inches long. One end was tapered to a point in order to give the burning a perpendicular flame front after ignition. The thickness of the propellant ranged from .003 to .020 inches.

As the propellant flame front passed the ionization gages the ionized gas of the flame front completed the circuit across the gages. The voltage change was recorded on a dual trace oscilloscope. Three ionization gages were mounted above the coupon at intervals of two inches. The first was used as a trigger gage for the oscilloscope. The remaining two were used as data stations. With the distance between the gages being known and the time at which the flame front passed the two ionization gages (obtained from the oscilloscope) the longitudinal velocity or burning rate of the propellant is found. See Figure IV.1 for a typical trace.

A more satisfactory apparatus was developed using photodiodes as data sensors. Associated with the flame front is a substantial amount of light which can be detected by a photodiode. The photodiodes were placed at one end of a hypodermic needle. The needles were used to collimate the light so that the diode would only see a point source of light. The end of the needles were at an elevation of .125 inches above the propellant. The inside diameter of the hypodermic needles was .008 inches. The propellant coupon was made in the same manner as those made for the tests performed with the ionization gages. The diodes were placed at two inch intervals and their data was recorded on the oscilloscope. The longitudinal burning rate was obtained in the same manner as described in the discussion of the ionization gages. See Figure IV.2 for a typical trace.

The photodiode sensors were found to be more reliable and recorded a more readable trace. The ionization gages recorded the variations in the ionization of the flame front, therefore, the traces were very irregular. The photodiode circuits record zero light or maximum light with no intermediate level, therefore, the data traces were straight lines. The response time of the photodiodes was found to be very fast, less than one microsecond. Both the photodiode and ionization gages were found to collect propellant residue, but both could be cleaned easily after each test.

The photodiode test apparatus was chosen for all further longitudinal burning rate tests because of the clearer data traces and greater reliability.

A photodiode test apparatus to be placed in a vacuum is being designed. This would give the capability of studying propellant burning race under a vacuum to which propellant is subjected prior to firing in the velocity launch tube.

Other test apparatus designs for ignition delay time and normal burning rate are being tried. One attempt was a system which used the shock tube at Texas A&M University. The shock ignited the propellant. Instrumentation on the shock tube gave the time of impact, and by using heat transfer gages and a Hopkinson bar arrangement, the ignition delay time and the normal burning rate were to be obtained. However, the geometry of thin propellants requires such small heat transfer gages that the idea was shelved.

Also under consideration are high speed movies of the propellant burning. This could lead to information about the normal burning rate.

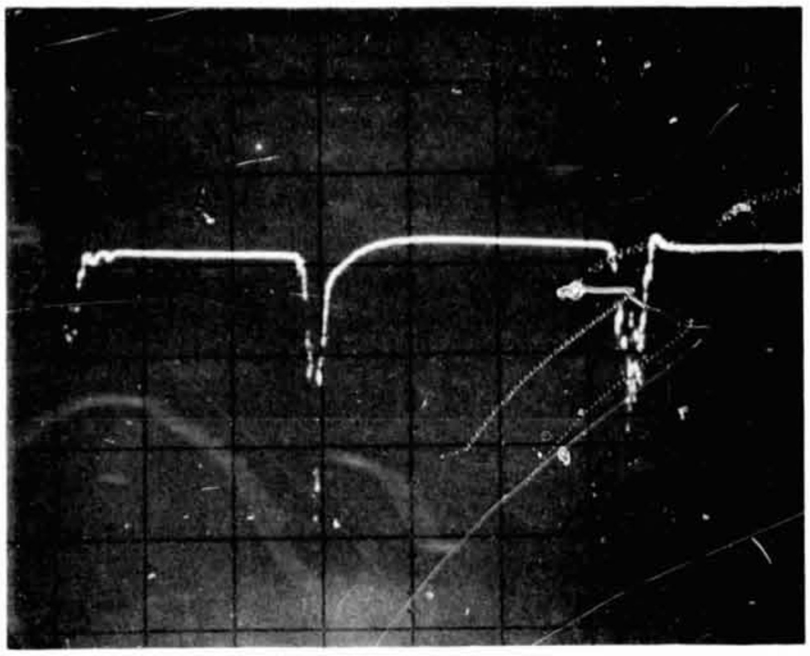


Figure IV.1: Ionization Gage Data trace

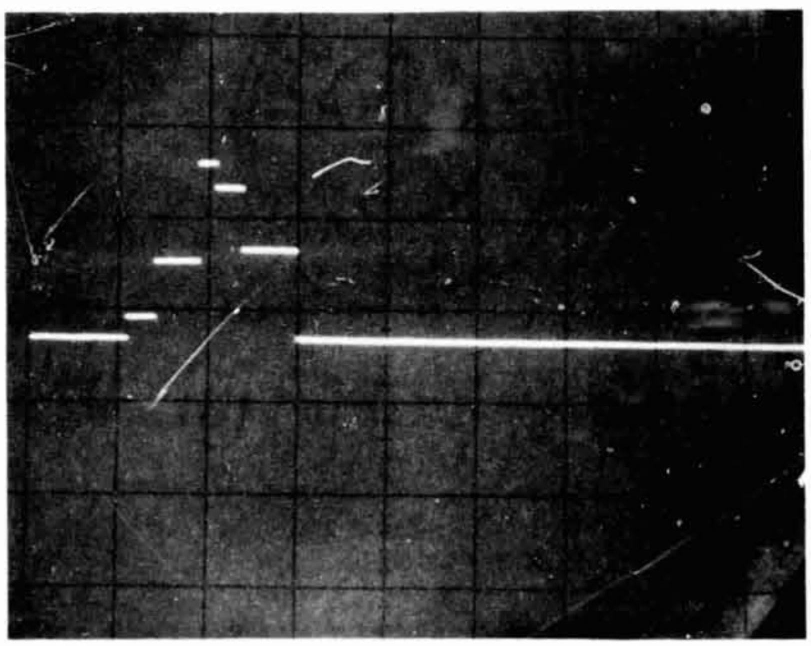


Figure IV.2: Photodiode Data Trace

FUEL/OXIDIZER STUDIES

Two principle oxidizer materials have been tested. One is ammonium perchlorate, NH_4CLO_4, and the other potassium nitrate, KNO_3. Ammonium perchlorate was discarded when it was found that the burning rate significantly decreased when burned in a near vacuum atmosphere.[3] It was also learned from the same source that a vacuum atmosphere did not effect the burning rate of potassium nitrate. Therefore, the burning rate studies were performed using potassium nitrate as the oxidizer. The percentage of the fuel/oxidizer in the mixture was one varible tested. The percentages varied from 23% to 75% of the total propellant mixture. See Table IV.A for results of tests. Two types of fuel materials used were monopropellants manufactured by McCormick-Selph and have identification numbers 104 and 164. Both were used to increase the burning rate of other oxidizer type compounds. Type 104 is recommended as the faster of the two, but less sensitive. Both were dissolved with potassium nitrate (without filmogen) and allowed to dry in a .25 inch deep trough. The monopropellants were mixed with the oxidizers in ratios of 3:1 and 1:1. Ionization gages were used for the velocity recordings. The burning rates obtained were in agreement with the burning rates claimed by the manufacturing company. The 1:1 mixture was found to be a faster burning mixture. See table IV.B. Also identical mixtures produced varying velocity recordings. All dry mixtures, without filmogen, tested had burning rates in the range of 200 ips to 8000 ips. Probable factors contributing to variation in burning rate were: Thickness of propellant,

TABLE IV.A

PROPELLANT STUDIES

TYPE OF FUEL/OXIDIZER	%	FILMOGEN	%	EXPLOSIVES	%	THICKNESS mils	VELOCITY[1] (ips)	COMMENTS
KNO_3 and MS 164 1:1 Ratio)	95	PVC[2]	5			20	95-665	Chalky
						10	45-83	IONIZATION GAGE USED
	92.5	PVC	7.5			20	2600	
						18	1000	
						11	118-220	
						9	100	
						8	286	
		NC[3]	7.5			13	14-16	PHOTO DIODE USED
						11	8-13	
						9	5-10	
						8	9.5-19	
						7	12-16	
						5	10	
	90	PVC	10			20	500	IONIZATION GAGES USED
						10	222	
						7	33	

[1]Velocity is value of one test or indicates range of multiple tests
[2]Polyvinylchloride
[3]Nitrocellulose

TABLE IV.A (con't)

TYPE OF FUEL/OXIDIZER	%	FILMOGEN	%	EXPLOSIVES	%	THICKNESS mils	VELOCITY[1] (ips)	COMMENTS
KNO$_3$ and MS 164 (1:1 Ratio)	90	NC	10			9	18	PHOTO DIODE USED
						7	15	
						5	7.5-10	
						4	6.25-10	
						1	9-10	
	85	PVC	15			9	400-666	PHOTO DIODE BURNING RATE GAGES USED
						8	125-800	
						7	33-222	
						6	35-400	
						5	100-250	
						3	133-145	
	67	PVC	15	LEAD AZIDE	18	6	140-500	water splashed on coupon
						5	666	Greater Sensitivity
		PVC	15	RDX	18	7	83	Greater Gas volume
						6	400	
						4	36-250	
						3	200	

TABLE IV.A (con't)

TYPE OF FUEL/OXIDIZER	%	FILMOGEN	%	EXPLOSIVES	%	THICKNESS mils	VELOCITY[1] (ips)	COMMENTS
	57	PVC	15	LEAD AZIDE	28	7	25-500	Greater sensitivity
						6	42.5-85	
		PVC	15	RDX	28	7	83	Greater Gas volume
						6	400	
						4	125-250	
						3	200	PHOTO DIODE GAGES USED

TABLE IV.B

FUEL/OXIDIZER WITHOUT FILMOGEN

TYPE	PERCENTAGE	TYPE	PERCENTAGE	VELOCITY	COMMENTS
KNO_3	66.6%	MS 164	33.3%	200	Propellant dried for one week
KNO_3	66.6%	MS 164	33.3%	>1000	Propellar dried over night
KNO_3	66.6%	MS 164	33.3%	1000	
KNO_3	50 %	MS 164	50 %	2500	
KNO_3	50%	MS 164	50 %	5000-8000	

age of monopropellant, humidity, temperature, surface smoothness, degree to which the compound was mixed, and drying time. The 1:1 mixture was recommended for faster burning rates by the manufacturer and was substantiated by our tests. Therefore, the monopropellant was added to the oxidizer in a 1:1 ratio for all further tests.

FILMOGEN STUDIES

The most critical parameter effecting the burning rate was found to be the type and amount of filmogen material used. Two types of filmogen binders have been tested to date. They are nitrocellulose and polyvinylchloride. The amount of filmogen added to the propellant mixtures were varied for the longitudinal burning rate tests.

First considered was nitrocellulose. With a 25% mixture it was found that the propellant would spark under the point where ignition energy was applied, but the propellant would not propagate a flame. By reducing the amount of nitrocellulose the propellant would propagate a flame front and the velocity of the flame front was increased with the decrease in percentage of nitrocellulose. With 5% nitrocellulose the propellant would not adhere to a metal surface. It was found that a minimum of 10% filmogen was required to coat the stainless steel tubes used for the hypervelocity launch tube. For less than this percentage, the propellant would flake off the surface. For the velocity range versus percentage of the binder, see Table IV.C.

