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Final Report

On the Feasibility of Obtaining

Hypervelocity Acceleration Using Propellant

Lined Launch Tubes

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AEROSPACE ENGINEERING DEPARTMENT

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"DTIC USERS ONLY"

Prepared Under Contract No. NAS 9-6812

for

Manned Spacecraft Center

National Aeronautics and Space Administration

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Final Report
On the Feasibility of Obtaining Hypervelocity Acceleration Using Propellant Lined Launch Tubes

Prepared by
Charles A. Rodenberger
Miles L. Sawyer
Michael M. Tower

Final Report Covering the Period
September 27, 1966 to May 5, 1970

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Prepared Under
Contact No. NAS 9-6812 by
Texas A&M University
College Station, Texas 77843

for Manned Spacecraft Center

"DTIC USERS ONLY"

National Aeronautics and Space Administration

October 1, 1970

Abstract

The purpose of this research was to investigate the feasibility of a new concept to accelerate projectiles to hypervelocities. The concept uses an explosive lining inside a launch tube as a reservoir of high pressure gas that is released by the passage of a projectile. The gas forms a stationary reservoir that maintains a relatively constant base pressure on the projectile through a small amount of gas that travels with the projectile.

The research has been successful in developing new methods and techniques of applying an explosive lining to the inside of thick-walled tubes, measuring the velocity of projectiles, measuring the internal pressure-time characteristics and obtaining higher velocities from lined tubes than from unlined tubes. The theoretical and experimental studies indicate that the lined-tube concept is not subject to the velocity limitations of the present light gas guns. The limiting factor for the lined-tube is the ignition and reaction rate of the explosive lining.

Extensive study has been put into thin film explosives. Tests were developed to determine burning rates, ignition and friction characteristics, and propellant sensitivities.

Contents

Illustrations

I. INTRODUCTION

This is the final report on the investigation of the use of propellant liner to accelerate projectiles to hypervelocities sponsored under Contract No. NAS 9-6812 by the Manned Spacecraft Center of the NASA. The basic concept of the Hypervelocity Launcher at Texas A&M University is to maintain pressure on the base of the projectile for the entire length of the launch tube. The pressure is maintained by providing constant energy per unit length along a launch tube, derived from a rapid reacting propellant lining the inside of the launch tube. The passage of the projectile ignites the propellant lining, which generates high pressure in the reservoir. The accelerating reservoir in contact with the base of the projectile will maintain an acceleration of the projectile for the entire length of the tube.

Purpose of Hypervelocity Research

There are three important areas of study resulting from hypervelocity research. The first area requires simulation in the laboratory of relative velocities associated with spacecraft and cosmic particles for the study of meteoroid damage to spacecraft and defuse against warheads. The average velocity of meteoroids with respect to the Earth has been measured at 35.3 ± 0.8 Km/sec (116,000 ft/sec)[1]. The velocity limits of particles with respect to the Earth lie between 11 Km/sec (36,100 ft/sec), which would be the velocity of a particle accelerated from rest a great distance from the Earth by the Earth's gravitational field, to 73 Km/sec (239,500 ft/sec)

the maximum velocity for a particle in elliptical orbit about the sun[2]. Relative velocities of warheads and intercepting weapons could range from 20,000 to 40,000 ft/sec.

The second area concerns accelerating aerodynamic shapes to hypervelocities. Apollo flights returning from the moon have demonstrated velocities in the range of 39,000 ft/sec. It has not been possible to study aerodynamic shapes at velocities above about 25,000 ft/sec.

The third area of study deals with high pressure physics. High energies are associated with hypervelocity impacts, which have application in areas relating to explosives and the application of nuclear energy.

Present Hypervelocity Status

Following World War II, 700 years after the invention of the gun, the maximum velocity of projectiles was 10,000 ft/sec. By 1960 gram size projectile velocities had been increased to 35,000 by the use of light gas gun. A maximum recorded velocity of 54,000 ft/sec was achieved by Wenzel and Gehring of General Motors, who accelerated projectile fragments, weighing .08 grams, by shaped charges. Since 1960 the maximum velocity with projectile integrity has only been increased to 37,060 ft/sec for .01 gram projectiles, achieved by NASA at Ames Research Center, April 1965.

Current laboratory facilities are based either on the shock tube concept to obtain micro second flow of, at maximum, Mach 200 past a model or gun principles of several types. The present status of the art can be described by the mass-velocity graph in Figure 1 taken from a survey by Lukasiewiz[4]. In the past four years no significant increases in velocity have been achieved.

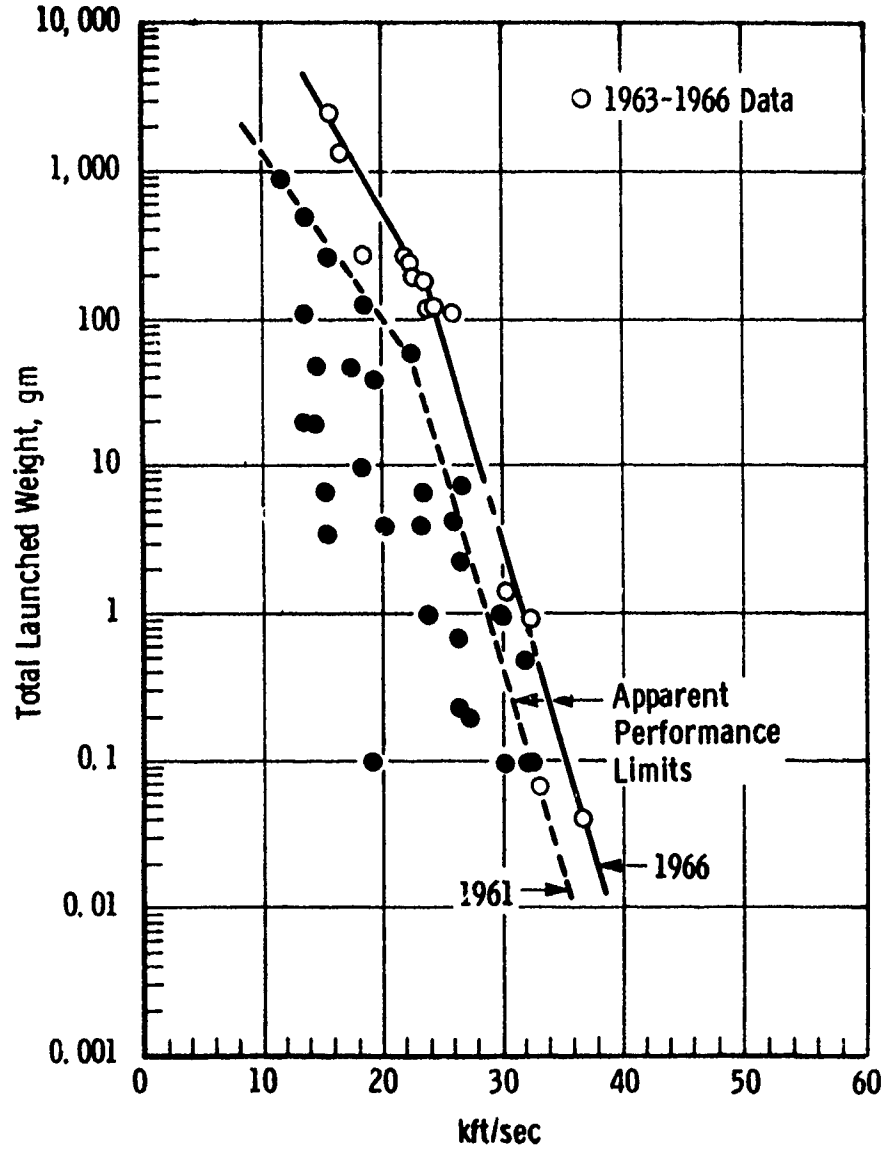


Figure I.1 Maximum Launch Velocities and Weights

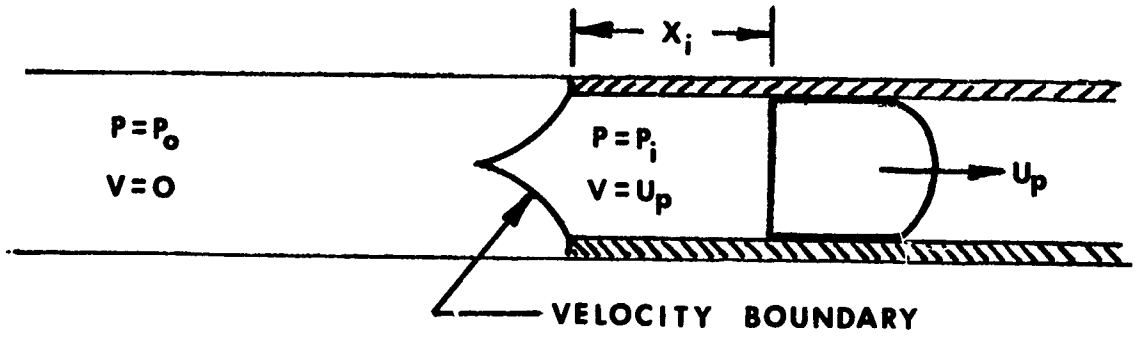


Figure I.2 Proposed Model

Operational Hypervelocity Devices

The devices that are currently in operation to simulate hypervelocity flights were discussed at length by Rodenberger[5]. These can be summarized in the following catagories

Explosive Types

Shaped Charges[3,6], Exploding foil gun[7], Electrostatic Accelerators[8]

Electrothermal Gun[9], Magnetohydrodynamic Rail-Type Accelerator[10]

Magnetically Augmented Rail Gun[11], a drooping square wave linear accelerator[12]

A major disadvantage to all of the above approaches is that the explosive characteristics of the device destroys any large model. Consequently it is useful primarily in achieving high velocities with fragmented projectiles for micro-sized particles. The ballistic gun-type development has taken several paths. The evolution of the gas driven gun has resulted in the current standard operations on the facility based on the use of hydrogen gas. These light gas guns can accelerate models in a working range of 18,000 to 25,000 ft/sec depending on the size and mass of the model. These concepts are well understood and are limited theoretically because of the gas dynamics sophistication in light gas guns has resulted from the use of staging indeformable pistons. The logical extension is to use the sabot enclosing the model as a deformable piston for its third stage. This has been tried[13] the results provided very little improvement over efficient two-stage guns. Another logical idea that has been investigated is the use of a travelling charge to propel the projectile in a rocket like fashion. The disadvantage to this system is a large mass ratio

this is required to fuel to projectile to achieve even reasonable velocity[14]. An obvious disadvantage to this concept is a large ratio of propellant weight to projectile weight is required. This means that a large amount of propellant mass must be accelerated which limits the practical velocity that can be obtained. The major problem with light gas guns and travelling charges that the velocities are limited has resulted the expended energy to move the propelling gas.

The continuing search for more efficient methods that led naturally attempts to provide an additional source of energy along the launch tube. An early attempt at this was the Hochdurckpumpe[15] in Germany. This was a cannon size device and was unsuccessful. Another unsuccessful device was an electrical discharge device proposed by General Electric[16]. A much more successful approach has been achieved by Physics Internation using an explosive charge to collapse the driver section of a light gas gur.[17]. The limitations to this approach are related to the limitations in detonation velocity of explosives although there are future potential developments that could overcome this characteristic through the use of ignition timing. For example, an explosive lensing system was developed[18] and resulted in a successful launch of a model in July 1969 to 12.2 km/sec[19]. Another proposed method of obtaining higher velocities was to drive in an external conical liner into the explosive to control the ignition at a rate higher than the detonation velocity[20]. This has been used successfully in shock tubes but successful projectile shots have not been made. Other approaches to the problem of maintaining a constant base pressure on the projectile have been suggested with little success[21]. The lined launch tube method proposed by this research is an attempt to provide constant energy per unit length along the launch tube by utilizing a liner inside the launch

tube composed of a rapid reacting propellant. This propellant is ignited by the passage of the projectile to provide a timing mechanism and the radio addition of energy is accomplished through the mechanism of the gas expanding from the rapidly burning wall. The original concept was that the gas from the cylinderical lining would form a massless piston to drive a small reservoir of gas attached to the base of the projectile. There is a question whether as to such a piston would form and this is discussed later in the report. Figure I.2 illustrates a schematic view of the imploding gun concept.