A second filmogen tested was polyvinylchloride recommended by Rocketdyne. It was recommended that a mixture of 15% be used. Variations in the percentages were tested and again it was found that as the filmogen percentage was decreased the burning rate was increased. The minimum percentage of filmogen that had adhesive properties was 5%, although this low a percentage of filmogen was not desireable in coat-

TABLE IV.C

FILMOGEN AND THICKNESS STUDIES

FILMOGEN TYPE	PERCENTAGE	THICKNESS (mils)	VELOCITY (ips)	COMMENTS
NC	25			Will not propagate a flame front
NC	10	9	18	PHOTODIODE GAGES USED
		7	15	
		5	7.5-10	
		4	6.25-10	
		1	9-10	
	7.5	13	14-16	
		11	8-13	
		9	5-10	
		8	9.5-19	
		7	12-16	
		5	10	
	5			Will not coat
PVC	15 Acetone Solvent	9	400-600	Acetone will not dissolve dissolve MS 164; PHOTODIODE GAGES USED
		8	800	
		7	133-222	
		6	200-400	
		3	133-145	

TABLE IV.C (con't)

FILMOGEN TYPE	PERCENTAGE	THICKNESS (mils)	VELOCITY (ips)	COMMENTS
PVC	15 Aceton Solvent	9	1000-2000	Questionable Data PHOTO-DIODE
	15 Butyl Acetate Solvent	8	125	
		7	33-50	
		6	35	
		5	100-830	Questionable Upper Limit
	10	20	500	Ionization gages used
		10	222	
		7	33	
	7.5	20	2600	
		18	1000	
		11	118-220	
		9	100	
		8	286	
	5	20	95-665	Chalky
		10	45-83	

ing a hypervelocity launch tube because the propellant would flake. Ten percent binder was found to be a suitable mixture to coat a launch tube. The type of slovent used also may have effected the burning rate in an indirect way. Butyl acetate was found to give a better mixture consistency. Acetone had orginally been recommended as the solvent, but the monopropellant material lumped.

The Polyvinylchloride filmogen has proved to be the most suitable filmogen of the two. It coats as well as nitrocellulose and has a higher burning rate than nitrocellulose for the same percentage and propellant thickness.

THICKNESS STUDIES

The literature concerns itself with cast propellants or very thick layers in the order of inches. There is a lack of literature on thin film propellant burning rates. The literature [4] does, however, indicate that as the thickness of the propellant decreases, the burning rate will do likewise. The tests performed have substantiated this fact. Over a range of thickness of three to twenty mils, there is a wide range of burning rates. For the thicker coats, i.e. twenty mils, the coating techniques varied. Twenty mils could be obtained withone to three coats. There did not seem to be any variation in burning rate due to number of coats required to give a desired thickness. For thickness versus burning rate see Table IV.A and IV.C.

ADDITIVES

Two classes of additives are being tested. One is the addition of explosives, both primary and secondary. The other type of additive is a friction material or hard, sharp materials. Tests are being performed on types of additives and percentages of additives.

Two explosive type additives have been tested. RDX was added and an increase in gas volume was expected and obtained. This fact was observed by placing the test coupon in a hood and quantitatively comparing the smoke generated. The RDX did not effect the burning rate significantly. The other explosive material added was lead azide. This material was expected to increase the sensitivity[6] which it did. However, it did not effect the burning rate. The burning rate versus percentage of explosives added may be found in Table IV.A.

The second type of additive is material to increase the frictional characteristics of the propellant. This type of additive is made up of such materials as powdered glass, sand, and aluminum. Tests for the effects of this type of additive have not been conclusive.

IGNITION TESTS

Designs are being considered for determining the amount of energy required to ignite the thin film propellant. The designs include drop tests, shock tube impacts, heat, exploding wires, and frictional devices.

At present, ignition characteristics are tested by striking the coupon with a hammer, scratching coupons with iron points, nylon and aluminum rods, heating with soldering iron and igniting with a gun powder fuse. Of these named methods, all except the nylon rod have been successful in igniting the propellant coupons.

CONCLUSIONS OF PRESENT PROPELLANT STUDIES

The three principle areas of investigation are ignition characteristics, longitudinal burning rate and normal burning rate. The fuel/oxidizer being tested has a burning rate believed to be relatively unaffected by vacuum pressures. The monopropellant material increases the burning rate of the fuel/oxidizer compound, and a 1:1 mixture was found most effective.

The amount of filmogen and the thickness of the propellant are the two greatest factors effecting the longitudinal burning rate of the thin film propellants. A decrease in filmogen increases the burning rate. The burning rate increases with an increasing film thickness. Polyvinylchloride filmogen was found to be the least inhibitive and a mixture of 10 to 15% is most feasible for coating the launch tube. Additives can be mixed with the propellant to increase the sensitivity without slowing the burning rate. The longitudinal burning rate test yields a wide range of burning rates for each type of propellant with identical thickness. This leads to the conclusion that a small variation in any parameter effects the rate substantially.

CHAPTER V

PROJECTILE DESIGN

The original concept of the propellant-lined launch tube was to have the projectile introduce sufficient energy to ignite the propellant in the belief that the ignition delay time would keep the burning front behind the projectile. As reported in the 1968 report[1] it was found that, when the friction was sufficient to ignite the propellant, the ignition delay time was so short that ignition ocurred at the nose tangency of the projectile.

Two approaches were taken to solve the problem of using the projectile to ignite the propellant and yet to keep the burning behind the projectile. One approach was the thermal igniter. The idea was to use a traveling charge as a heat pulse to ignite the propellant. This has the added characteristic of supplying some gas on the base of the projectile moving at projectile speeds. A variation of this concept may be required to provide gas if the propellant gases mix with the traveling reservoir as discussed in Chapter II.

Consultation with the Director of the Thermodynamics Research Center at Texas A&M University resulted in the belief that the heat pulse of a traveling charge was probably insufficient to provide ignition without delay. Because previous tests with friction had indicated immediate ignition, it was decided to develop a projectile that would have a plastic forebody and seal, in a proven configuration, but to attach a metallic afterbody that would fire the propellant by friction.

Several of the configurations that have been tested are shown in Figure V.1. A plastic projectile, a traveling charge and three projectiles using friction rings are shown. The designs were selected for their vibrational characteristics. Cantilever strikers were originally postulated, but analysis of the vibrational modes indicated that the end of the cantilever would swing away from the surface and the natural frequency would carry it back so that it would strike once every foot if the projectile was traveling at 10,000 feet per second. The situation would become worse at higher velocities. The ring configuration with its very high natural frequencies and limited deflection characteristics will provide constant contact and ignition.

The problem with this type of igniter is the structural failure of the attachment. Subsequent analysis indicated that better geometry could improve the strength but it is still stressed near the maximum stress of the material.

A search for a better design has led to configurations that are shown in Figure V.2. These three designs have indicated by analysis, that they are stronger structurally. The designs will require refinements in order to be manufactured and will be tested to see if they perform satisfactorily. The concept is to use metal pins or staples as friction igniters and relieve the plastic afterbody to allow gas to flow to prevent the creation of high pressure in the annulus that might cause the propellant to flash forward ahead of projectile.

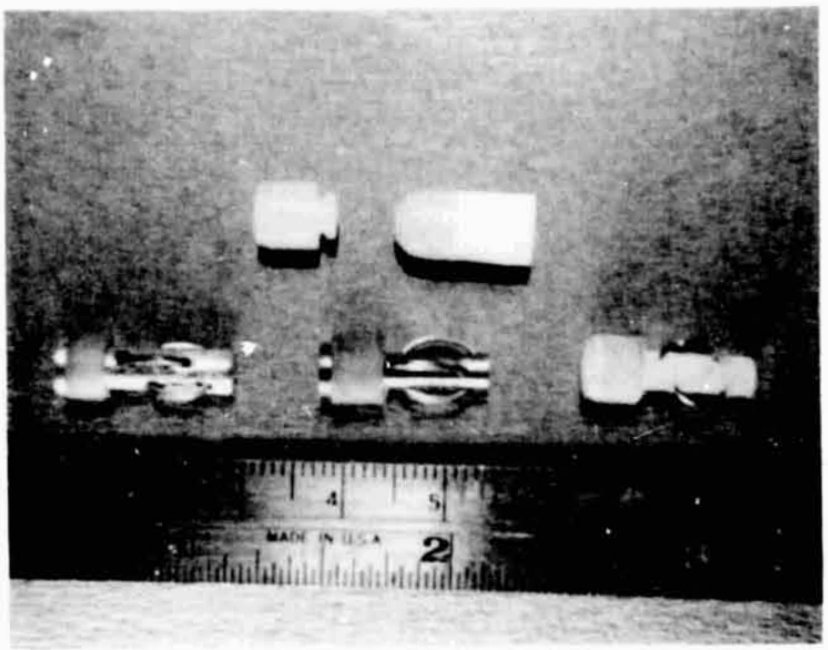
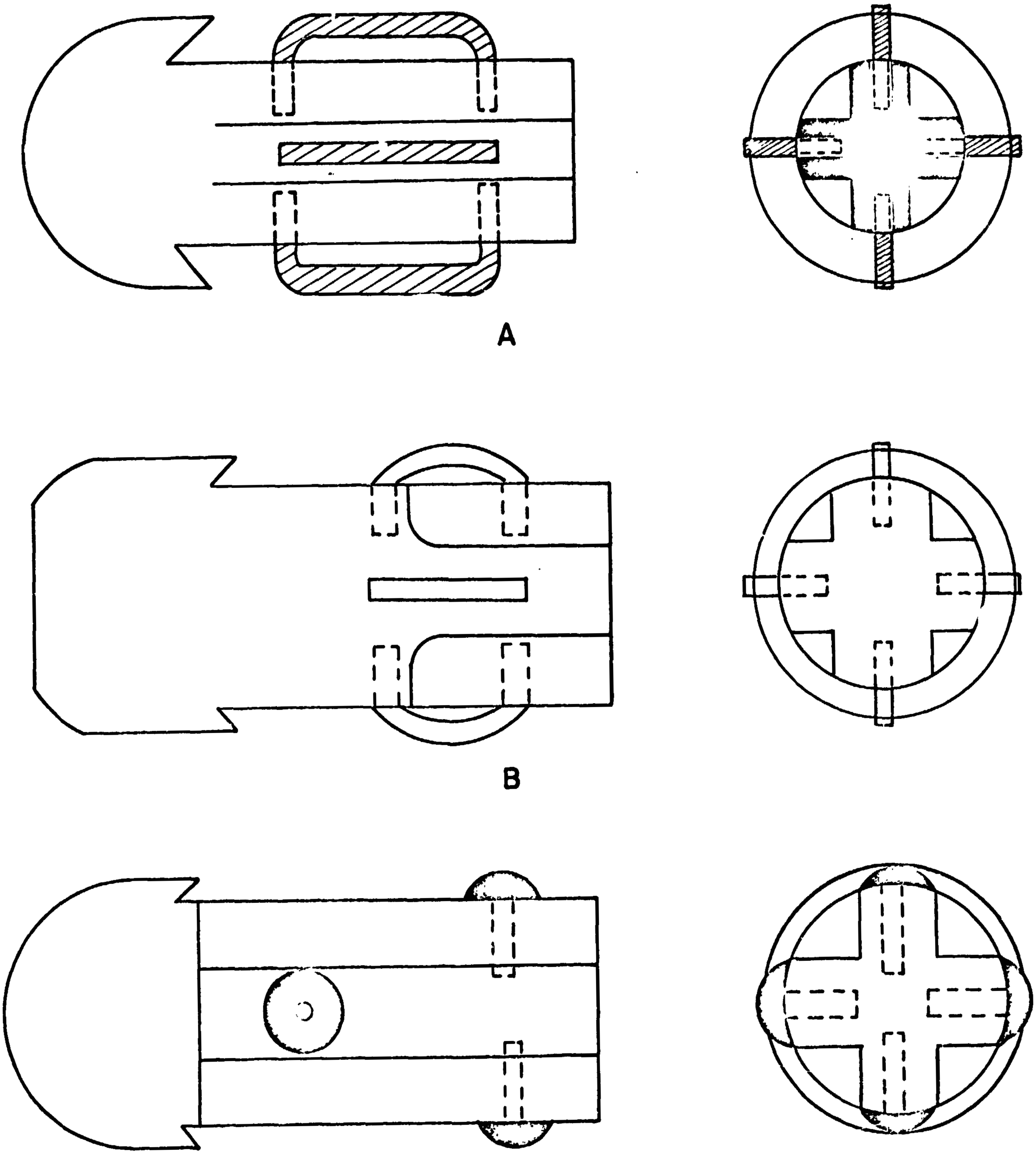


Figure V.1: Various Projectile Designs



A

B

C

FIGURE V-2

PROJECTILE CONFIGURATION

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The most important finding of this reporting period was the fact that the nitrocellulose filmogen was inhibiting the burning of the fuel/oxidizer materials. The low burning rate of 3 inches per second does result in a increase in velocity of a projectile in a lined tube over that of one in an unlined tube. Orders of magnitude difference in burning rate was obtained by changing from nitrocellulose to polyvinylchloride. The higher burning rates with the proper ignition control should result in higher velocities. A study is needed of the effect of various filmogens, fuels, oxidizers and additives on the burning rate of the propellant at normal pressures and vacuums. A test facility is being constructed to measure burning rate at a vacuum of the same magnitude as the launch tube vacuums as well as at standard pressure. Another facility will be constructed to measure the energy required to ignite the propellant to screen various compounds.