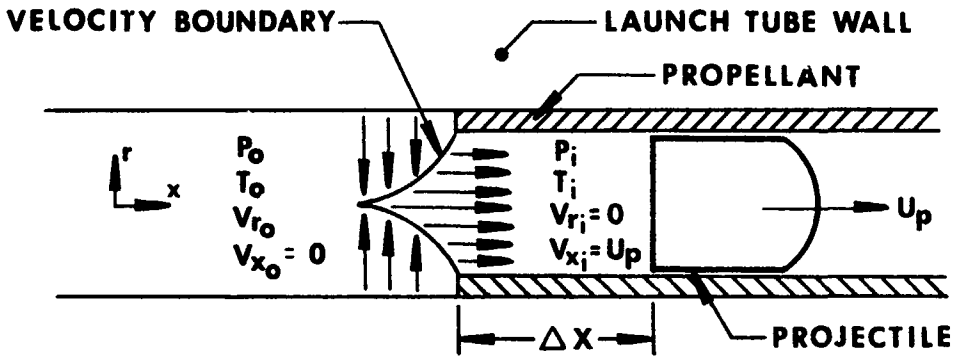
II. Theoretical Considerations

Fundamentals of the Lined Tube Concept

The theory of high speed gas driven guns has been adequately presented by Seigel[21]. He developed mathematical relations for several types of high speed guns with various reservoir conditions. Most of the operational guns today operate on the chambered reservoir concept. Seigel shows that the maximum achievable velocity for light gas guns is three times the speed of sound of the driving gas. This velocity is in the order of 35,000 fps.

To improve the performance of guns Seigel recommends the constant base pressure concept. The imploding tube concept of Physics International[19] and the Lined Tube concept of Texas A&M are constant base pressure types currently under development.

Figure II.1 illustrates the model of the Lined Tube concept. The projectile with a velocity U_p ignites the propellant. There is an ignition delay time associated with ignition. During this delay time the projectile moves a distance ΔX. At ignition the propellant releases a gas in the radial direction. The properties of the radial imploding gas are P_o, T_o, $V_{x_o} = 0$, V_{r_o}. The gas has zero velocity in the axial direction. There exists another region of gas bounded by the projectile, the walls of the launch tube and the conical boundary. The gas in this region is moving at the same velocity as the projectile, U_p. The gas in this region has no radial velocity component. At the conical boundary there is a velocity discontinuity, however there is no pressure shock wave. The pressures in



II.1 Model of Projectile

the two regions vary across the velocity boundary, but the pressure distribution is continuous.

It is assumed that the conical boundary formed by the radial imploding gas constitutes a massless piston, which drives the gas in the traveling reservoir section.

To obtain a better understanding of the lined tube concept considerable effort has been applied to theoretical studies. Ignition delay studies were performed to determine velocity limitations. A simple mathematical model was formulated to determine the distance required to achieve given final velocities versus acceleration. The model was also used to determine the pressure required to obtain the desired accelerations. A discussion of this model is presented in the next chapter under the section entitled "Pressure Requirements". More sophisticated mathematical models were formulated both for one-dimensional and two-dimensional finite difference computer model cases. These models were used for parametric studies of parameters capable of being experimentally altered.

Velocity Limitations Due to Ignition Delay Time

One effect of the ignition lag time or distance behind the projectile is to increase the amount of gas that must be accelerated with the projectile. This added mass results in a reduced acceleration and resultant velocity for a given travel. To investigate this effect, it is assumed that the projectile friction is negligible and that a constant base pressure, P_o, is maintained.

Using Newton's law

$$a = \frac{F}{M}$$

where F is the pressure times the area of the projectile and M is the

combined mass of the projectile and the traveling reservoir.

$$a = \frac{P_o \pi D^2}{4 M_p + \rho V \tau_i \pi D^2}$$

$$a = \frac{dv}{dt} = \frac{P_o}{\frac{4M_p}{\pi D^2} + \rho V \tau_i}$$

Integrating in terms of velocity

$$\int_{V_1}^{V_2} [\frac{4M_p}{\pi D^2} + \rho V \tau_i] dv = \int_{t_i}^{t_2} P_o g \, dt$$

but $dt = \frac{ds}{v}$

Therefore

$$\int_{V_1}^{V_2} [\frac{4M_p}{\pi D^2} + \rho V \tau_i] dv = \int_{S_1}^{S_2} Pog \frac{ds}{v}$$

or

$$\int_{V_1}^{V_2} [\frac{4M_p V}{\pi D^2} + \rho V^2 \tau_i] dv = P_o g \int_{S_1}^{S_2} ds$$

Integrating and simplifying

$$V_2^3 = \frac{3}{o\tau_i} [P_o g(S_2 - S_1) - \frac{2M_p}{\pi D^2} (V_2^2 - V_1^2)] + V_1^3$$

which gives the relationship of velocity to constant valves of ignition lag time, τ_i. This equation is plotted in Figure II.2 for the following valves:

P_o = 20,000 psi

$g = 32,174 \frac{lb_m}{lb_z} \frac{ft}{sec^2}$

M_p = 150 mg

D = .250 inch

$\rho = 1.56 \frac{lb}{ft^3}$

τ_i = lapse time in microseconds

Velocity Limitations Due to Constant Ignition Lag Distance

To obtain the velocity variation related to a constant ignition lag distance X_i, which can possibly be controlled by a mechanical igniter system, the derivation is the same as in the previous case noting that $X_i = V \tau_i$.

$$a = \frac{dv}{dt} = \frac{P_o g}{\frac{4M_p}{\pi D^2} + \rho X_i}$$

Integrating as before gives:

$$V_2 = \left[\left(\frac{2 P_o g}{\frac{4M_p}{\pi D^2} + \rho X_i}\right) S_2 + V_1^2\right]^{\frac{1}{2}}$$

Using the same parameters as in the previous case the equation is plotted in Figure II.3.

Mathematical Models of the Lined Tube Concept One-Dimensional Model - A one-dimensional model for the computer analysis of the gas dynamic process operative in a propellant lined launch tube has been formulated. The differential conservation equations and boundary conditions were transformed into a projectile oriented coodinate system since certain difficulties in numerical computation are avoided by this technique. The resulting equations were written in finite-difference form and programmed for the IBM 360-65 computer.