The theoretical attempts to mathematically model the projectile motion and the dynamics of the gases behind the projectile has helped to clarify the understanding of possible problems and advantages of the concept. The calculations that assume a solid piston is formed by the gases from the propellant lining, indicates that the concept can provide major increases in velocity over the light gas gun. A one-dimensional computer model will examine the limitations of the concept using the assumption of complete instantaneous mixing of the propellant gases with the gas traveling with the projectile. It is recommended that parametric studies be made of burning rate, temperature and propellant thickness using the one dimensional computer model as a lower bound solution. The exact solution should fall between the solid piston and complete mixing. A continuing effort should be directed toward determining a better model of the boundary between the propellant gas and the traveling gas with regard to mixing, jetting, pressure and velocity distributions.

The design of the projectiles relates directly to the ignition delay problem. It is recommended that the development of frictional igniter types be continued and compared to the results from thermal igniters.

The development of large spacecraft operating for months and years will either require a large amount of weight devoted to meteoroid protection or an unacceptable risk to the spacecraft unless laboratory methods are developed to simulate meteoroid impact.

The proposed concept holds the promise of reaching meteoroid velocities and should be continued until it is fully developed.

APPENDIX I

Hypervelocity Laboratory Instrumentation

Figure 1 illustrates the basic layout of the instrumentation developed for the measurement of pressure in the launch tube and determination of projectile velocity and integrity. The pressure determination is measured from the resistance changes of either foil type strain gages or semiconductor gages mounted 180° apart in pairs in the hoop direction. The series connection delivers twice the resistance change of a single gage and cancels any bending that may occur during the shock of firing. The first gage is a single high output semiconductor gage which is used to trigger the oscilloscope trace for the data gages.

The projectile velocity is determined by the interruption of a circuit printed on thin paper. The projectile integrity is obtained from the sharp edged hole cut in the paper. The circuit for the semiconductor strain gage trigger is shown schematically in Figure 2.

A semiconductor strain gage was utilized to detect the hoop strain produced due to the entry of the projectile into the launch tube. The higher output of the semiconductor strain gage provides a signal of suitable amplitude to exceed the trigger signal conditioner threshold determined by the LEVEL SET Control.

An output pulse of approximately five (5) volts is produced as the input signal exceeds the threshold level. Due to system noise, a threshold level of approximately 60 to 90 millivolts was normally used to prevent noise triggering of the system.

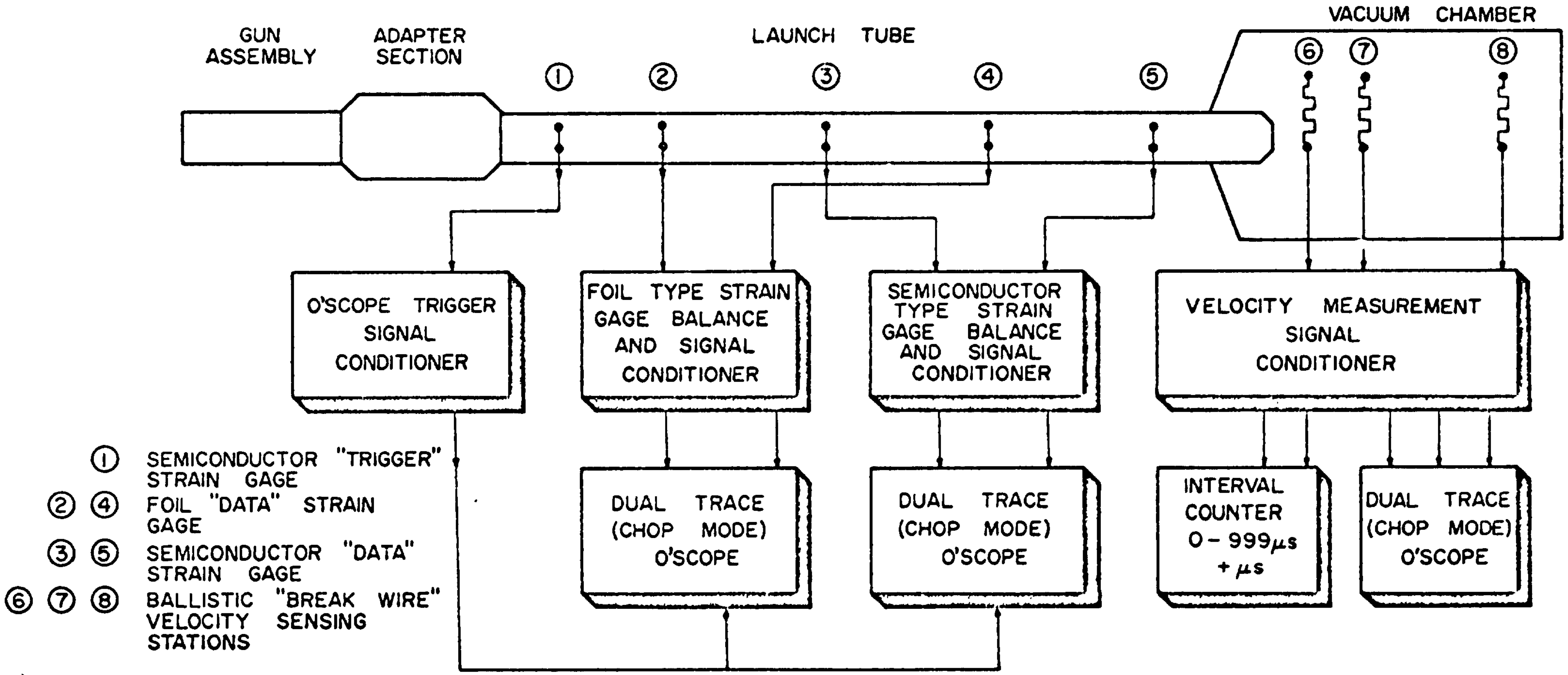


FIGURE-1 HVL INSTRUMENTATION - GENERAL LAYOUT

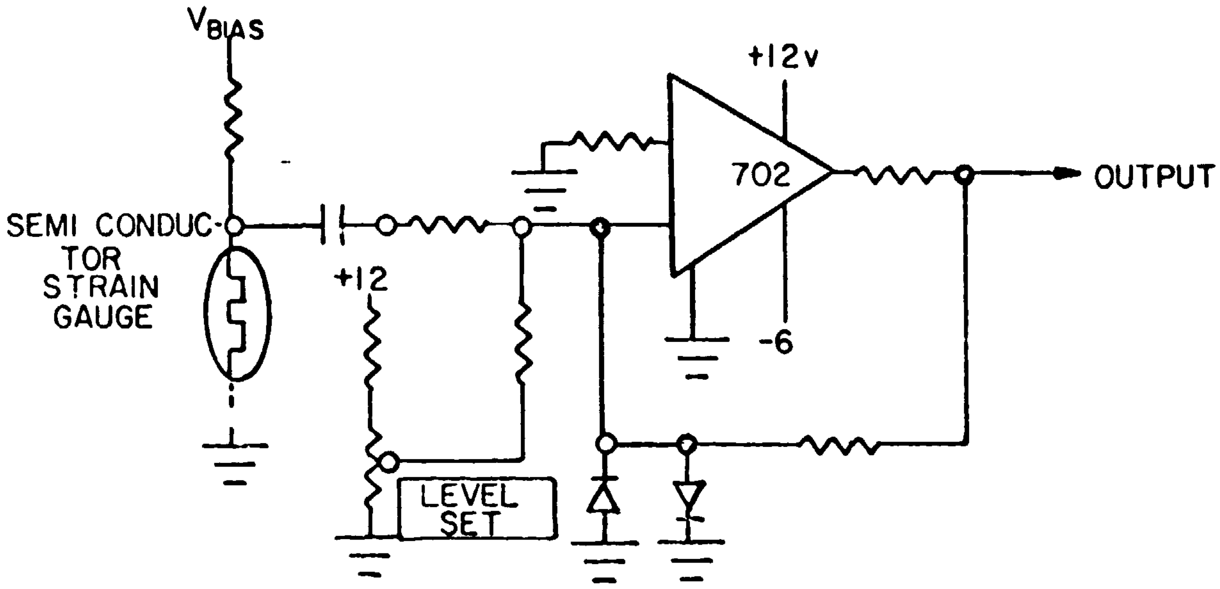


FIGURE 2 TRIGGER SIGNAL CONDITIONER

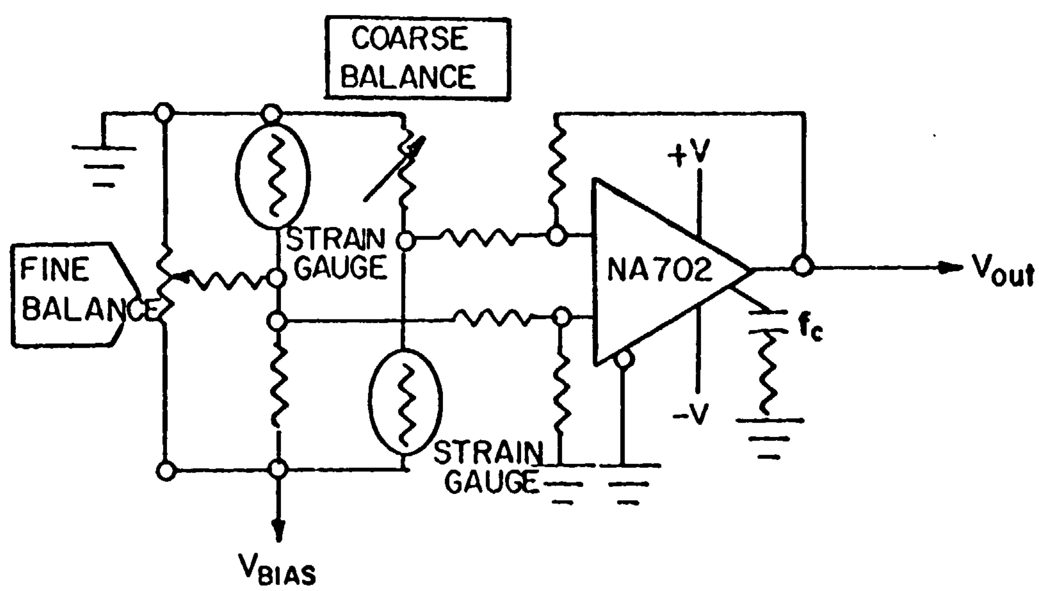


FIGURE 3 FOIL TYPE STRAIN GAUGE BALANCE & SIGNAL CONDITIONER

Actual triggering occurred at varied times. This was due to the fact that unlined tubes and slower burning propellants produced pressure trace with a low slope. A spacirg of three to five inches between the trigger gage and first data gage provided sufficient time to effect scope triggering prior to data acquisition at the first data gage.