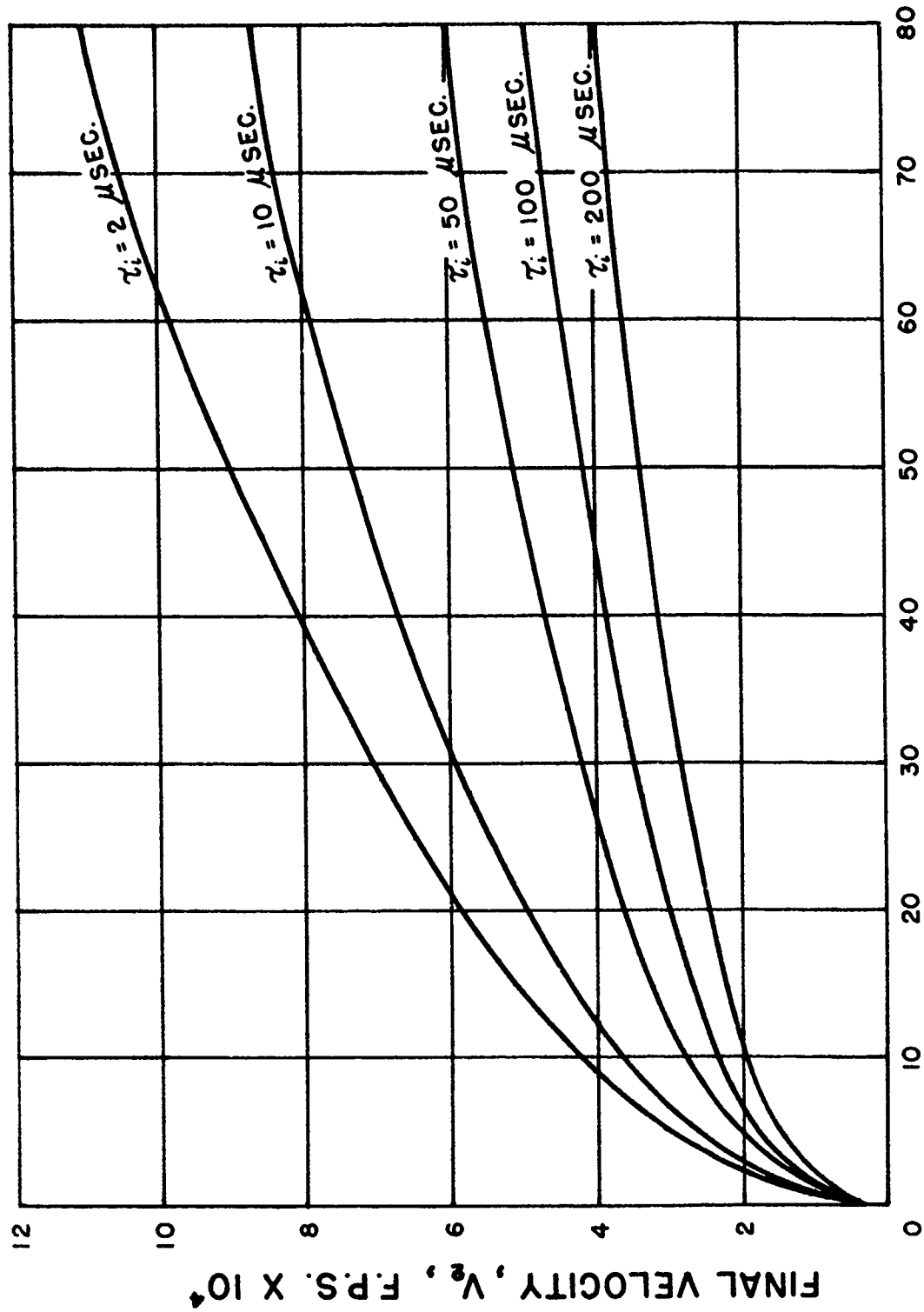


Figure II.2 Velocity vs Ignition Lag Time

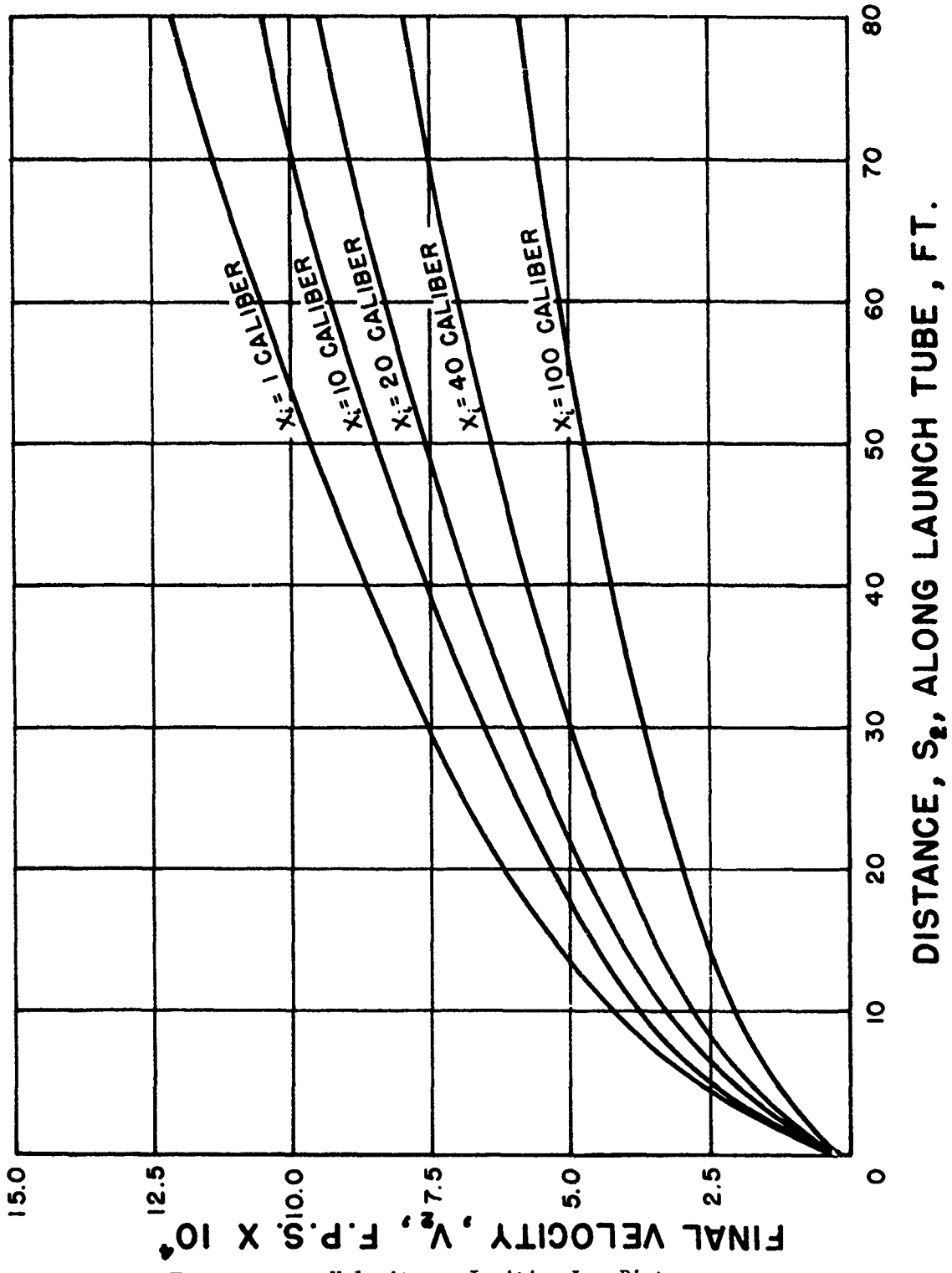


Figure II.3 Velocity vs Ignition Lag Distance

The propellant lined gun problem for the one-dimensional case is basically a modified unlined gun problem which takes into account the mass input due to burning. The choice of which form of equations to be used in the model should then be based on its ability to handle mass injection. Eulerian and Lagrangean forms of equations are those most commonly used for the calculation of time dependent flow problems. Because of the problem of keeping track of mass points due to the addition of mass from the wall, the Lagrangean form does not lend itself well to the solution of the propellant lined situation. The Eulerian form of equations is then the form that is best suited in the calculations.

One major assumption is made in deriving the equations. The assumption is that there will be an instantaneous total mixing of the gas in the tube with the burned propellant. This is done in order to simplify the calculations and reduce the program run time.

One problem is encountered when casting the equations in finite difference form. The problem is that finite difference methods cannot handle calculations which involve large, local variations in the dependent variables. The method that is used to avoid this problem is that which is suggested by F. W. Walker[22]. This method involves altering the equations so that the discontinuities are "blurred" into regions where all flow variables are continuous, but rapidly changing. This procedure smooths the discontinuity over several segments and thereby enables the finite difference technique to handle the problem.

The coordinate system used in the model is attached to the projectile in order to calculate accurately the base pressure on the projectile. This means that the coordinate system is accelerating and certain inertia terms produced which must be taken into account. This is done by deriving a

transformation equation which converts the governing equations from stationary laboratory coordinates to accelerating projectile coordinates. In this way the inertia terms will be properly represented.

The assumptions made in this model are as follows:

1. The gun has an infinite reservoir at a constant pressure.
2. Boundary layer effects in the tube are negligible.
3. The projectile starts from rest at some initial displacement.
4. The region in front of the projectile is a perfect vacuum.
5. The friction drag acting on the projectile has a constant value.
6. The tube inlet conditions are assumed to be similar to a convergent nozzle of infinite area and zero velocity.

Due to the large number of parameters associated with the propellant lined gun, many types of cases are possible. The model, therefore, was written in a general manner so as to be able to calculate all of these cases. By varying the associated parameters, one can gain insight into such things as best projectile starting position, best propellant thickness, and best burning rate. The various types of runs of the unlined type are infinite chamberage gun, unchambered gun, displaced start, and traveling reservoir. The runs in the lined group are constant burning rate and pressure dependent burning rate.

The results of this program have been checked whenever possible with established results such as those appearing in AGARDOGRAPH 91, The Theory of High Speed Guns. However, there are many features in this program which can not be verified directly.

Since a number of the results violate what one would intuitively expect, certain aspects of this program were suspect. In particular, the mathematical transformation was questionable in its ability to handle the

burning propellant in an unsteady situation. In addition, the boundary condition at the breech of the launch tube seemed to give results which are experimentally unattainable. At very high burning rates, the results indicate that the projectile base pressure remains constant or increases which would indicate a computational difficulty in the projectile boundary condition.

Although the one-dimensional model is capable of duplicating published results for unlined launch tubes, the transformation of those equations involving mass, momentum and energy addition could not be verified. Therefore, a second program was developed which solves conservation equations without transformation. Although the moving boundary at the projectile causes severe errors at high velocities, this program has proved to be invaluable in the verification of certain aspects of the program previously described.

In order to establish confidence in this second program, a number of results are presented here as Figures II.4, II.5, and II.6. The projectile velocity at each point along the barrel is shown in Figure II.4 for no burning and a finite reservoir. This result is significant for two reasons. First, it is in agreement with the non-dimensional results produced by Seigel in Agardograph 91. The results were obtained by assuming those reservoir conditions which would yield a ratio of reservoir mass to projectile mass of one (G/M = 1). Therefore, the code, with the exception of those terms involving burning is verified. Secondly, it should be noted that this result predicts a projectile velocity of 3000 ft/sec at 6 inches and 3500 ft/sec at 66 inches of travel. These results are in basic agreement with the observed data obtained for unlined tubes in the Hypervelocity Laboratory. It can be safely concluded that the cartridge

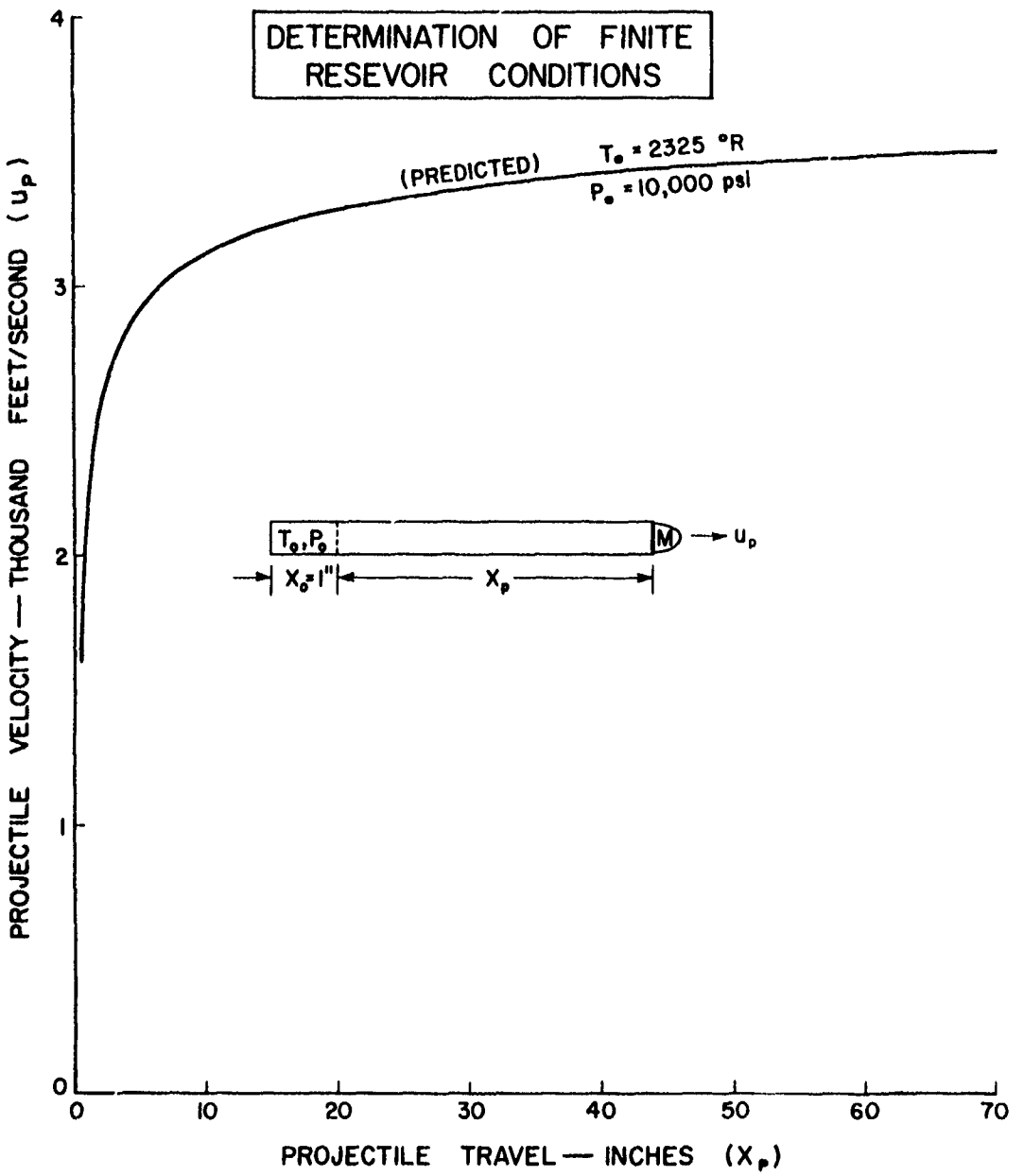


FIGURE II.4 Projectile Velocity as a Function of Length for G/M=1

used to launch projectile in the Hypervelocity Laboratory may be adequately modeled as a bore sized chamber of air ($\gamma = 1.4$) one inch long, with initial pressure and temperature of 10,000 psi and 2325°R, respectively.

A second set of results are presented in Figure II.5 which tend to lend credence to, or at least explain why, diverse opinions exist as to the feasibility of this concept. Here the non-dimensional velocity is shown as a function of non-dimensional projectile travel for both the unlined tube and liners of typical rocket propellants with known properties. Both propellants are characterized by a burning rate which is senitive to the pressure, according to the power law:

$$r = b\ p^n$$

The appropriate constants are given by Huggett, et al. in Solid Propellant Rockets, as shown in the following table:

PROPELLANT	BURNING RATE (in/sec @ 2000 psi)	PRESSURE INDEX (@ 2000 psi)	TEMPERATURE (°R)
JPN Ballistite	1.02	0.73	6000
Composite A	1.95	0.45	6000

It should be noted that the addition of gases from these propellants yields an insignificant improvement in projectile velocity.

A third set of analytical results is presented in Figure II.6. The nondimensional velocity is shown as a function of non-dimensional projectile travel for two different rates of mass addition, pr, and a variety of temperatures. It is interesting to note that not only significant improvement may be achieved with the addition of the right propellant, but severe degradation will result if the added gas is not sufficiently energetic. In addition it should be noted that the rate of mass addition will affect only the magnitude of the improvement or degradation of the

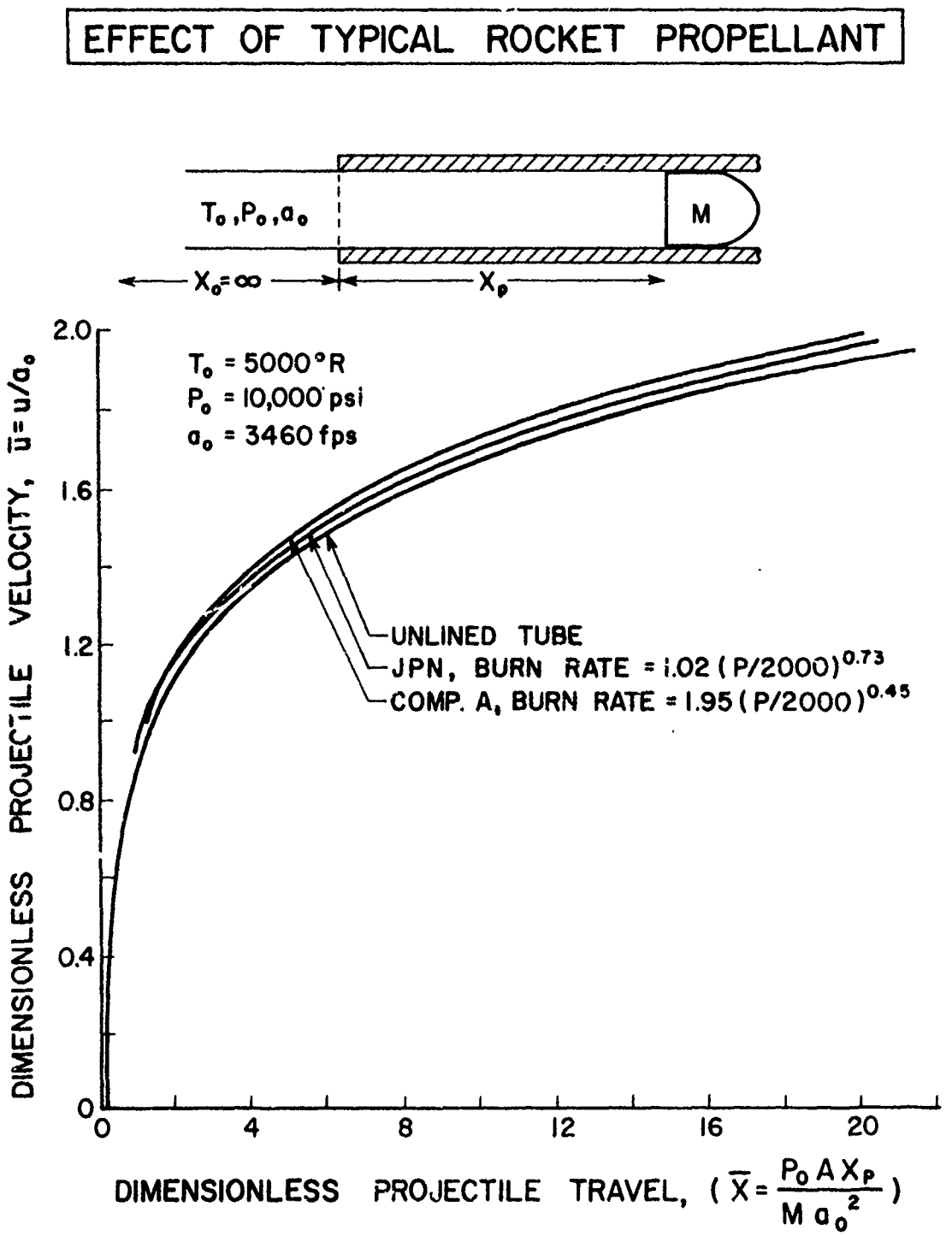


FIGURE II.5 Response of Lined Tube to Typical Rocket Propellants

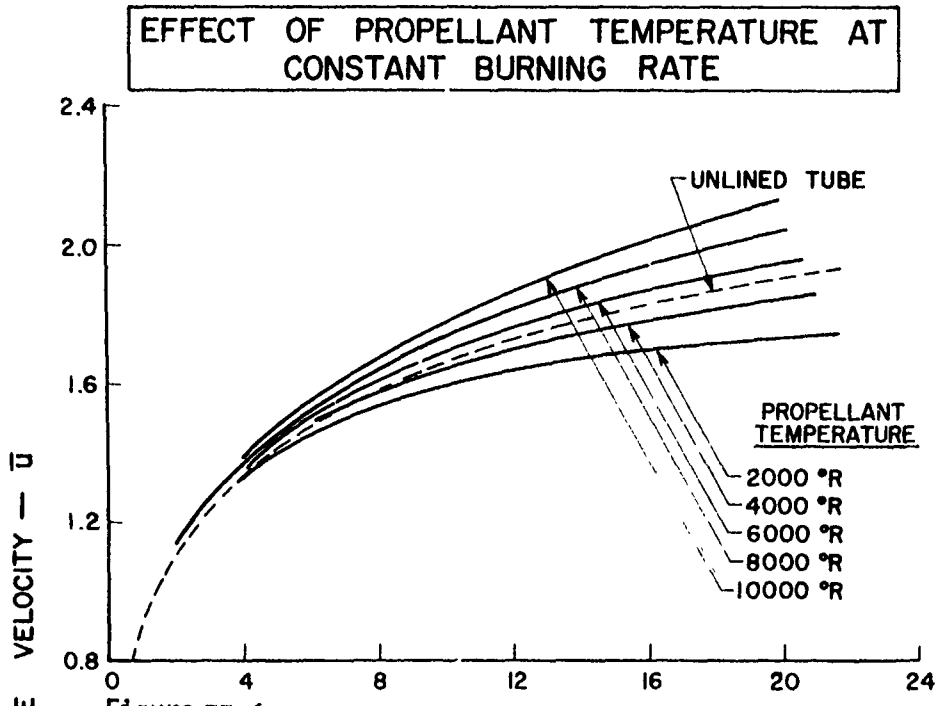


Figure II.6a

Effect of Mass Addition at 1 in/sec

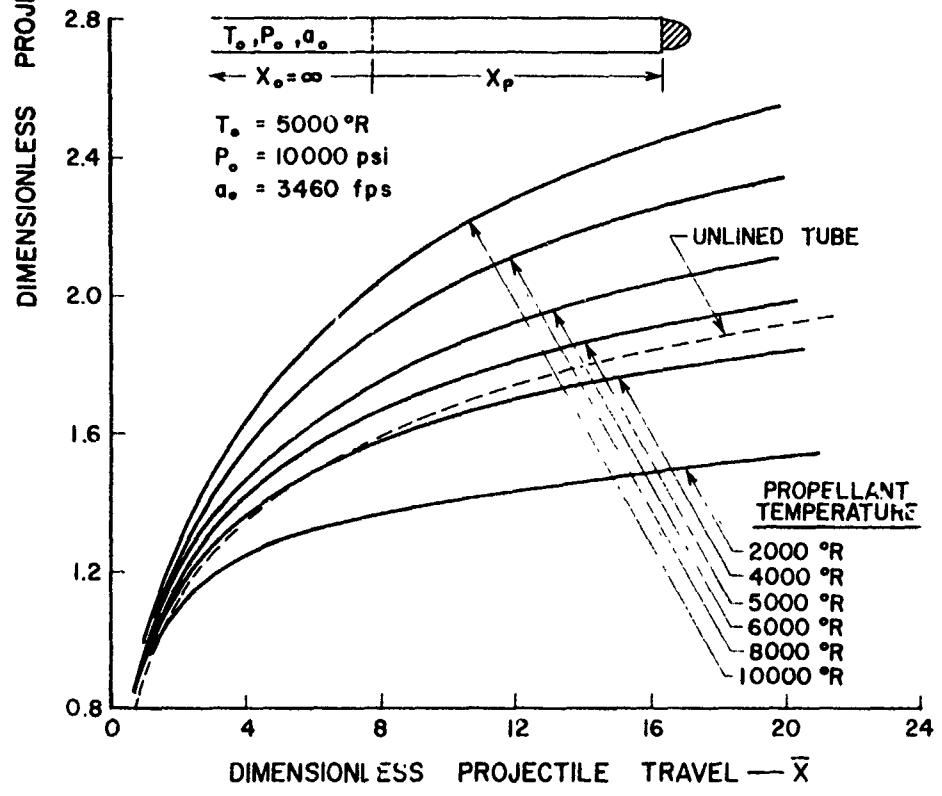


FIGURE II.6b

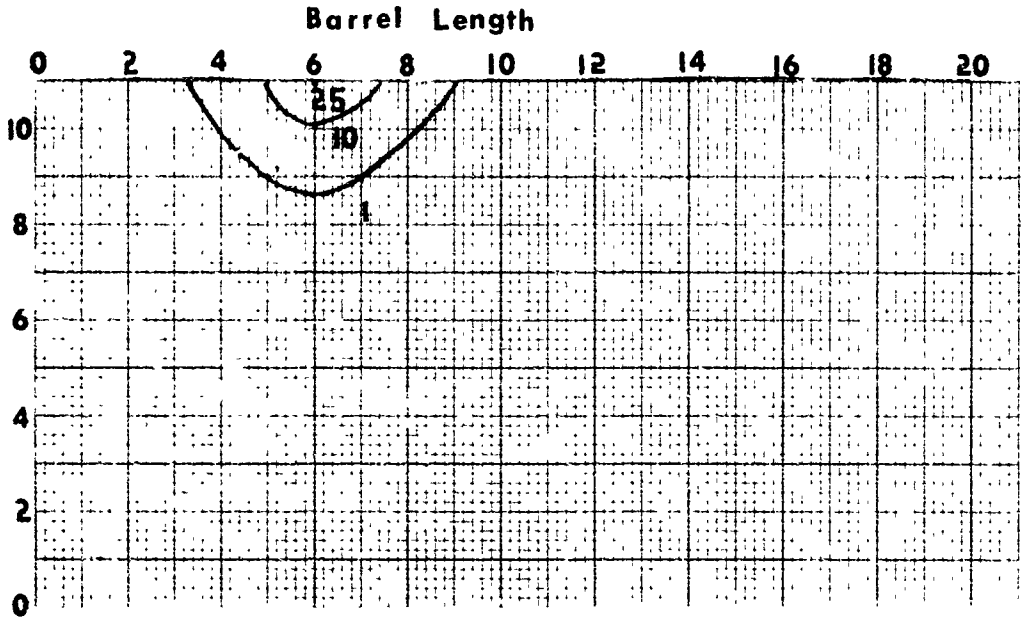
Effect of Mass Addition at 30 in/sec

system whereas the temperature (or energy) of the added gas relative to the stagnation conditions already there, will determine whether or not improvement should be anticipated.

A fourth set of results produced by the one-dimensional model indicated that complete mixing of the burned propellant with the gas in the tube will prevent operation of the lined tube concept. The model produced a limit to velocity because it assumed that gas from the walls completely filled cells each cycle. However, this is physically impossible at high velocities. Therefore the complete mixing assumption is invalid for high velocities.

Two-Dimensional Model

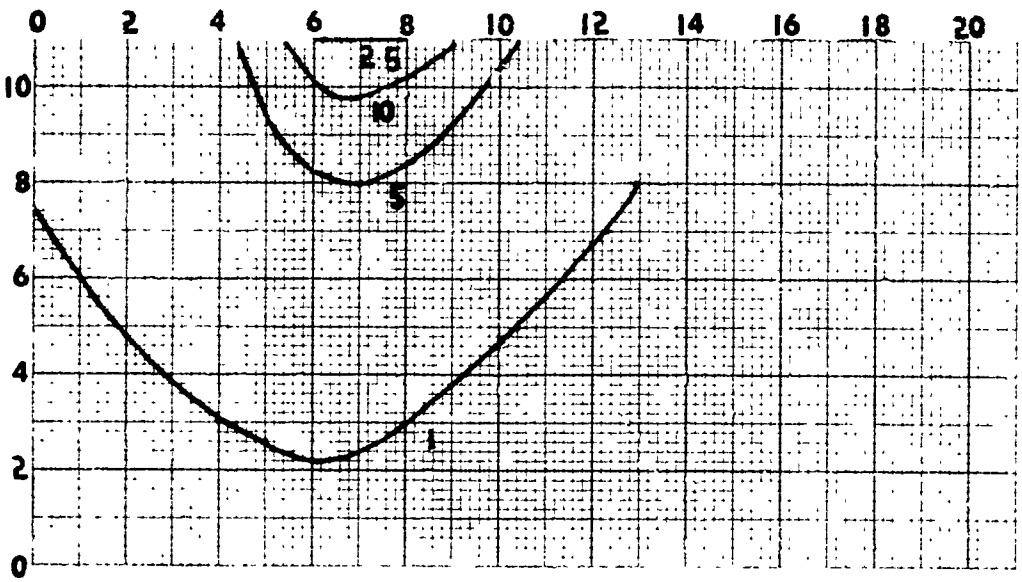
In order to obtain more accurate mathematical predictions of the process to allow parametric studies, a two-dimensional mathematical model was developed to study the gas interaction for a short distance behind the projectile. The model could not be used to obtain a complete launch run because of the large amount of core storage and computing time required. Some initial runs of the two-dimensional model at low projectile velocity indicates the gas produced by the burning propellant can increase the base pressure on the projectile. A sample run is shown in Figures II.7 to II.14. The problem starts with the burning of the propellant when the projectile has a velocity of 3000 feet per second with a uniform field pressure of 2000 psi and a velocity equal to the projectile. The burning is assumed to generate gas at 50,000 psi (pressure ratio of 25) with zero velocity. The plots show the pressure ratios at various times and time planes. The boundary indicated by 1 is the leading edge of the shock disturbance and is indicative of the degree of blurring in the model. The plots indicate that waves can travel from the cylinder walls to the center and back in 4 microseconds.