A foil type strain gage balance and signal conditioner circuit is shown in Figure 3. Although this is a fairly straight-forward circuit, some deviation from standard practice was found to be necessary in this application.

For example battery power for both gage bias and op-amp supply was necessary due to a low level input signal. Also one element (coarse balance) of the bridge completion circuit was made variable to accomodate the variation in gage resistance for different launch tubes.

The op-amp gain was adjusted by selection of circuit values to provide the highest gain with maximum upper frequency response.

"Antenna effect" noise was always a problem, however the low 120 ohm output resistance of the bridge provided the best signal to noise ratio.

Careful grounding of the electronic circuits, as well as the launch tube itself, was necessary.

The circuit for the semiconductor strain gage balance and signal conditioner is shown in Figure 4. An investigation of the characteristics of a transistor connected in the grounded base configuration disclosed the fact that different values of emitter resistance would cause a shift in the transistor's operating (Q) point. Therefore experiments were conducted using semiconductor gages as the emitter resistor. Results have been encouraging and have provided data comparable to the more elaborate

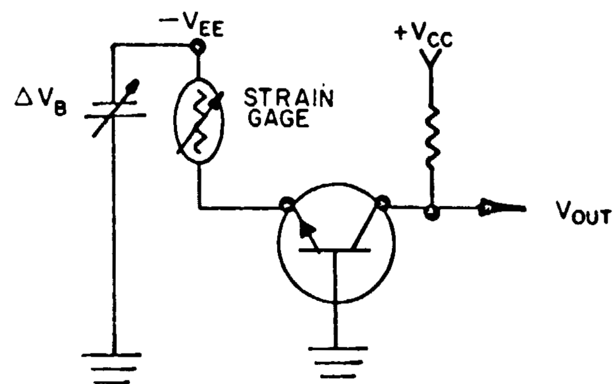


FIGURE 4 SEMICONDUCTOR STRAIN GAGE BALANCE & SIGNAL CONDITIONER

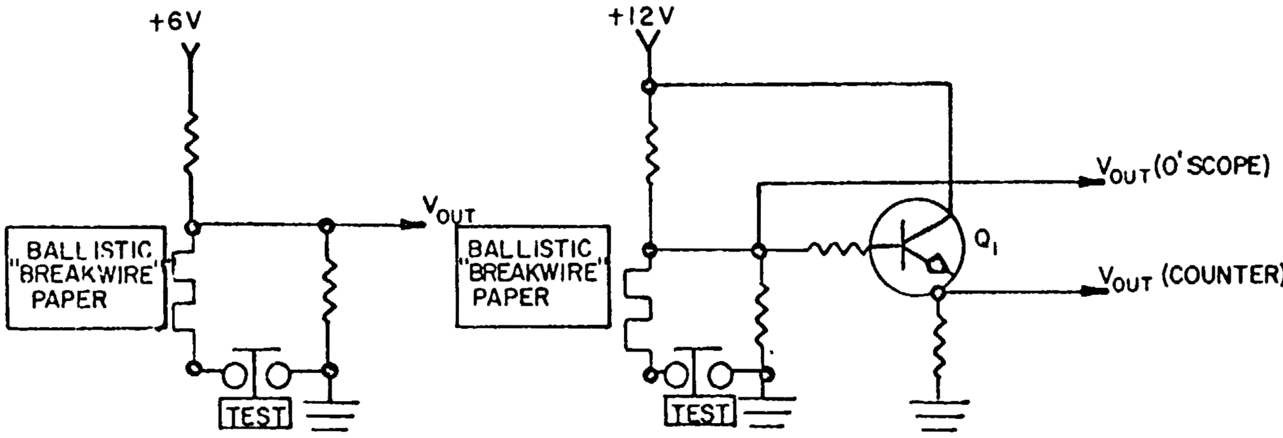


FIGURE 5 VELOCITY MEASUREMENT SIGNAL CONDITIONER

foil gage and signal conditioned system

Figure 5 shows the schematic of the velocity measurement signal conditioner. This simple break-wire system has proven to be quite effective for velocity measurement.

Several variations have been tried and the most satisfactory solution is shown.

Some difficulty was encountered with both "open" ballistic paper and plasma effects and were eliminated by the final design.

A test switch was installed to permit simulation of circuit activation as encountered during data acquisition periods. The addition of the interval counter required the addition of a common collector connected transistor to prevent low resistance loading of the system.

The interval counter-system block diagram is shown in Figure 6. Low cost commercial counters did not provide the accuracy desired. Therefore a relatively low cost counter was design to fulfill the particular requirements for this application.

A 2.0 mhz oscillator and a divide by two I.C. module was used to provide 1.0 mhz timing pulses. Gating voltages were taken from the velocity measuring signal conditioner and controlled three mod-10 decades. Meter readout provided an inexpensive method of interval indication.

The input gate and ready indicator for the velocity measuring system is shown in Figure 7. The interval counter (Fig. 6) was at first tried using only the gating voltages to provide start and stop signals to a simple gating IC circuit. Plasma effects at the ballistic stations resulted in spurious resistance changes that created several voltage excursions of

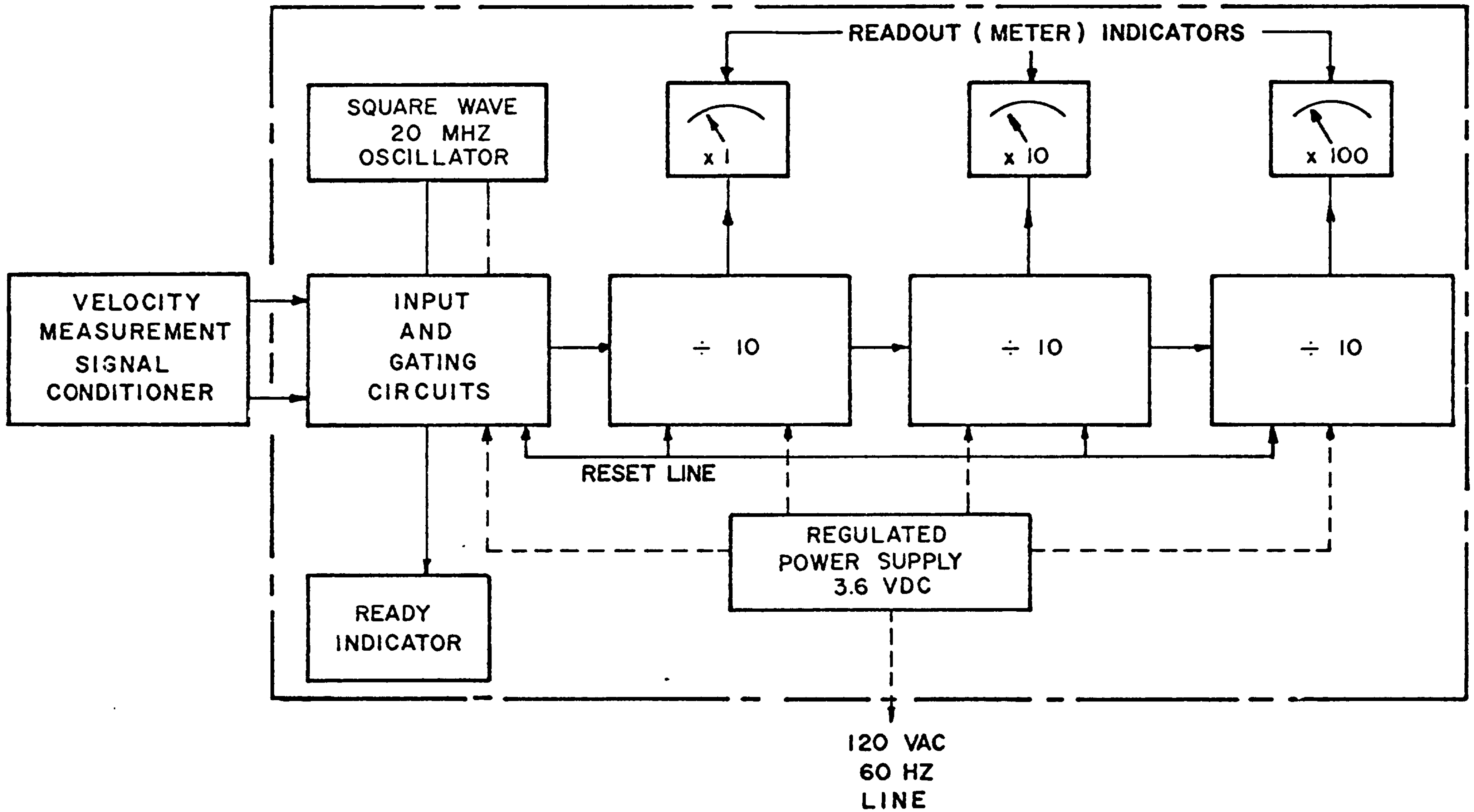
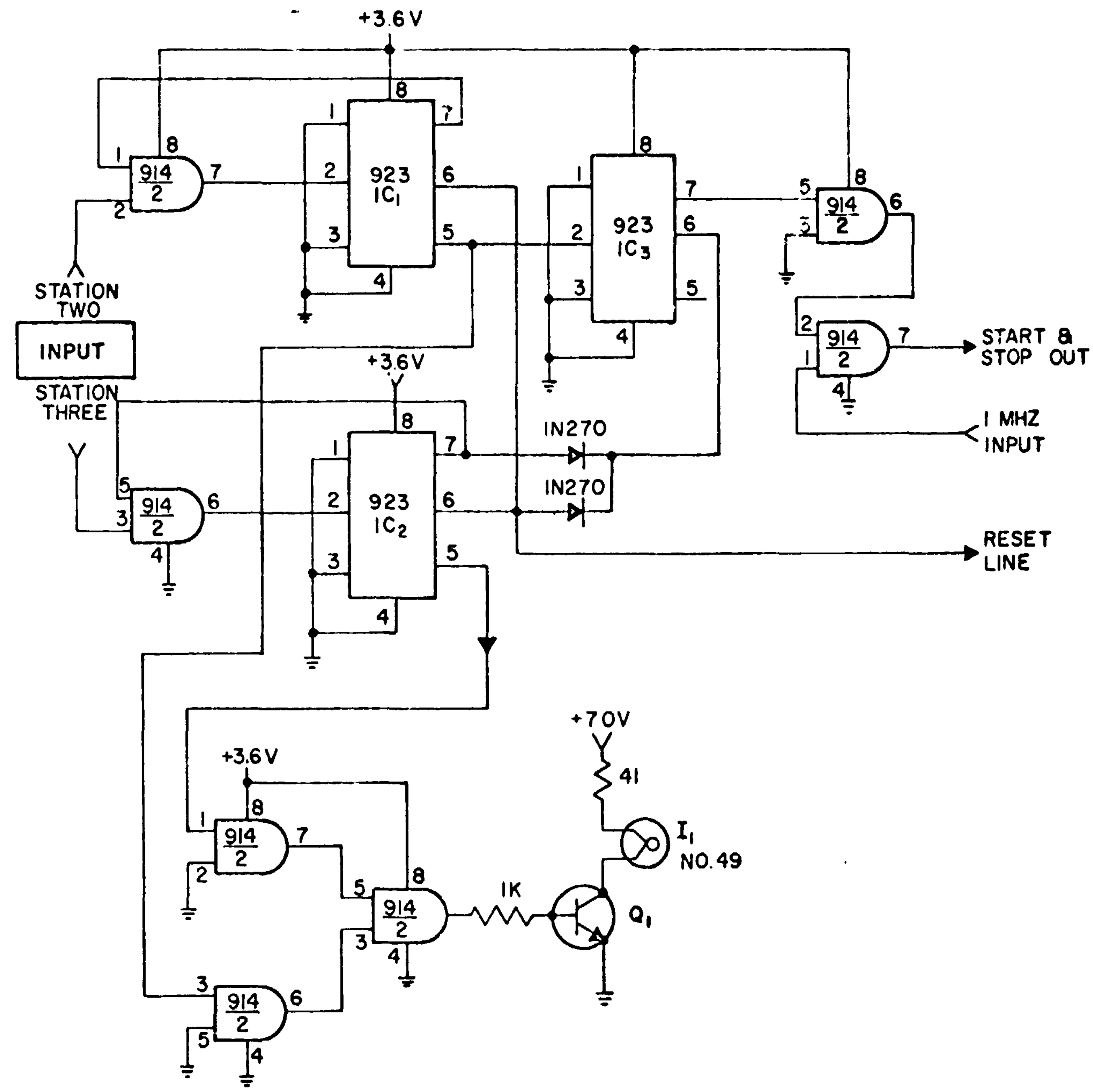


FIGURE - 6 INTERVAL COUNTER - SYSTEM BLOCK DIAGRAM



FIGURE—7 VELOCITY MEASURING SYSTEM—INPUT GATE & READY INDICATOR sufficient amplitude and polarity to cause false velocity indications.