TP 3

.11693 μs

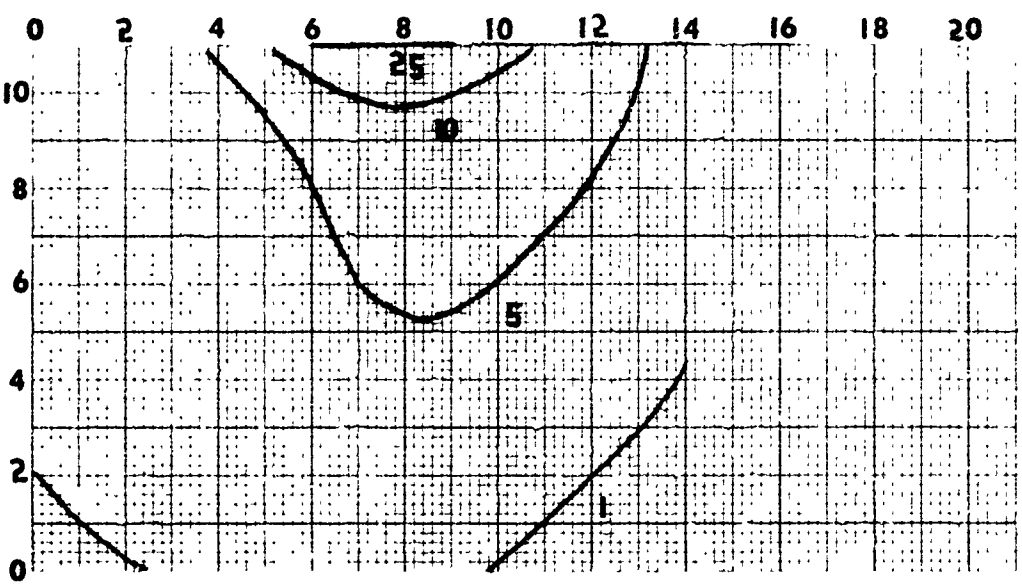
Figure II.7



TP 11

.49837 μs

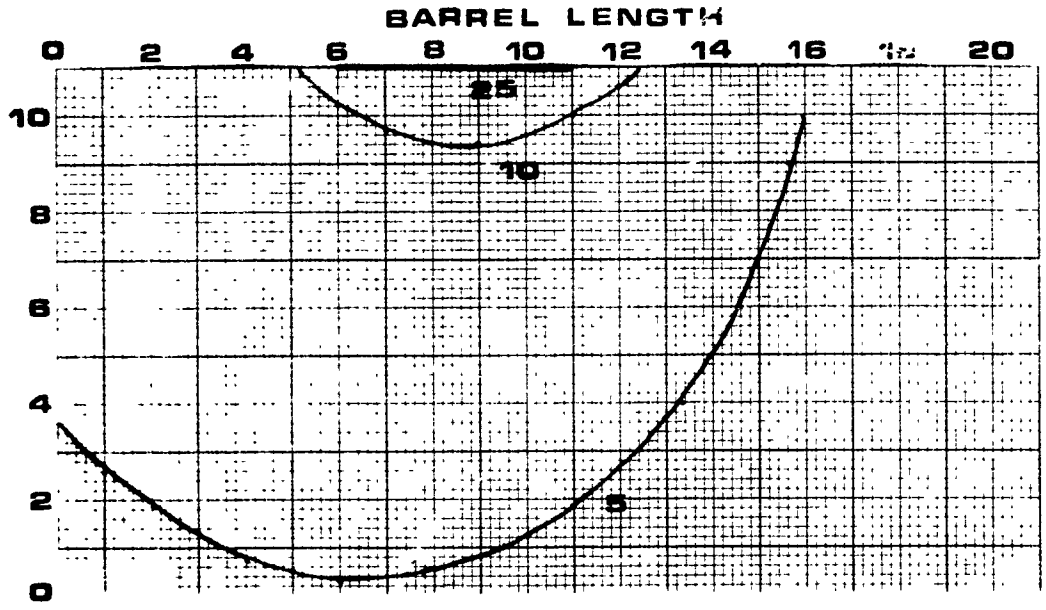
Figure II.8



TP 21

1.0479 μs

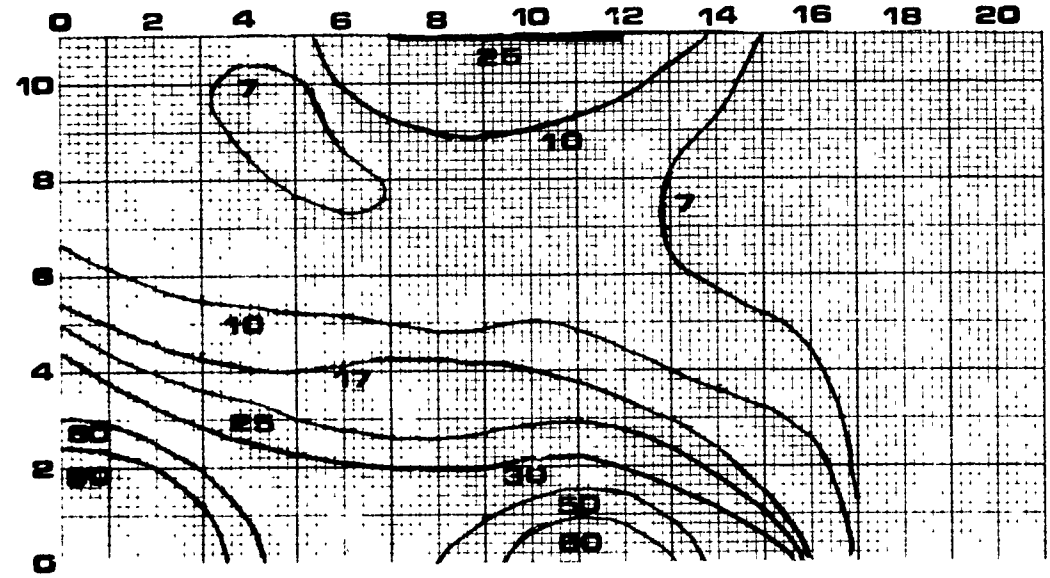
Figure II.9



TP 31

1.6073 μS

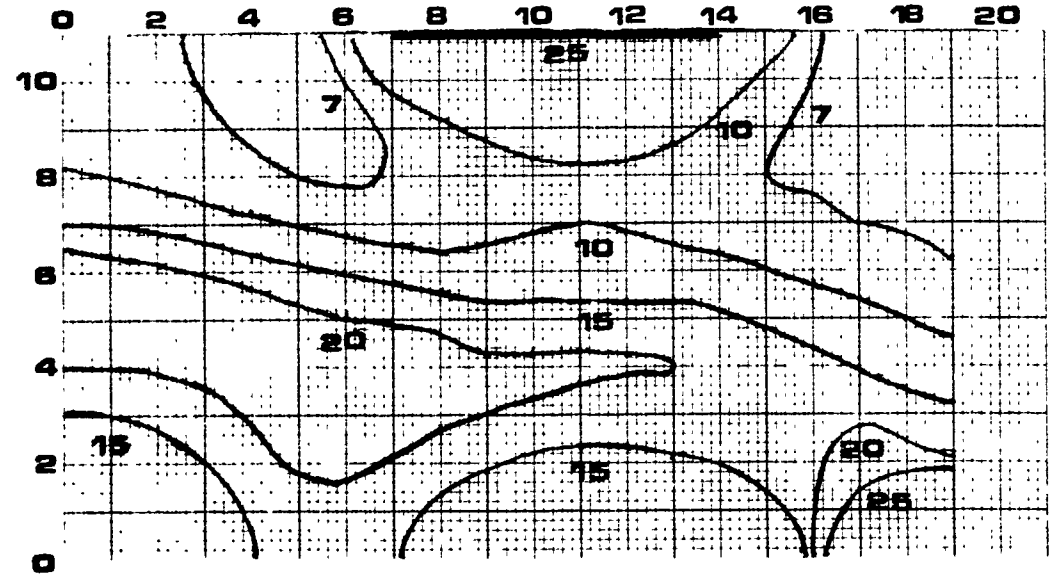
FIGURE II.1



TP 41

2.1339 μS

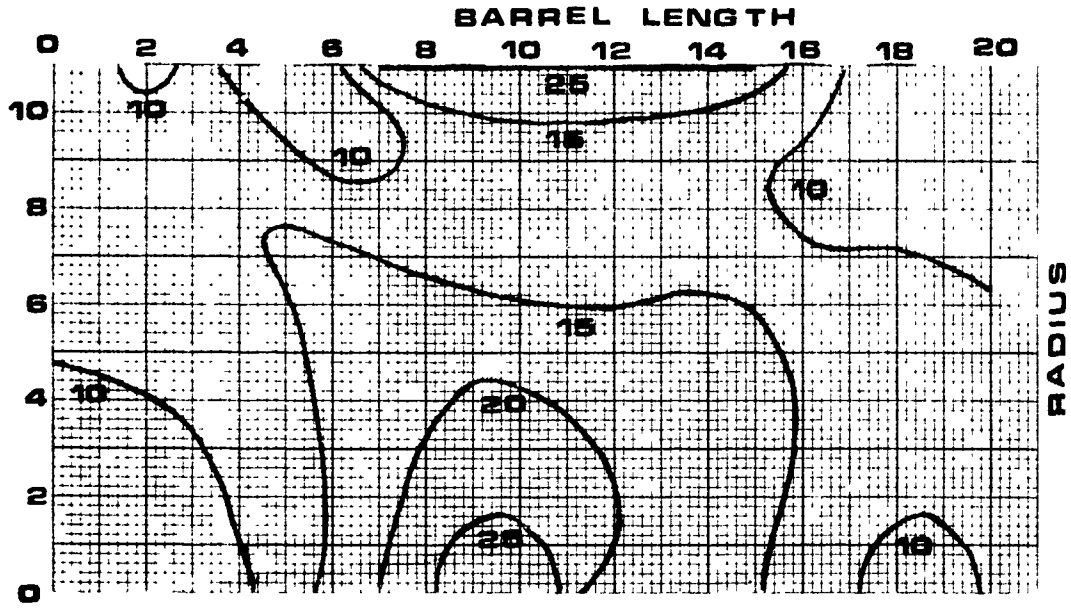
FIGURE II.1



TP 51

2.6223 μS

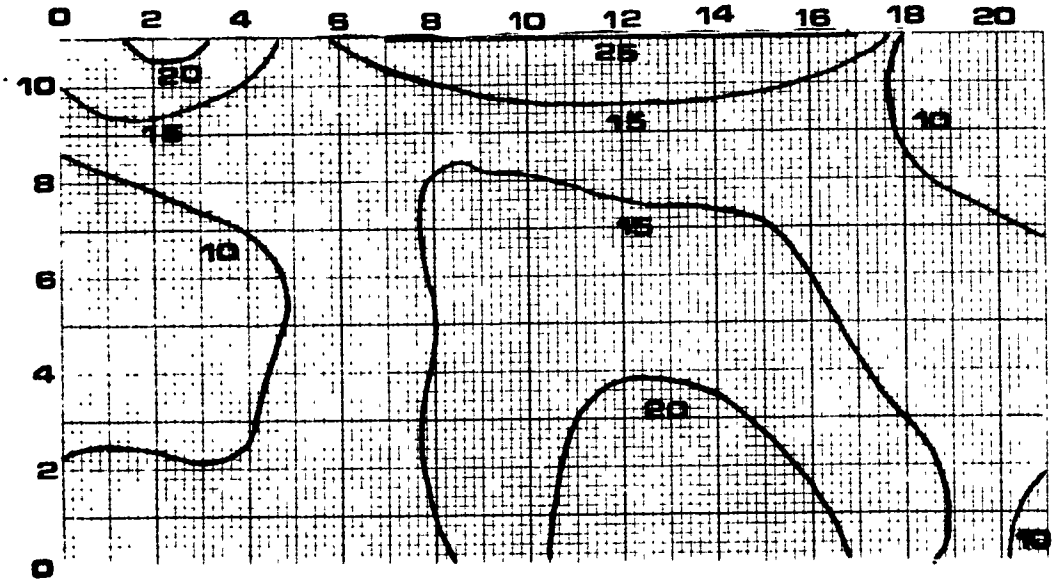
FIGURE II.1



TP 61

3.0978 μS

FIGURE II.13



TP 71

3.5696 μS

FIGURE II.1

The two-dimensional model requires that an artificial dissipative or blurring term be introduced in the mathematical scheme. This term handles discontinuities or rapidly changing functions. The term can be used to represent a shock in a fluid flow. Unfortunately the blurring term must be established by the programmer, therefore the intensity of the shock discontinuity can be varied or even obliterated. The discontinuity boundary in the physical system is one of the extremely questionable areas and the boundary will require a different type of mathematical model. The two-dimensional mathematical model was very helpful in determining gas interactions for short distances behind the projectile. Since the model could not be used to represent the entire gun system more effort was put into the study of the one-dimensional mathematical model.

Reservoir Pressure Calculations

The reservoir pressure was examined by John B. Watson, Dr. Stephen P. Gill and Gerry Steel of Physics International. A model of the reservoir cone was formulated for three conditions. By investigating the pressures in the reservoir the limiting velocities could be predicted for the lined tube concept.

Zero Mass Addition Model - The first performance model proposed is called the zero mass addition model. In this model an assumption is made that a volume of captive gas is bounded by the projectile and an effective piston is formed by the explosive products. The effective piston is formed by a solid wall moving radially inward at the escape velocity of the explosive products. The choice of effective piston does not have an effect in this model.

The following assumptions are made regarding the operation of the gun:

1. The explosive liner initiates instantaneously at the rear of the projectile.
2. The explosive products form a solid wall and move radially inward at the escape speed $\hat{u}$ of the products.
3. The projectile, along with some captive gas (M_o) is injected into the system at a velocity v_o.

Consider the zero mass model in Figure II.15

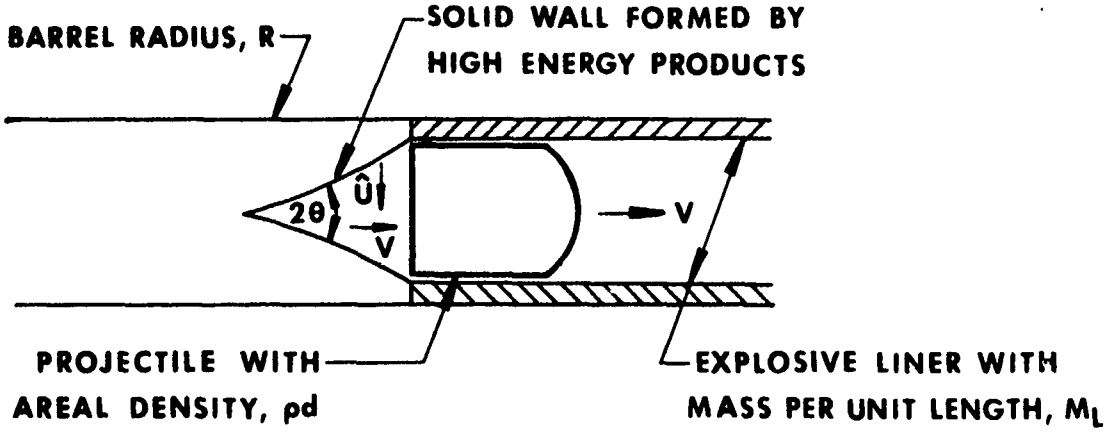


FIGURE II.15: ZERO MASS MODEL

The explosive liner is assumed to collapse to a quasi-steady state and the captive gas is at a uniform pressure P_1. The volume of the captive gas is proportional to the projectile velocity and is given by:

$$V = \frac{\pi}{3} \frac{R^3 v}{u}$$

Assuming isentropic behavior of the captive gas and no gradients in the captive volume, the pressure is given by the proportionality:

$$P \alpha V^{-\gamma}$$

Therefore

$$P = P_o \left(\frac{V_o}{V}\right)^{\gamma}$$

Since ($\nu \alpha V$)

$$P = P_o \left(\frac{\nu_o}{\nu}\right)^{\gamma}$$

If the captive gas remains uniform during acceleration, then the motion of the projectile is given by:

$$P = (\rho d)\ \nu \frac{d\nu}{dx}$$

Thus

$$P_o \left(\frac{\nu_o}{\nu}\right)^{\gamma} = (\rho d)\ \nu \frac{d\nu}{dx}$$

Integrating

$$\nu_f = \left[\frac{P_o\ \nu_o^{\gamma}\ (\gamma + 2)}{(\rho d)}\ X_f + \nu_o^{\gamma + 2}\right]^{1/\gamma + 2}$$

where

X_f = barrel length

ν_f = muzzle velocity

considering a typical example:

$(\rho d) = 1$ gm/cm^2 (a 2 gm, 5/8 in. diameter projectile with a density of 1.4)

$\gamma = 1.4$

$\nu_o = 3200$ fps (injection velocity)

$P_o = 30{,}000$ psi

See Figure II.17 which relates muzzle velocity against barrel length.

Jetting Model - The second performance model is called the jetting model. Again the assumption of isentropic process is made. Further it is assumed that the enthropy of the injected mass is the same as the entropy of the original captive gas. These assumptions lead to higher performance than can be realistically expected.

Consider a performance model with mass input by jetting, Figure II.16. The model assumes that the exploded propellant forms a solid mass V that converges at a single angle upon the origin and jets upon convergence.

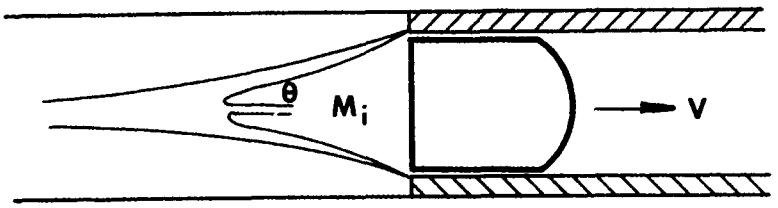


FIGURE II.16: JETTING MASS MODEL

The mass input rate is approximated for the cylindrical case by the planar case as:

$$M_i = M_L \frac{1 - \cos\theta}{2} \nu; \quad \cos\theta = \frac{\nu}{(\nu^2 + \bar{u}^2)^{1/2}}$$

where

M_L = Liner mass per unit length

M_i = Jet mass flux

If the captive gas is assumed isentropic:

$$P = P_o \left(\frac{\rho_o}{\rho}\right)^{-\gamma}$$

$$\rho = \frac{M_o}{V_o} = \frac{3 M_o \bar{u}}{\pi R^3 \nu_o}$$

As an upper limit on the performance of the device consider all the mass of the liner is input into the captive gas.

$$P = P_o \frac{\nu_o}{\nu} \left(1 + \frac{M_L}{M_o} X\right)^{\gamma}$$

Inserting this in

$$P = (\rho d)\, \nu \frac{d\nu}{dx}$$

and integrating

$$v_f = \{(\frac{\gamma + 2}{\gamma + 1}) \frac{P_o v_o \gamma}{(\rho d)} \frac{M_o}{M_L} [(1 + \frac{M_L}{M_o} X_f)^{\gamma + 1} - 1] + v_o{}^{\gamma + 2}\}^{1/(\gamma + 2)}$$

Consider the following example:

$(\rho d) = 1 \text{ gm/cm}^2$

$\gamma = 1.4$

$v_o = 3200$ fps

$P_o = 30{,}000$ psi

$M_o = 0.2$ (typical amount of gas injected by first stage cycle)

$M_L = 0.01$

See Figure II.17 which relates muzzle velocity against barrel length.

Mass Input Due to Traveling Charge Model - The third performance model presented is for a mass input caused by the decomposition of the propellant attached to the base of a projectile.

Assume one half of the projectile is propellant that is released at a constant rate over time t_r. The volume of captive gas is made up of a volume of initially injected gas, V_g, plus a volume of propellant products, V_p.

$$V = V_g + V_p$$

$$Vg = V_{g_o} (\frac{P}{P_o})^{1/-\gamma_g}$$

$$Vp = V_{p_o} (\frac{P}{P_o})^{1/-\gamma_p}$$

where

P - the mixture pressure

P_o - the reference pressure and the initial pressure of the injected gas

V_{g_o} - volume of injected gas at time = 0, when Po is injection P

V_{p_o} - $f \frac{t}{t_r} V_{p_{p_o}}$ - is a volume of gas at P1

t_r - total release time

V_{pp_o} - volume of propellant initially in the projectile

f - expansion factor to reach reference pressure P_o

$\gamma_g = \gamma_p = \gamma$ - all gas constants are equal for simplicity

Using the above definitions

$$P = P_o \left(\frac{V}{V_{g_o} + V_{p_o}}\right)^{-\gamma} = P_o \left(\frac{V}{V_{g_o} + f \frac{t}{t_r} V_{pp_o}}\right)^{-\gamma}$$

as in previous models

$$V = \frac{\pi}{3} \frac{R^3 \nu}{\Lambda_u}$$

substituting

$$P = P_o \left(\frac{\nu_o}{\nu} + \frac{3 f \frac{t}{t_r} V_{pp_o} \Lambda_u}{\pi R^3 \nu}\right)^{\gamma}$$

Using

$$P = (\rho d) \frac{d\nu}{dt}$$

and integrating between 0 and t_r and between ν_o and ν_f one obtains

$$\nu_f = \left\{\frac{\pi R^3 t_r P_o}{3 f V_{pp_o} \Lambda_u (\nu d)}\left[\left(\nu_o + \frac{3 f V_{pp_o} \Lambda_u}{\pi R^3}\right)^{\gamma + 1} - \nu_o^{\gamma + 1}\right] + \nu_o^{\gamma + 1}\right\}^{1/(\gamma + 1)}$$

Consider the example

R = .312 inches

P_o = 30,000 psi

f = 5

$V_{pp_o} = \pi R^2 \ell$

ℓ = .197 inches

Λ_u = 9,600 ft/sec

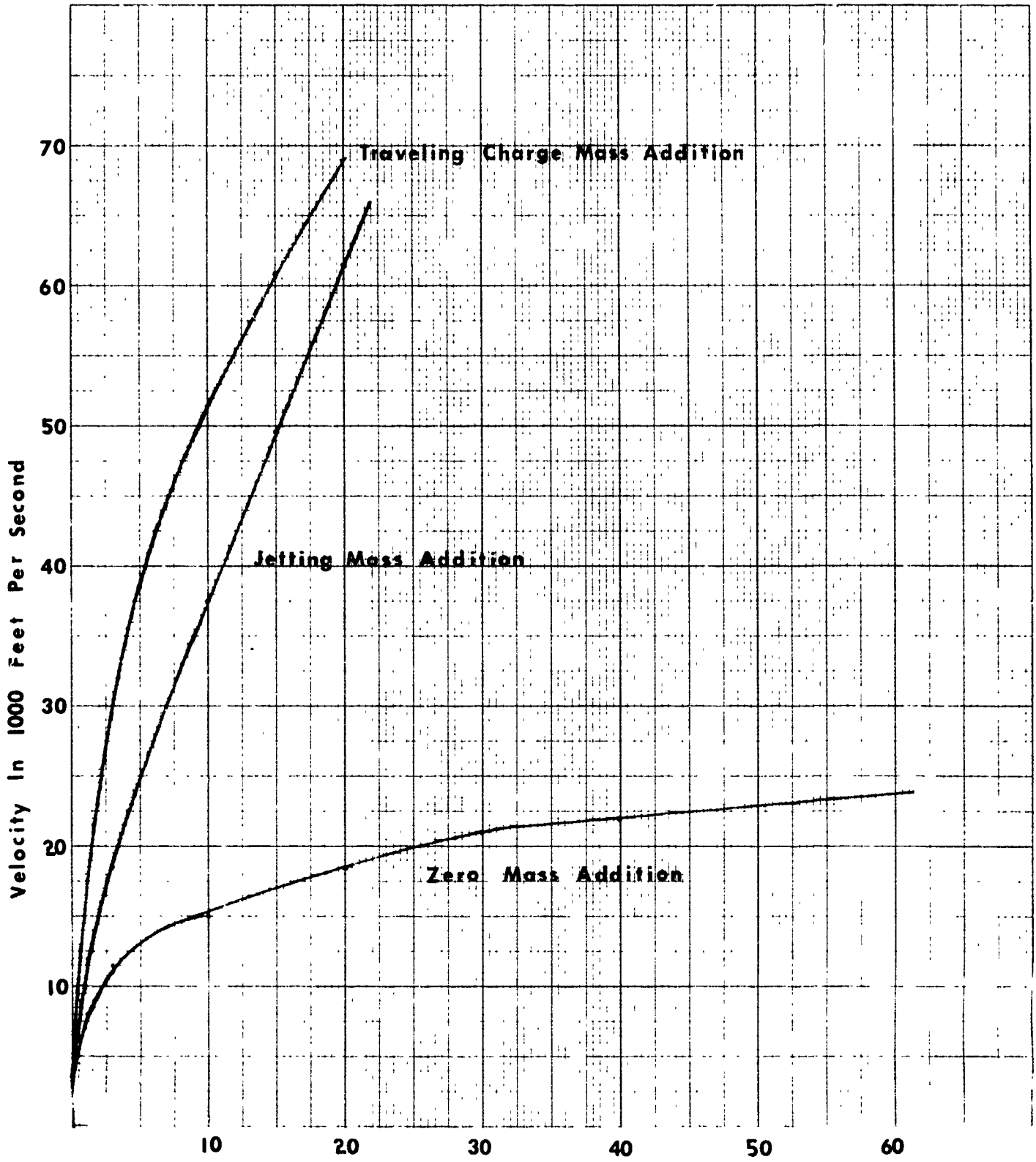


Figure II.17: Reservoir Pressure Model Velocities

$(\rho d) = 1 \text{ gm/cm}^2$

$v_o = 3200 \text{ ft/sec}$

$\gamma = 1.4$

See Figure II.17 which relates muzzle velocity with barrel length.