The circuit of Figure 7 was devised to "lock up" on the final ballistic station change so that subsequent plasma induced changes would not create false gating signals. Since "turn-on" of the interval counter could produce either a rest or non-reset condition a "Ready indicator" was included to eliminate the improper condition as well as provide counter reset indicator. The indicator I_1 will be illuminated only when the correct ready to count condition exists and is extinguished when either the second or third ballistic station is open.

Figure 8 shows the circuitry for the velocity measuring system and divide by 10 decade and meter readout system. Three conventional Mod 10 decades were employed to provide x1, x10 and x100 indication of the gated one microsecond interval pulses. The summing circuit was devised by a student and has proven to be an inexpensive method of digital readout. Each meter was calibrated to indicate 10 units and provided direct readout.

Figures 9 and 10 show the block diagram and schematic of the circuitry for the longitudinal burning rate data system using photodiode sensors. Four 2N2175 photodiodes were installed in adjustable height assemblies shown schematically in Figure 9. Various sized hypodermic needles were placed over the detector to allow limitation of the field of view by collimating the light produced by the burning of the propellant.

The first photodiode (T) was used as a trigger to start the scope trace. Velocity measurements were made by the displacements of the three remaining photodiode outputs. This was accomplished by using the change

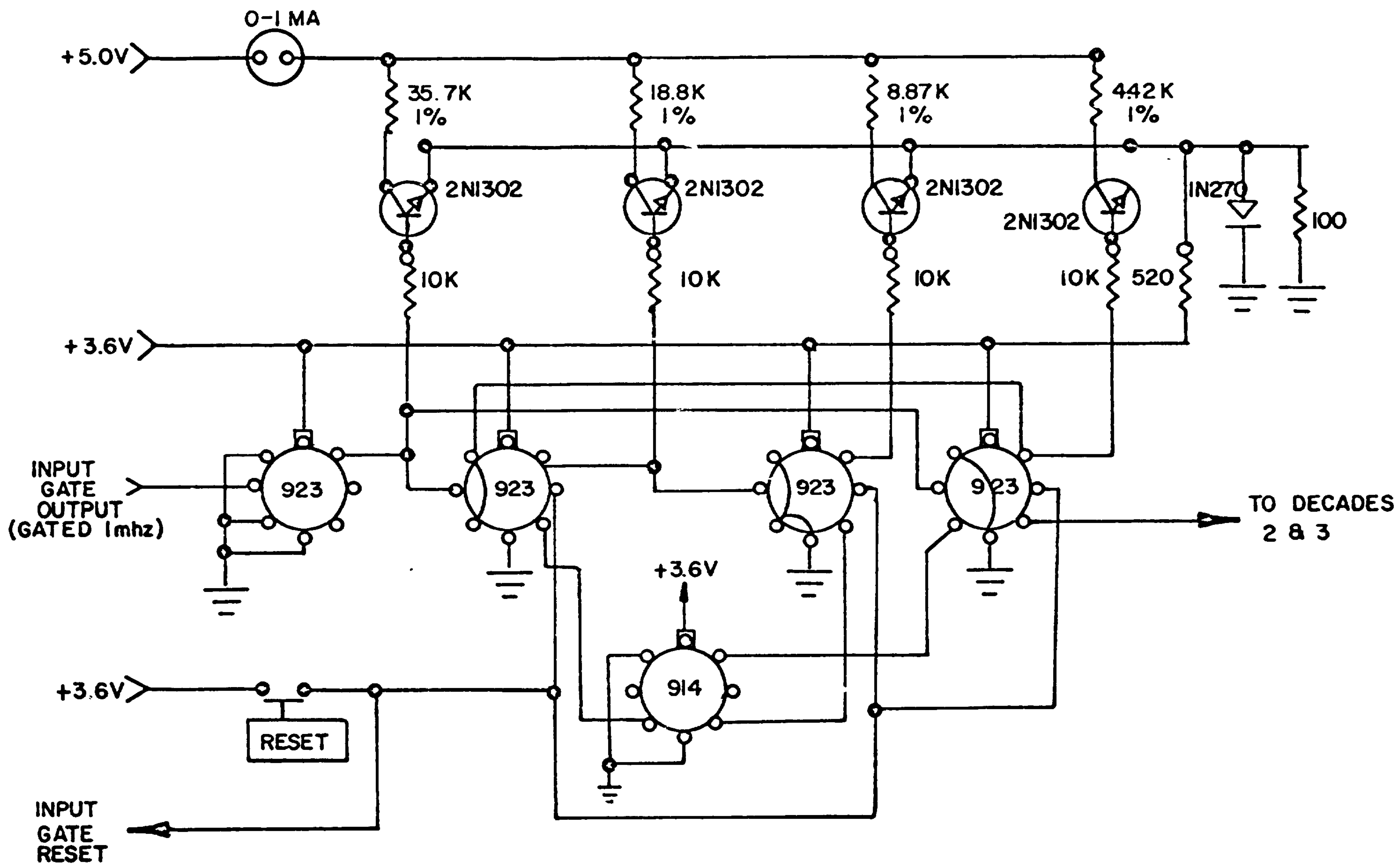


FIGURE 8 VELOCITY MEASURING SYSTEM - ÷ 10 DECADE & METER READOUT SYSTEM

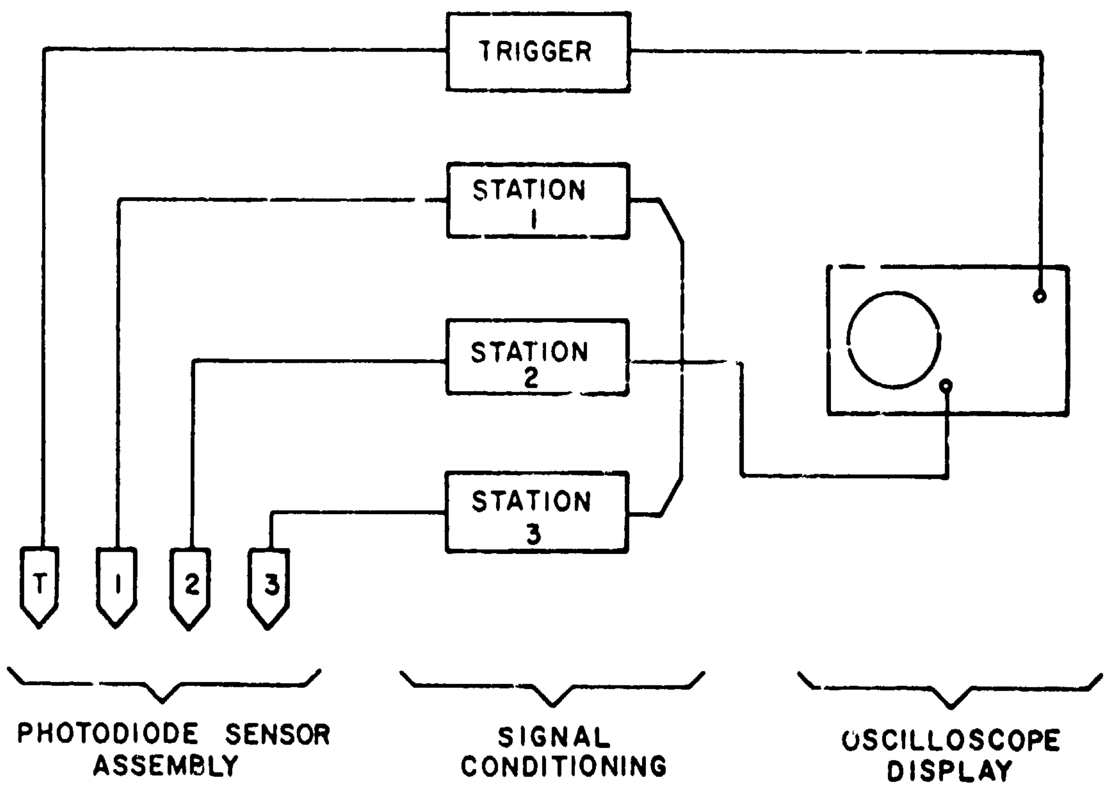
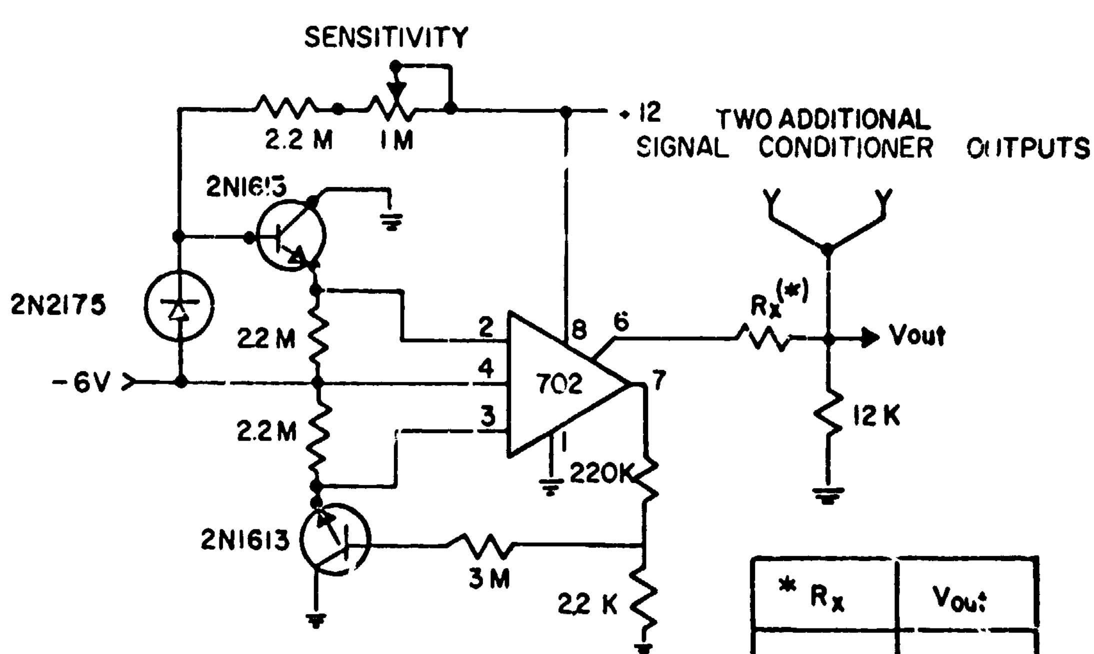


FIGURE 9 BLOCK DIAGRAM - PHOTODIODE LONGITUDINAL BURNING RATE DATA SYSTEM



* Rx	Vout
47 K	1 V
15 K	3 V
10 K	5 V

FIGURE 10 SCHEMATIC DIAGRAM - PHOTODIODE SIGNAL CONDITIONER

of resistance of the photodiode to develop enough voltage change to drive a Schmidt trigger connected operational amplifier shown in Figure 10. The output signal is provided from the frequency compensation (pin 6) to give RTL current limited drive without the use of clamping diodes. The data station outputs are paralleled to provide a single data output channel.

In order to be able to identify which diodes are sensing, when all combinations are possible, the voltage output from each was set so that additions of combinations would result in unique values. In order, the stations are one, three and five volts as shown in Figure 11. Various combinations are illustrated in Figure 12. Knowing when each station triggers gives velocities between any two stations for evaluation of consistant burning characteristics.

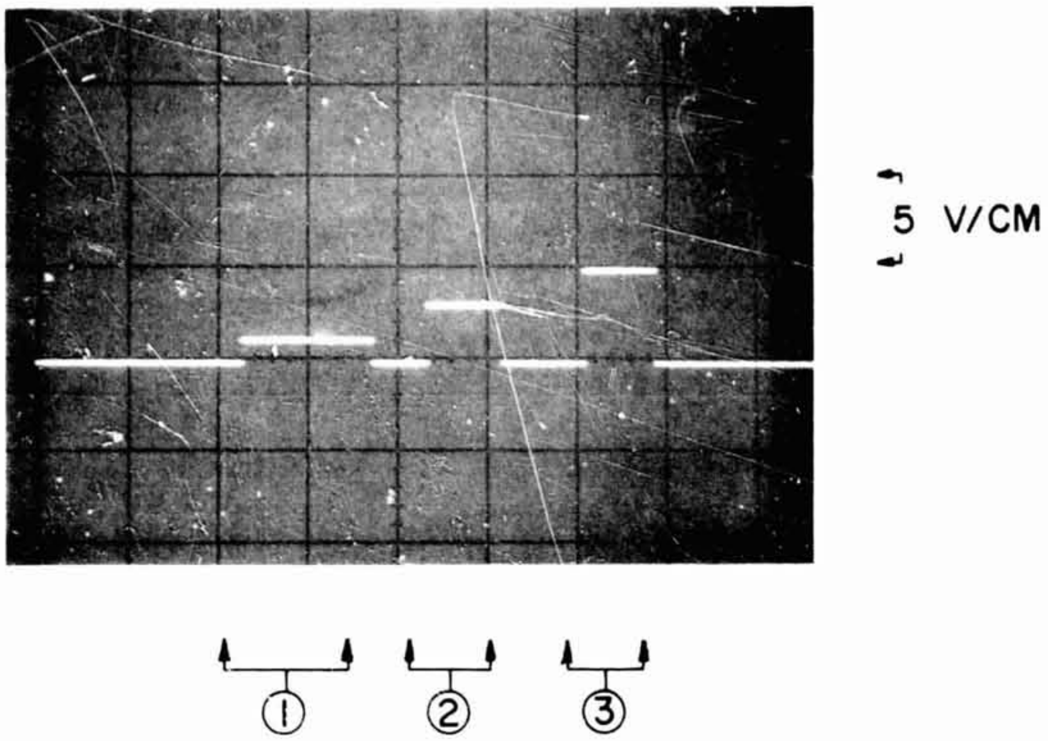


FIGURE 11 INDIVIDUAL STATION OUTPUT SIGNALS

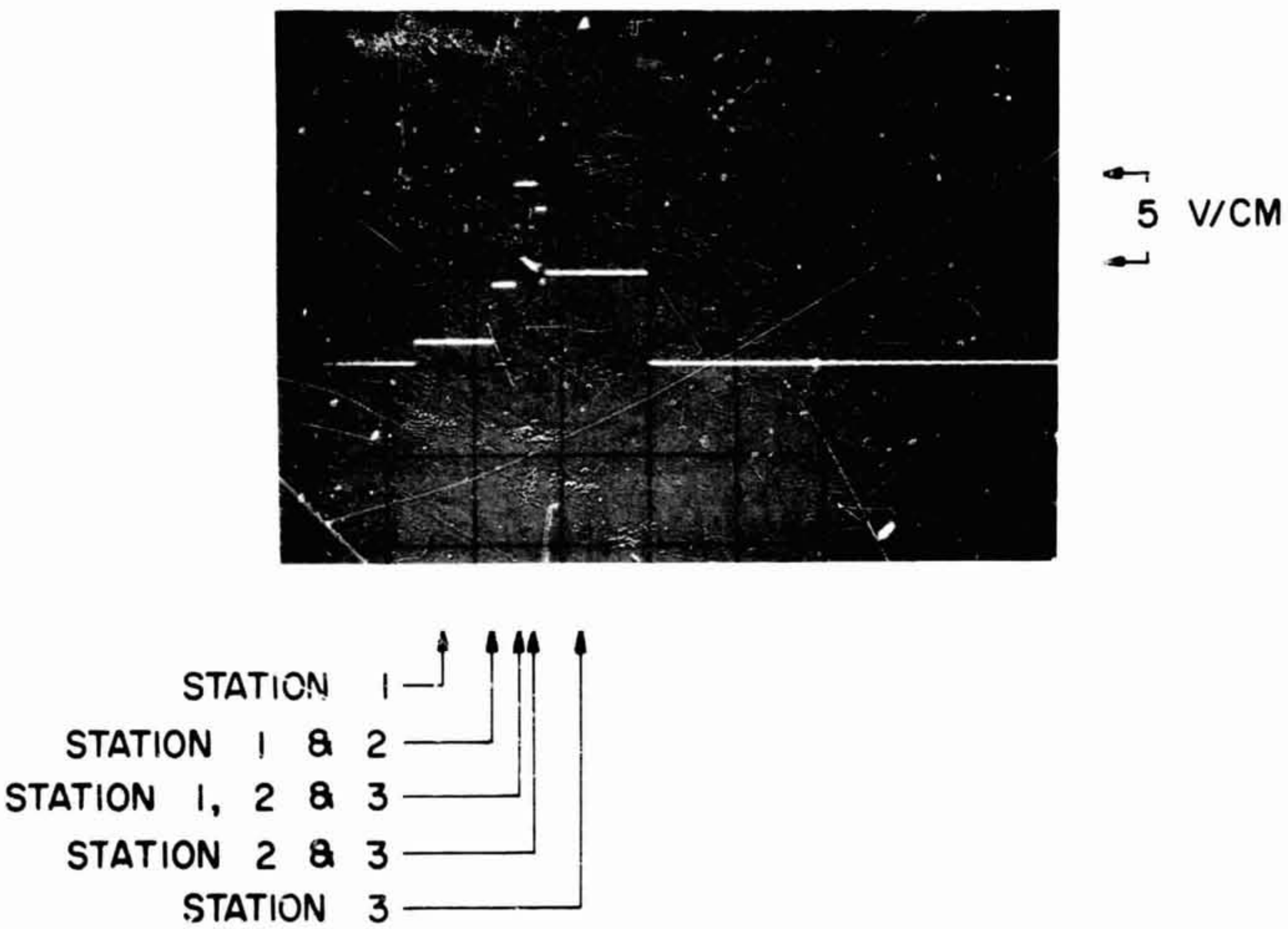


FIGURE 12 COMPOSITE SIGNAL OUTPUT

APPENDIX II

Summary of Results 22 March 1968 to 13 May 1969

Table of Results

DATE	VEL fps	TANK PRESS	COAT-ING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTILE SPECIFICATIONS			PENETRATION		GAUGE NO IN.	BASE PRESS PSI	SLOPE [illegible]/SEC	ULT. PRESS PSI	AVE. VEL. BTWN GAUGES fps	COMMENTS
						LENG IN	DIA IN	MASS GR	DEPTH	DIA IN.						
March 22	2870	9	5.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.485	.243	.183/.343	28L	----						Flapper caught blast.
March 25	----	10	4.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.507	.243	.192/.349	---	----						Projectile hit flapper valve
March 25	2650	12	---	-	Unlined	.527	.243	.189/.326	32L	.375						
March 25	2920	11	---	-	Unlined	.262	.242	.191	35L	.400						
March 26	----	14	5.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	----	----	.198/.388	29L	----						
March 27	----	16	6.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.524	.243	.186/.341	---	----						Projectile reversed direction and came out of breech
April 2	3800	11	5.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.549	.242	.192/.372	19L	.375						
April 2	6200	19	4.5	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.524	.242	.213/.375	31L	.375						
April 18	----	25	2.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.509	.241	.197/.402	26L	.375						Tube slid forward three inches.
April 18	1979	--	---	3	1NC, 1.5 RDX	.541	.241	.190/.480	23L	.375						
April 18	2777	--	4.0	1 2 2	1NC, .5G 1NC, 1.5 RDX 1NC, .5 G	.542	.242	----	29L	.375						
April 19	2770	12	4.5	1 2 2	1NC, .5G 1NC, 1.5 RDX 1NC, .5 G	.540	.242	.187/.492	28L	.250						
April 19	3300	14	5.0	1 3	1NC, .5G 1NC, 1.5 RDX	.560	.243	.198/.566	36L	.50						Tube blown forward three in.
April 24	4150	18	2.0	4	1NC, BA	.498	.2425	.182/.412	31L							
April 25	4600	9	1.0	4	1NC	.547	.244	.190/.447	30L							
April 25	4150	--	2.25	4	1NC	.547	.244	.190/.447	30L							
April 27	5300	11	3.5	4	1NC, 1 RDX	.529	.242	.183/.427	25L	1.0						
April 27	4800	12	3.5	4	1NC, 1 RDX	.529	.243	.196/.357	31L	.25						
April 30	4976	11	1.0	4	1NC, .05 Al	.520	.243	.192/.372	32L							
May 1	5183	10	3.5	4	1NC, 1 RDX, .1G	.507	.243	.195/.378	30L	.50						
May 3	3600	9	3.0	3	1NC, 1 RDX, .1G	.561	.242	.187/.327	33L	.50						
May 6	4461	15	2.5	1 2	1NC, 3Al 1NC, 1 RDX	.592	.241	.184/.444	33L	.875						
May 7	[illegible]	17	[illegible].5	4	1NC, 3Al, .5G	.541	.243	.182/.428	28L	.50						

Table of Results (Con't)

DATE	VEL fps	TANK PRESS cm	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTILE SPECIFICATIONS LENG IN	DIA IN	MASS GR	PENETRATION DEPTH	DIA N.	GAUGE NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVE.VEL. BTWN GAUGES fps	COMMENTS
May 7	4150	12	2.5	3	1NC, 3Al, .5F	.551	.293	.177 .399	31L	.375						
May 9	5500	17	1.0	4	1NC, 3Al	.572	.243	.191 .613	26L	.80						
May 13	2400	8	1.0	4	1NC, 3Al	.529	.240	.176 .462	26L	.75						
May 13	5250	9	1.5	4	1NC, 3Al	.537	.242	.200 .494	33L	.80						
May 14	6300	8	4.0	4	1NC, $2NH_4ClO_3$, .5Al, .5G	.582	.242	.197 .506	33L	1.0						
May 14	----	8	5.0	4	1NC, $2NH_4ClO_3$, .5Al, .5G	.522	.242	----	---	---						Tube was warm; fired in front of projectile.
May 17	5900	11	4.0	3	1NC, $2NH_4ClO_3$, .5Al, .5F	.520	.243	.189 .461	30L	.75						
May 17	5920	—	3.5	3	1NC, $2NH_4ClO_3$, .5Al, .5G	.550	.243	.196 .477	33L	.69						
May 20	4200	14	3.0	1 3	1NC, 3Al 1NC, 1 RDX, .1G	.615	.243	.192 .590	38L	.375						
May 20	4900	11	3.0	4	1NC, 3Al	.632	.243	.196 .609	26L	.50						
May 21	5200	11	4.0	1 3 1	1NC, 3Al, .1G 1NC, 1 RDX, .1G 1NC, $2NH_4ClO_3$, .1G	.612	.243	.193 .598	---	---						Tank blown back one inch.
May 24	5652	12	4.5	1 2 2	1NC, 3Al, .5G 1NC, 1RDX, .5G 1NC, $2NH_4ClO_3$, .5Al, .1G	----	----	.196 .609	19L	.35						
May 29	1700	13	4.0	1 3	1NC, 3Al 1NC, $2NH_4ClO_3$, .5Al, .2G	.650	.244	.196 .663	---	---						
June 4	3011	10	---	1 2	10NC, 3Al 1NC, $2NH_4ClO_3$, .5Al, .2G	.483	.243	.194 .424	23L	.63						
June 4	1540	16	2.5	1 2	10NC, 3Al 1NC, $2NA_4ClO_3$, .5Al, .2G	.467	.243	.197 .393	13L	.375						
June 5	5500	14	3.5	3	1NC, $2NH_4ClO_3$, .5Al, .2G	.467	.243	.188 .404	31L	.05						
June 5	2400	18	2.2	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.483	.243	.194 .424	23L	.63						
June 6	----	24	3	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.467	.244	.207 .425	---	---						Hit flapper valve Apparently fired ahead of projectile
June 12	2308	25	3.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.548	.243	.197 .466	23L	---						
June 19	1861	26	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.462	.242	.186 .424	18L	.25						
June 19	3700	10	2.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.568	.442	.193 .531	27L	.50						
June 20	2300	27	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.495	.243	.199 .487	20L	.375						
June 20	2450	14	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.465	.244	.200 .400	21L	.375						