Discussion of Reservoir Pressure Models

The zero mass addition model is clearly not a constant base pressure gun ($p \alpha v^{-\gamma}$). To obtain real hypervelocities at relatively low base pressures, mass addition will be required.

The jetting model shows that very high velocities are predicted. However, Watson and Steel feel that jetting significant amounts of mass into the captive gas would be too much to hope for as only a very small fraction (which decreases with increasing velocity) of the total liner mass could be expected to jet.

The mass addition due to a traveling charge model also predicts very high velocities. Watson comments "Perhaps some combination of mass input by jetting and a slow burning propellant contained in the projectile will get you into an interesting range of velocities."

General Discussion

There are several theoretical problem areas that are presently being studied. There is the possibility of gaseous mixing across the velocity boundary. The traveling reservoir concept would be impossible with mixing. The solution to this problem would be to create a boundary. This could be achieved by coating the propellant with a hard noncombustible coat. The coat would be collapsed with the propellant ignition, thus physically forming the velocity boundary.

The ignition delay time being too short or too long creates a problem.

With the ignition delay too short the imploding gas collapses on the reservoir and sucks the reservoir away from the projectile. For the case of too a delay the traveling reservoir becomes stretched out, thus reducing the pressure. The ignition delay effect has been modeled and presented previously in this section.

Preferably, the conditions in the traveling reservoir should remain constant. There is a phenomenon associated with cylindrical implosions known as jetting. At the center of implosion, for a cylinder this would be the axis, the gases create extremely high pressures, which result in a jetting action along the axis in the direction of the projectile. The jetting action would not be harmful to the lined tube concept, because it would be increasing the pressure in the traveling reservoir, which would be advantageous.

The jetting action is obviously advantageous and this resulted in searching for other reservoir pressure increasing devices. The most advantageous one found is the traveling charge model. This basically works on the rocket engine principle, see Figure II.18. A slow burning solid propellant is cast on the base of a nylon projectile. The propellant is ignited with the initiation of motion and releases a high energy gas into the reservoir. The mass addition in the reservoir due to jetting and traveling charge exhaust gas is a favorable mechanism for increasing the reservoir pressure.

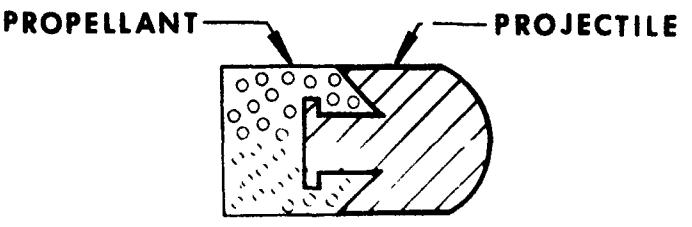


Figure II.18 Model of Traveling Charge Projectile

III. Critical Parameters

The critical parameters are those variables that central the success or failure of operation when the variations of the parameters exceed an acceptable value range. The theoretical development indicates that most of the parameters critical to the successful operation of the hypervelocity launcher are associated with the propellant characteristics. The critical propellant parameters are the ignition of the propellant by the passage of the projectile, the rate at which the propellant generates gas and the volume of gas released. More specifically the propellant parameters can be distinguished as ignition delay time, propellant burn rate, gas volume and the associated pressure. Other critical parameters that have appeared as a result of experimental tests are propellant lining characteristics, such as smoothness and hardness, and the gas seal that the projectile makes with the sides of the cylindrical walls.

The first estimates of required propellant thicknesses were in the 5 to 15 mil (.005 to .015 inches) range. These are classified as thin films in propellant and explosive literature. Very few studies of explosives in thin films have been made because the prime use of explosives is for large energy applications. One source of thin film explosive studies was the experiments using PETN reported by Bowden and Yoffe[23]. Other experiments were conducted by Flagg[24] with lead azide.

The desired characteristics of the explosive film are that the low energy input of the projectile friction not ignite it, but an ignition system moving with the projectile supplies sufficient energy to generate an ignition in microseconds. The tests reported by Bowden, Yoffe and Flagg seemed to indicate that secondary explosives would be desired. However, comments by Bowden and Yoffe were:

> The speed with which a burning propellant spreads in a thin film depends on a number of factors. The heat of reaction is, of course, one of the most important. The intensity of the igniting source, the degree of confinement, the surrounding gas pressure, the thermal constants and the size of the solid film all affect the burning speed. The structure and decomposition mechanism must also be taken into account.

Burning Rates

Propellant burning rate is important to the operation of the hypervelocity launcher, because gas must be added behind the projectile very rapidly. This research has developed propellants with burning rates between previously known values of deflagration and detonation and has shown that the speed of burning can be altered dramatically by the thickness of the film and the type binding agent or filmogen used. These properties are discussed more fully in Appendix A.

In order to bond the propellant to the walls of the launch tube, the use of a filmogen introduces the effect of such agents on the ignition and detonation properties of the explosive. According to Bowden and Yoffe[23] the burning speed of a film can be altered by coating the crystals with very thin layers of inert liquids and solids. They state that dilutents can both increase and decrease the velocity of detonation depending on the nature of the dilutent, and in the case of solid additives, on the particle size and density. The current propellant investigations have shown that nitrocellulose will inhibit both burning and detonation. On the other hand polyvinylchloride will support deflagration.

Ignition Time

Another property of the propellant that must be controlled in order to provide proper operation of the hypervelocity launcher is the ignition time. It is desired to ignite the propellant as close to the base of the projectile as possible always keeping the reaction behind the base of the projectile. Some

of the possible initiation methods that are applicable to the hypervelocity launcher are described by Bowden and Yoffe[23].

Initiation By Heat - This is the simplest way of initiating an explosion. An explosion can result when heat is liberated by reaction at a greater rate than heat is lost. From a knowledge of the mechanism of decomposition, and of parameters such as the heat of reaction, energy of activation, and thermal conductivity, it is possible to estimate the size of the small nucleus of decomposition or "hot spot" required for the growth of the reaction to explosion.

Initiation By Shock - The sensitivity of explosive materials to shock is a well-known phenomenon. An explosion may be brought about by impact or friction and the conditions which determine the incidence of explosion are fairly well established. That is to say the mechanical energy of the impact or of the rubbing must first of all be degraded into heat to give a "hot spot" of suitable size and temperature within the material. Hot spots may result from the adiabatic compression and heating of enclosed gas spaced or from frictional heating during the rubbing of solid surfaces. There is little evidence for a direct "tribo-chemical" break-up of the molecules during impact or friction.

The time required for ignition of the explosive was considered to be a major problem area at the first of the research effort. Conversations with personnel at ordnance research laboratories all expressed the opinion that because ignition is a thermal phenomenon heating of the material and the chemical reaction would cause a delay that could be several hundred microseconds. The data presented by Cook[25] shows minimum time lags of 40 and 45 microseconds for PETN and RDX subjected to impact initiation. Bowden and Yoffe[23] state that for a liquid such as nitroglycerin time delays of the order 0-20 microseconds are observed between impact and explosion due to the adiabatic compression of trapped gas. With solids such as PETN and RDX and primary explosives such as

lead ozide they report time delays of 60-145 microseconds, attributing this delay to the time for compressing the solid film.

Davis[26], in referring to the difficulty in igniting ammonium nitrate, states that other explosive liquids or solids, such as liquid or solid DNT, TNT, or TNX, nitroglycerine, nitrostarch, or nitrocellulose may be used to sensitize the ammonium nitrate and to make the mixture more easily detonated by a blasting cap. Non-explosive combustible materials, such as rosins, coal, sulfur, cereal meal, and paraffin, also work as a sensitizer for ammonium nitrate.

Unfortunately no tests have been found on ignition time of thin film explosives under friction ignition devices although such a test is standard for examining explosive sensitivities for safety requirements. If the ignition delay exceeds ten microseconds it is conceivable that the projectile could be used as the source of friction. To test this hypothesis, projectiles made of steel aluminum and wood were fired early in the program and resulted in firing the propellant liner ahead of the projectile. It is assumed that the ignition occured in the annulus restraining the projectile and allowing the combustion to move ahead. The nylon projectiles did not fire ahead and were used for the remainder of the experiments.

The projectile and propellant combination must be selected so that the projectile friction does not provide enough energy to ignite the propellant. If the propellant were ignited by the projectile the delay time would be so short that detonation would occur next to the projectile thereby destroying it. However, the possibility exists of providing a constant delay distance behind the projectile by attaching a mechanical or thermal device to the base of the projectile that will supply the necessary energy to ignite the propellant. Several possible designs are presented in the next section.

Gas Requirements

The determination of propellant thickness is based on the assumption that the gas required must fill the volume previously occupied by the vacuum ahead of the projectile. The gas must fill the tube with a pressure greater than the desired constant base pressure. Using the values of gas volume from Explosive Handbook [illegible] and assuming that the expansion is adiabatic between the standard conditions and the conditions in the launch tube, a pressure of 20,000 psi in a .250 inch tube would require approximately 20 mils propellant thickness. These calculations are based on 2 parts RDX with a gas volume of 883 to result in 900 cc/gm for the mixture.

The largest factor affecting the results of such calculations is the value of γ, the ratio of specific heats. Corner[26] suggests a value of 1.25 as a good approximation for the gases and temperatures encountered in the common propellants for guns.

Pressure Requirements

A very simple mathematical model will describe the motion of the projectile, because the resisting forces are small compared to the pressure on the base of the projectile. The projectile acceleration is readily related to base pressure and mass of the projectile. Figure III-1 shows the relationship between the acceleration and launch tube length for various velocities. The base pressure required to achieve these accelerations for projectiles with diameters of .125, .250 and .500 inches, with the density of plastic material, is shown in Figure III-2. From these figures it is seen that the acceleration of a .250 inch projectile to thirty kilometers per second in a distance of eighty feet would require only 24,000 psi for the constant base pressure.