Table of Results (Con't)

DATE	VEL fps	TANK PRESS ps	COAT-ING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTILE SPECIFICATIONS LENG IN	DIA IN	MASS GR	PENETRATION DEPTH	DIA IN.	GAUGE NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVL.VEL. FROM GAUGES fps	COMMENTS
June 21	4460	9	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.445	.241	.189/.340	38L	.625						
June 25	5340	10	3.75	3	1NC, $2NH_4ClO_4$, .5Al, .10	.510	.242	.190/.449	33L	.60						
June 27	1035	18	2.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.461	.343	.200/.445	19L	.50						Tube fired intermittently.
June 28	3220	--	---	-	Unlined	----	.244	----	---	---						
June 28	3002	15	---	-	Unlined	----	.249	----	---	---						
June 28	2300	12	4	4	1NC, $2NH_4ClO_4$, .5Al,.1G	.488	.242	.198/.472	28L	---						
July 1	1400	16	3.75	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.522	.242	.197/.456	26L	.375						Adapter blown off.
July 3	1200	11	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.495	.242	.209/.447	20L							
July 3	1200	--	2.75	3	1NC, $2NH_4ClO_4$, .5Al, .10	.454	.242	.179/.406	17L							
July 8	1920	8	4.0	-		.480	.242	.207/.451	21L	.375						
July 8	5950	7	4.0	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.511	.242	.187/.445	29L	.85						
July 9	1734	-	4.5	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.480	.243	---	25L	---						
July 12	1300	11	3.5	3	1NC, $2NH_4ClO_4$ .5Al, .10	.504	.242	.204/.462	---	---						
July 12	2230	--	--	-		.465	.243	---	---	.75						
July 17	6789	8	4.5	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.498	.243	.189/.458	---	.75 x .4						
July 19	----	9.5	3.5	3	1NC, $2NH_4ClO_4$, .5Al, .10	.502	.242	.190/.480	33L	.375	12	--	1.67 2.50	7,500 11,200	5450	Approxmate velocity- 3700 ft./sec.
July 22	5338	---	3.5	3	1NC, $2NH_4ClO_4$.5Al, .1G	.510	.242	.177/.449	35L	.80	12	--	0.20 0.58	500 4,200	5180	
July 22	5270	9	3.5	3	1NC, $2NH_4ClO_4$, .5Al0	.50'	.243	.182/.452	30L	.625	12 48	500	0.25 0.80	2,000 4,200	6240	
July 23	2686	15	4.5	4	1NC, $2NH_4ClO_4$, .5Al, .10	.450	.241	.177/.401	13L	.375	12 48	---	0.26 0.66	2,500 4,200	4680	Part of projectile sheared off in tube
July 23	3394	12	4.0	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.456	.242	.180/.390	26L	.375	12 48	---	0.40 0.62	4,200 6,000	4050	
July 24	2918	12	4.75	3	1NC, $2NH_4ClO_4$,.5Al, .1G	.465	.244	.191/.409	21L	.375	12 48	500	0.25 1.21	4,200 6,000	4840	
July 24	2226	12	4.25	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.485	.245	.191/.428	10L	.375	12 48	1000	0.22	3,000 4,500	4680	
July 25	4430	14	4.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.521	.242	.195/.509	26L	.50	12 48	----	0.29 1.25	6,000 9,000	4170	
July 25	5628	13	4.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.493	.244	.198/.481	26L	.75	--	----	----	-----	----	Adapter blown off
July 26	715	25	---	-	Unlined	.368	.243	.195	9L	.375	--	----	----	-----	----	

Table of Results (Con't)

DATE	VEL fps	TANK PRESS mm	COAT-ING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTING SPECIFICATIONS LENG IN	DIA IN	MASS GR	PENETRATION DEPTH	DIA IN.	GAGE NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVE.VEL. BTWN GAGES fps	COMMENTS
July 29	5361	15	3.0	1 2	1NC, Ba 1NC, $2NH_4ClO_4$, .5Al, .1G	.479	.243	.197 .436	32L	.80	12 48	--	0.37 0.75	3,500 4,500	5770	
July 29	2340	17	---	-	Unlined	.242	.282	.190	26L	.375	--	--	---	-----	-----	
July 29	1297	760	---	-	Unlined	.287	.243	.199	.6	---	--	--	---	-----	-----	
July 29	1414	760	---	-	Unlined	.280	.242	.186	7L	---	---	-	---	-----	-----	
August 1	2057	30	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.440	.246	.213 .347	22L	.50	12 48		0.75 0.38	7,000	4840	Plasma reclosed Station # 2
August 1		17	4.0	1	NC 1NC, $2NH_4ClO_4$, .5Al, .1G	.437	.248	.213 .336	27L	1.0	12 48	1000	0.27 0.75	3,000 8,000	4680	
August 1	1881	22			Unlined	.454	.242	.195 .391	23L	.375						
August 14	5920	15	4.0	3	1NC, $2KClO_3$, .5Al, .1G	.498	.249	.214 .389	26L	1.0	12 48	1,000	0.50	7,000		Strain gauge #48 not working
August 14	5920	11	4.0	1 3	1NC 1NC, $2KClO_3$, .5Al, .1G	.497	.248	.213 .326	26L	1.0	12 48	250	0.36	3,000 6,500	5000	
August 15	6035	13	4.0	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.485	.249	.215 .353	26L	1.0						
August 15	6214	11	4.0	4	1NC, $2KClO_3$, .5Al, .1G	.445	.249	.214 .322	40L	0.9						
August 16	5892	12	4.0	4	1NC, $2KClO_3$, .5Al, .1G	.445	.249	.214 .322	40L	0.9	12 48	500 900	0.31 0.83	500 800	4400	
August 19	2105	14			Unlined		.242	.190								
August 19	2600	14			Unlined		.242	.190								
August 19	3313	16			Unlined		.242	.190								
August 19	4767	14			Unlined		.242	.190								
August 19	3460				Unlined		.242	.190								
August 20	5892	14	4.0	4	1NC, $2KClO_3$, .5Al, .1G	.504	.249	.210 .394	25	.562	12 48	1,000 500	0.36 0.80	4,000 6,500	5360	
August 21	1614	14	4.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.486	.249	.208 .404	.1	.375	12 48		1.0 1.5	5,500 8,000	6,000	
August 21	1530		4.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.489	.248	.212 .416	.1	.375	12 12v		0.45 0.83	5,000		
August 22	4842	20	4.5	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.514	.249	.203 .401	.375	.50	12 48		0.62 0.75	5,000 8,500	5,770	
August 23	5270	16	3.5	2 1	1NC, $2KClO_3$, .5Al, .1G 1NC, 2 Lead Azide	.467		.206 .377	.20	.60	12 48		0.25 0.32	3,200 5,000	4,840	Black residue on stations 1 & 2
August 23	5227	16	3.0	2 1	1NC, 1 $KClO_3$, .5Al, .1G 1NC, 3 Lead Azide	.477	.248	.203 .384	.20	.60	12 48		0.32 0.67	6,000 3,500	4,240	Black residue on stations 1 & 2
August 23	861	14	4.0	3	1NC, 1.8NH_4ClO_3, .2x-104 .5Al	.437	.249	.203 .356			12 48		0.50 0.75	3,500 6,000	6,550	Black residue on stations 1 & 2,
August 23	2946	16	4.0	3	1NC, 2NH ClO , .5Al, .1G	.502	.248	.211 .373			12 48 12v		0.60 0.68 0.75	5,500 9,000	6,550	
August 29	5756	17	4.0	1	NC 1NC, $2KClO_3$, .5Al, .1G	.471	.249	.212 .370	.375	.626	12 48		0.51 0.75	3,500 5,000	4,680	

Table of Results (Con't)

DATE	VEL fps	TANK PRESS mm	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTILE SPECIFICATIONS LENG IN	DIA IN	MASS GR	PENETRATION DEPTH	[illegible]	GAUGE NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVE. VEL. BTWN GAUGES fps	COMMENTS
August 29		14	4.0	1	1NC 1NC, 1.8NH_4ClO_4, .2X-104 .5Al	.459	.252	.190 .368			12 48	1,200	0.15 0.88	3,500 7,000	4,000	
August 30	841	14	4.0	1	1NC 1NC, 1.8NH_4ClO_4, .2X-104 .5Al	.427	.249	.197 .363			12 48		0.23 0.88	2,500 6,000	3,360	
August 30		17	4.0	1 3	1NC 1NC, 1.8NH_4ClO_4, .2X-104 .5Al	.431	.249	.203 .372	.25	.625						
September 2		15	4.0	2	1NC, 2$KClO_3$, .5Al, .1G 1NC, 1.8NH_4ClO_4, .2X-104, .5Al	.438	.249	.206 .373	.25	.625	12 48	1,000 1,000	0.23 0.78	3,500 5,000	4,400	
September 2	5948	15	4.0	2 1	1NC, 2$KClO_3$, .5Al, .1G 1NC, 1.8 NH_4ClO_4, .2X-104 .5Al	.437	.248	.204 .372	.25	.625	12 48	250 500	0.36 0.80	2,500 4,500	4,400	
September 4	6575	14	4.0	2 2	1NC, 2NH_4ClO_4, .5Al, .1G 1NC, 1.5NH_4ClO_4, .5X-104, .1G	.426	.249	.201 .369	.25	.625	12 48	750	0.50 1.67		5,770	
September 5	4109	14	4.0	2 1 1	1NC, 2$KClO_3$, .5Al, .1G 1NC, 3 Lead Azide 1NC, .5G	.414	.249	.225 .372	.125	.375	12 48		0.08 0.56	4,500 4,000	4,200	
September 5	4043		3.5	2 1 1	1NC, 2$KClO_3$, .5Al, .1G 1NC, 3 Lead Azide 1NC, 1G	.435	.125	.206 .359	.375							
September 6	4918	14	3.5	2 1 1	1NC, 2$KClO_3$, .5Al, .1G 1NC, 1.5 NH_4ClO_4, .5 X-104 .5Al,.1G 1NC, 2$KClO_3$, 1X-104,.5Al, .1G	.452	.249	.209 .365	.25	.50	12 48		0.22 1.29	4,000 4,000	4,200	
September 6	1918	14	3.0	2 2	1NC, 2$KClO_3$, .5Al 1NC, 2$KClO_3$, 1X-104, .5Al, .1G	.437	.249	.501			12 48		0.10 0.68	3,000 4,000	4,500	
September 9	739	18	3.5	2 2	1NC, 2$KClO_3$, .5Al 1NC, 2$KClO_3$1X-104 .5Al, .1G	.435	.248	.200 .421			12 48	750	0.25 0. 0	3,000 4,000	536	
Sept. 10	5783	14	3.5	2 2	1NC, 2$KClO_3$, .5Al 1NC, 2$KClO_3$, 1X-104, .5Al, .1G	.505	.249	.191 .397	.25	.375						
Sept. 10	2005	14	3.5	2 2	1NC, 2$KClO_3$, .5Al, .1G 1NC, 2$KClO_3$, 1X-104 .5Al, .1G	.457	.249	.204 .357			12 48		0.38 0.91	3,500 4,500	6,550	
Sept. 11	1338	14	3.0	3	1NC, 2$KClO_3$, .5Al 1NC, 1.8NH_4ClO_4, .2X-104, .5Al, .1G	.446	.248	.196 .430								
Sept. 11	6472	14	3.25	1 3 2	BA 1NC, 2$KClO_3$, .5Al 1NC, 1.8NH_4ClO_4, .2X-164, .5Al	.414	.249	.212 .401	.25	.625	12 48	1,000 11,000	0.50 1.43	500 800	5,000	
Sept. 12	6939	14	4.5	2 2	1NC, 2NH_4ClO_4, .5Al, .1G 1NC, 1.8NH_4ClO_4, .2X-164, .5Al, .1G	.473	.249	.212 .453	.25	.75	12 48		0.51 1.95	650 900	4,410	Adapter slid back 1 inch.
Sept. 12	5576		4.5	2 2	1NC, 2NH_4ClO_4, .5Al, .1G 1NC, 1.8NH_4ClO_4, .2X-164. .5Al, .1G	.441	.249	.212 .403	.25	.625	12 48 12v	500	0.46 0.71 0.75	500 950	4,640	
Sept. 13	6506	14	4.0	3 2	1NC, 2$KClO_3$, .5Al 1NC, 1.8NH_4ClO_3, .2X-164 .5Al, .1G	.438	.249	.207 .394	.25	.625	12 48		0.58 1.25	5,700 6,500	4,500	

Table of Results (Con't)

DATE	VEL fps	TANK PRESS mm	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTING SPECIFICATIONS LENG IN	DIA IN	MASS GR	PENETRATION DEPTH	DIA IN.	GAUGE NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVE. VEL. BTWN GAUGES fps	COMMENTS
Sept. 13	3832		4.0	3 2	1NC, $2KClO_3$, .5Al 1NC, $1.8NH_4ClO_4$, .2X-164, .5Al, .1G	.428	.248	.207 .390	.125	.375	12 48	750 500	0.25 1.00	6,000 6,000	4,110	Blast chamber blown back 4 inches.
Sept. 16	6680	18	4.0	3 2	1NC, 1.5 RDX 1NC, $1.8NH_4ClO_4$, .2X-164, .5Al	.450	.249	.207 .47[illegible]	.25	.625						
Sept. 17	6503	14	4.5	2 3	1NC, $2KClO_3$, .5Al 1NC, $1.8NH_4ClO_4$, .2X-164 .5Al	.439	.249	.207 .395	.25	.625	12 48		0.15 2.00	5,700 8,000	5,000	
Sept. 17	6506	14	4.0	2 3	NC, $2KClO_3$, . Al 1NC, $1.8NH_4$, ClO_4, .2X-164 .5Al	.454	.249	.207 .395	.25	.625	12 48	750 500	0.60 1.54	5,000 8,000	5,360	
Sept. 20	6277	8	3.5	3	1NC, $1.8NH_4ClO_4$, 2X-164 .5Al 1NC, $1.8NH_4$, ClO_4, .2X-164 .5Al, .1G	.417	.249	.212 .380	.25	.625	12 48		0.42 1.15	4,000 5,000	4,670	
Sept. 20	4322	8	3.5	3	1NC, $2NH_4ClO_4$, .5Al 1NC, $2NH_4ClO_4$, .5Al, .2X-164, .1G	.431	.249	.200 .236	.125	.375						
Sept. 23	6506	12	5.0	2 3	1NC, $2NH_4ClO_4$, .5Al 1NC, 2NH ClO , .5Al, .2X-164	.449	.249	.218 .406	.25	.625						Did not trigger
Sept. 23	1737	15	4.0	2 3	1NC, $2NH_4ClO_4$, .5Al 1NC, $2NH_4ClO_4$, .5Al, .2X-164	.496	.249	.213 .358			12 48		1.0	10,000		No trace on #12.
Sept. 24	2128	12	4.0	3 1	1NC, $2NH_4ClO_4$, .75RDX, . .5Al 1NC, $1.7NH_4ClO_4$, .3X-164 .5Al	.477	.249	.219 .368			12 48	1,600	0.18 1.20	6,400 8,000	4.700	
Sept. 24	2073	10	4.0	3 1 1	1NC, $2NH_4ClO_4$, .75RDX, .5Al 1NC, $1.7NH_4ClO_4$, .3X-164, .5Al	.466	.249	.206 .360			12 48		0.25 1.00	4,200 10,000	4,700	
Sept. 26	6439	11	4.0	3 1	1NC, $2NH_4ClO_4$, .5Al 1NC, $1.7NH_4ClO_4$, .3X-164, .5Al	.481	.249	.214 .381	.25	.625	12 48	1,600	0.40 1.30	8,000 10,000	5,000	
Sept. 26	3100	11	4.0	3 1	1NC, $2NH_4ClO_4$, .5Al 1NC, $1.7NH_4ClO_4$, .3X-164 .5Al	.503	.249	.211 .422			12 48		0.42 1.30	6,000 8,000		Trace triggered early
Sept. 27		11	3.5	2 2	1NC, $2KClO_3$, .5Al 1NC, $2KClO_3$, 2 Lead Azide, .1G, .5Al, .1X-164	.471	.248	.211 .400			12 48		0.50 1.10	4,800 6,400	5,000	
Sept. 30	1989	12	5.0	2 3	1NC, 2KClO , .5Al 1NC, $1.8NH_4ClO_4$, .2X-164, .5Al	.495	.249	.202 .377			12 48	1,600	1.60 2.80	8,000 10,000	6,250	
Sept. 30	1411	10	5.0	2 3	1NC, $2KClO_3$, .5Al 1NC, $1.8NH_4ClO_4$, .2X-164, .5Al	.596	.249	.219 .397			12 48	11,600	3.00 2.50	10,000 10,000	6,800	
October 1	2586	14	3.5	1 3	1NC, $2KClO_3$, .5Al 1NC, $1.8N_4ClO_4$, .2X-164, .5Al	.515	.249	.213 .398			12 48		0.66 0.20	3,000 1,500	5,700	
October 2	2021	12	3.75	1	1NC, $2NH_4ClO_4$, .5Al 1NC, $1.8NH_4ClO_4$, .2X-164 .5Al	.516	.249	.210 .391			AA AA					Triggered early
October 17	5602	14	2.5	5	1NC, $1.8NH_4ClO_4$, .2X-164 .5Al, .1G	.500	.248	.216 .407	.25	.375	12 48		0.50	6,400		Did not trigger

Table of Results (Con't)

DATE	VEL fps	TANK PRESS mm	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTING SPECIFICATIONS			PENETRATION		GAUGE NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVE.VEL. BTWN GAUGES fps	COMMENTS
						LENG IN	DIA IN	MASS GR	DEPTH	DIA IN.						
October 18	6901	14	4.5	7	1NC, 1.8NH_4ClO_4, 2X-164, .5Al, .1G	.483	.248	.200 .395	.25	.625	A					No Data
October 22	3773	20	4.5	1 6	1NC 1NC, 1.8NH_4ClO_4, .2X-164 .5Al, .1G	.439	.248	.171 .357	.125	.375	12 48					Triggered late
Nov. 25	6438	8	2.0	4	1NC, 1NH_4ClO_4	.450	.248	.207 .420	.375	.625	14 32 56 105		3,500 4,800 3,000	3,500 4,800 3,000		Gauge #105 did not work.
Nov. 26		9	3.0	1 5 3	1NC 1NC, 2NH_4ClO_4 1NC, 1NH_4ClO_4	.565	.240	.207 .400			14AA 32 56AA 105		0.70 0.40 1.70	6,000 8,000 16,000		Gauge #105 did not work.
Dec. 9		8	4.0	1 7	1NC 1NC, 2NH_4ClO_4	.537	.241	.208 .424			14AA 32 56AA 105		1.00 0.50 1.00 0.20	10,000 8,000 20,000 4,000	5,000 6,000	
Dec. 1[illegible]	6732	9	3.5	1 1 6	1NC 1NC, 2NH_4ClO_4 1NC, 1NH_4ClO_4, 1X-164	.54[illegible]	.24[illegible]	.19[illegible] .452	.375	.625	14AA 56AA		1.00 2.50	16,000 16,000	4,600	#35 & #105 not used.
Dec. 16	6609	9	3.0	1 2 3	NC 1NC, 1.8NH_4ClO_4, .2X-164, .5Al, .1G 1NC, 3NH_4ClO_4	.574	.241	.220 .465	.375	.625	14AA 32 56AA 105		1.30 0.50 1.00	16,000 8,000 4,000	3,800 3,000	#105 was bad
Dec. 18		13	4.0	1 3 5	1NC 1NC, 3NH_4ClO_4 1NC, 2NH_4ClO_4, 1X-164	.536	.241	.206 .449			14AA 32 56AA 105		1.60 1.60 0.60 0.40	16,000 10,000	6,000 4,000	
Dec. 20	1867	8	3.5	1 3 2	1NC 1NC, 1.8NH_4ClO_4, 2X-164 .5Al, .1G 1NC, 1NH_4ClO_4, 1X-164	.52		.207 .445								Data Bad.
Feb. 28	5226	25	2.5	3	1NC, 3.8KNO_3, 1.9MS164	.460	.248	.177 .378	.25	.375						Pressure gauges not used.
March 5	1542	7	1.0	5	4NC, 5.7X-164, 11.3 KNO_3	.480	.242	.202 .409			12 48	1,500	0.66 0.50	6,400 4,000	6,000	
March 10			3.5	3	1NC, 3MS164, 3KNO_3	.460	.248	.230 .460			12 48		1.00 0.80	4,000 4,000,	5,300	
April 24	4600	8	5.0	1 1	NC 3KNO_3, 3MS164, 1 PVC	.486	.248	.210 .406	.25	.25	12 48					Did not trigger
April 24	4879	25	4.5	1 2	NC 3KNO_3, 3MS164, 1PVC	.557	.242	.202 .370	.25	.25	12 48					Did not trigger
April 25	5001	25	4.5	1 2	NC 3KNO_3, 3MS164, 1PVC	.487	.449	.202 .406	.25	.25	12 48	1,500	2.50 2.00	11,000 10,000	4,200	
April 29	2300	22	6.0	1 2	NC 3KNO_3, 3MS164, 1PV		.243	.566 .243			12 48	1,500	5.00 3.00	10,000 13,000	5,400	
April 29	3800	25	3.5	1	3KNO_3, 3MS164, 1PVC		.243	.606			14AA 32		2.00 2.00	6,000 6,000	3,000	
April 30	4976	25	7.0	2	3KNO_3, 3MS164, 1[illegible]VC	.435	.242	.198 .305	.25	.25	12 48		1.20 5.00	8,000 11,000	4,200	
May 9		/	6.5	1 2	NC 3KNO_3, 3MS164, 1PVC		.243	.684			12 48		2.00 3.00	10,000 14,000	4,800	
May 13			7.0	1 2	NC 3KNO_3, 3MS164, 1PVC	.643	.242	.556			12 48		3.00 2.00	5,000 8,000	4,300	

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