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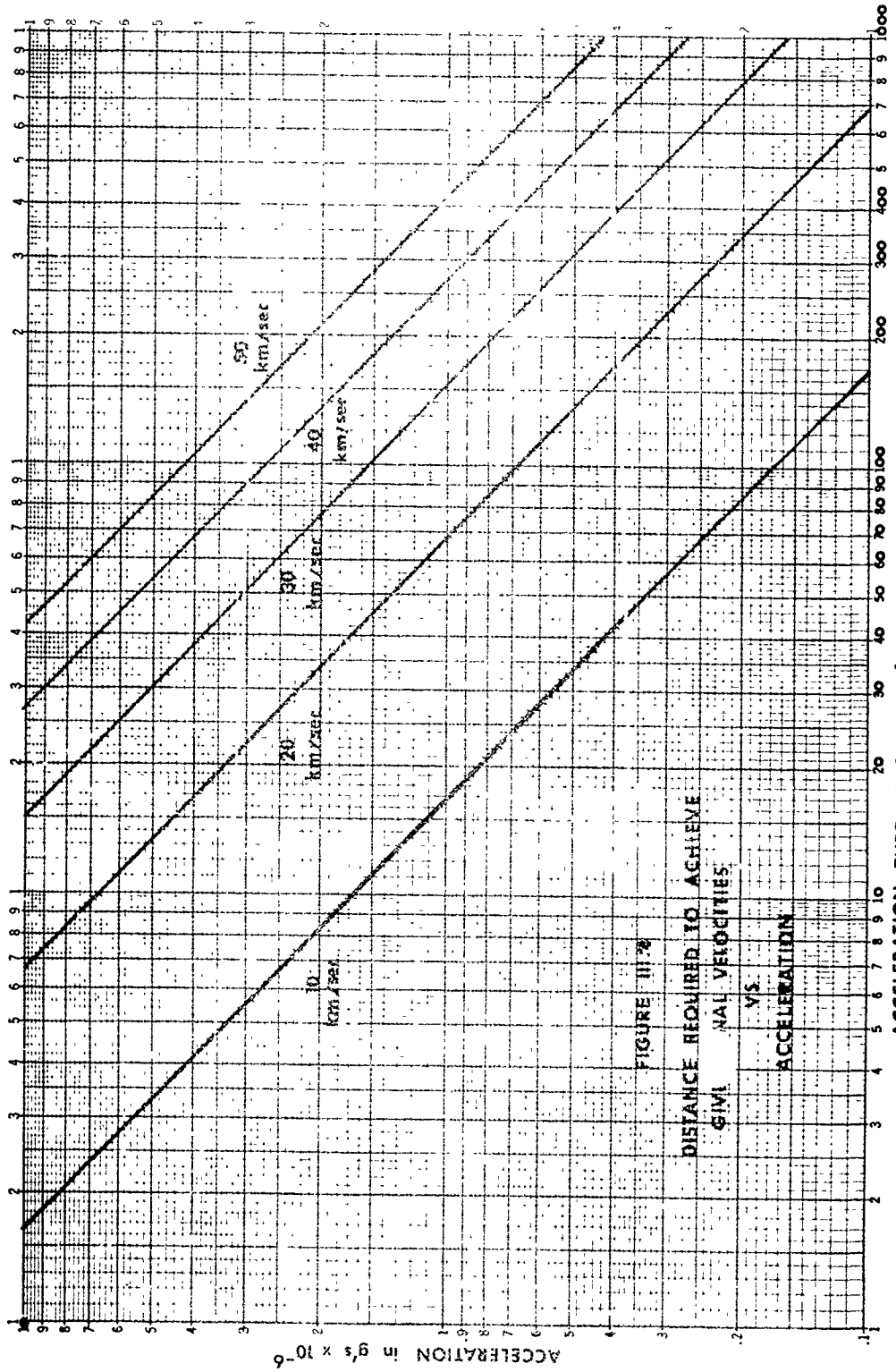

FIGURE III-2

DISTANCE REQUIRED TO ACHIEVE GIVEN VELOCITIES VS ACCELERATION

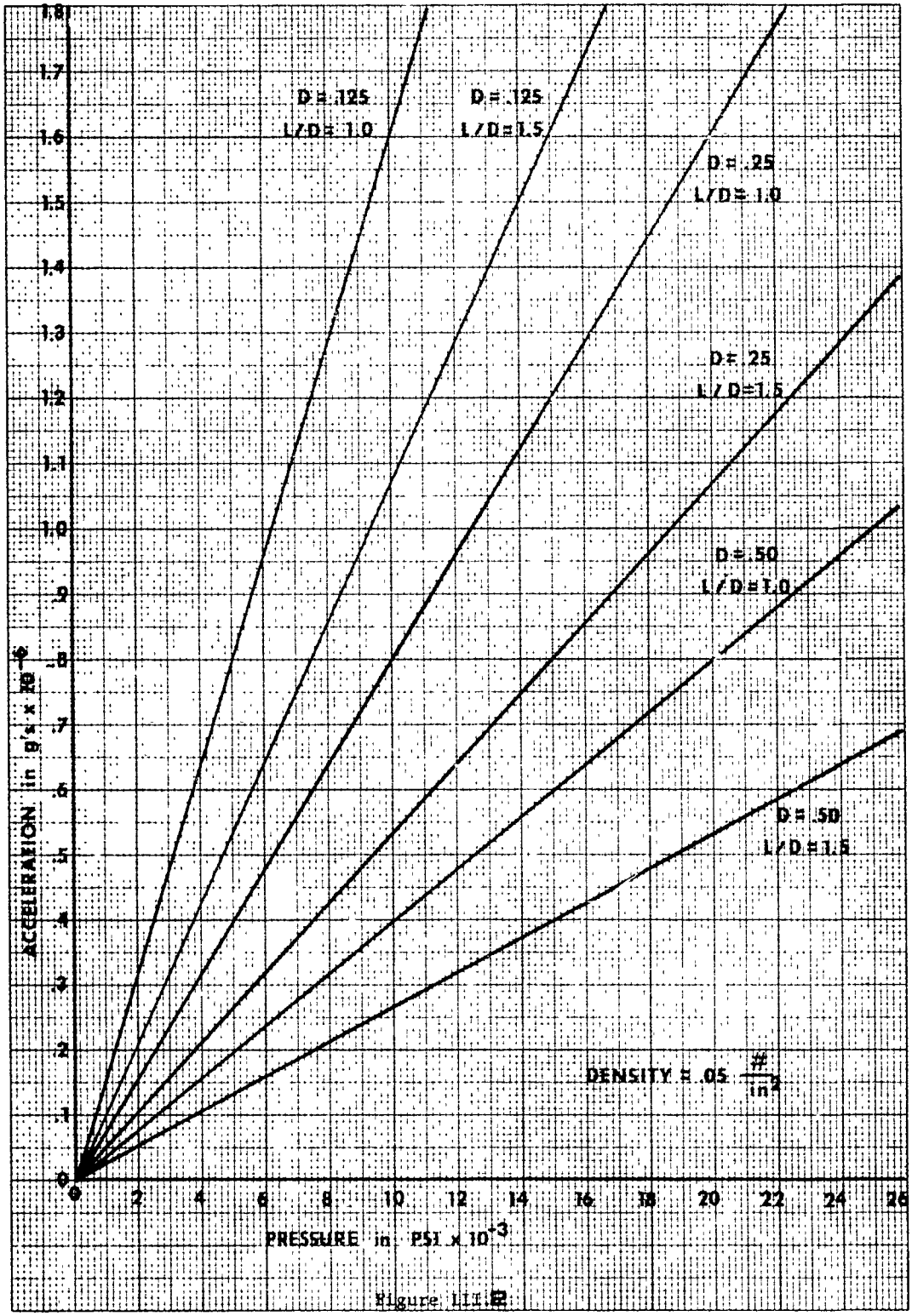
D = .125
L/D = 1.0
D = .125
L/D = 1.5
D = .25
L/D = 1.0
D = .25
L/D = 1.5
D = .50
L/D = 1.0
D = .50
L/D = 1.5
DENSITY = .05 #/in²
ACCELERATION in g's x 10⁻⁶
PRESSURE in PSI x 10⁻³
0
2
4
6
8
10
12
14
16
18
20
22
24
26

Figure III-2

Propellant Lining Characteristics

An important factor in the development of the hypervelocity launcher is to apply uniform smooth layers of propellant to the inner surface of the cylindrical launch tubes. One important result of the test shots was that when a rough spot resulted from the coating operation this generally resulted in a firing of the lining ahead of the projectile. Attempts to patch or repair the lining when it pulled loose from the walls were not successful. It was concluded that any flaws whatsoever in the lining is adequate reason to remove the lining and recoat the tube.

The hardness of the propellant is another important characteristic of the lining. If the propellant is not adequately hardened the projectile will scrap it off the launch tube walls. The energy the projectile imparts to the propellant scraps off the propellant instead of igniting it.

Gas Seal

The gas seal between the projectile and the launch tube walls is required to contain the traveling reservoir behind the projectile. The clearance between the projectile and the launch tube wall is a critical parameter.

Theoretically a small clearance is required because the diameter of the projectile will expand during acceleration. The frictional forces act aft and the base pressure acts forward creating compression in the projectile, thus increasing its diameter.

It was found by trial and error that 2 to 4 mils clearance was adequate to account for expansion and maintain the required gas seal.

To facilitate a flexible gas seal a conical recess was cut into the base of the projectile. This created a lip on the projectile which was very flexible. The lip expanded for the gas seal, but did not produce excessive frictional drag.

For more complex projectile designs, such as, the traveling charge and

mechanical igniters, a lip was machined on the aft end of the head of the projectile, which performed the function of the gas seal.

IV. Critical Design Features

The critical design features differ from the critical parameters in that they can be controlled through proper design. Laboratory experimentation has revealed two critical design areas. The first is projectile design which can be subdivided into more specific features, such as, material, strength, length to diameter (L/D) ratio, gas seal, and igniter system. The second area is that of the propellant characteristics. Specifically ignition, burn rate, pressure producing capability, thickness, smoothness, hardness and coating techniques. Other areas related to propellant design are ignition testing, burn rate testing and friction testing.

Projectile Design

One of the critical parameters for obtaining maximum velocity is the mass of the projectile. This was kept as small as possible by using low density material. Based on the experience of previous investigators, nylon was chosen as the basic projectile material although the ignition characteristics of aluminum, steel, hard plastics and wood were investigated. For the chlorate and perchlorate base propellants containing powdered glass it was found that aluminum, steel, wood and certain hard plastics would cause ignition, while nylon and teflon would not. The preliminary experiments were made with a projectile configuration shown in Figure IV-1. The conical recess in the base was provided in order to both reduce the we ght and provide better flexibility for gas sealing.

Figure IV.1 Conical Base Projectile (Left)
Flat Base Projectile (Right)

Because the original concept was based on using the projectile as a friction igniter of the lining, several tests were made using aluminum, wood and plastic projectiles. In one of the first tests with an aluminum projectile, the tube fired ahead of the projectile and forced it backwards where it lodged against the breech of the velocity initiator with very little damage. Microscopic examination revealed a deep pit near the nose of the projectile where it is tangent to the wall. Other aluminum projectiles as well as the wooden and acrylic plastic projectiles were destroyed with only small particles found in the impact tank. It was thus concluded that these projectiles cause pre-ignition. Nylon was selected as the best material obtainable from the standpoint of low friction and high strength.

The design of the projectile length to diameter ratio was a required consideration. The required L/D ratio was found to be greater than one. A ratio of greater than one restricted projectile wobble and prevented the projectile from tumbling.

Projectile strength was important because of the high stresses due to acceleration. The solid nylon projectiles were of sufficient strength to remain intact. However, attachment of thermal and mechanical igniters to the nylon head required careful design to fulfill the necessary structural considerations.

The design of the projectile gas seal was mentioned in the previous section. Briefly, it was found that 2 to 4 mils clearance was necessary and a lip on the aft of the projectile produced an adequate gas seal.

The ignition of the propellant at the nose tangency of the projectile led to the concept of an igniter afterbody attached to a non-igniting forebody. Nylon projectiles were used with various materials and geometric configurations attached to the base. An aluminum plug was glued

to the nylon projectile, but the aluminum broke loose at the glue line. In order to better attach the aluminum to the nylon, several configurations were tried in which the aluminum was made with a stem that was inserted through the nylon. When this was fired the aluminum pulled out, allowing the gases to vent through the resulting hole. Another configuration consisted of a number of small wires extending from the base of the projectile and bent to form a brush type of contact with the walls. Several configurations of holes, adhesives and wire shapes were used trying to prevent the separation of the wires during launch. However, none were successful.

Thermal Igniter - Two approaches were taken to solve the problem of using the projectile to ignite the propellant but 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. The projectile shown in Figure IV-2 is a thermal igniter. An igniter composed of black powder bonded with nitrocellulose is cast around the stem. Attempts to bond the traveling charge to the conical projectile base proved futile. The stem configuration proved more feasible. Several shots resulted in the stem being broken off by either the acceleration stresses or the more probable result of the burning of the traveling charge producing a high pressure between the base of the projectile and the charge which broke the stem. This is the type of failure that occurs in solid rocket propellant grains that are not properly bonded to the case.

The formulations of the black powder and nitrocellulose used methyl ethyl ketone as a solvent and frequently would shrink away from the projectile in addition to developing large internal voids. Improvement in the charge integrity was made by using less solvent and by using

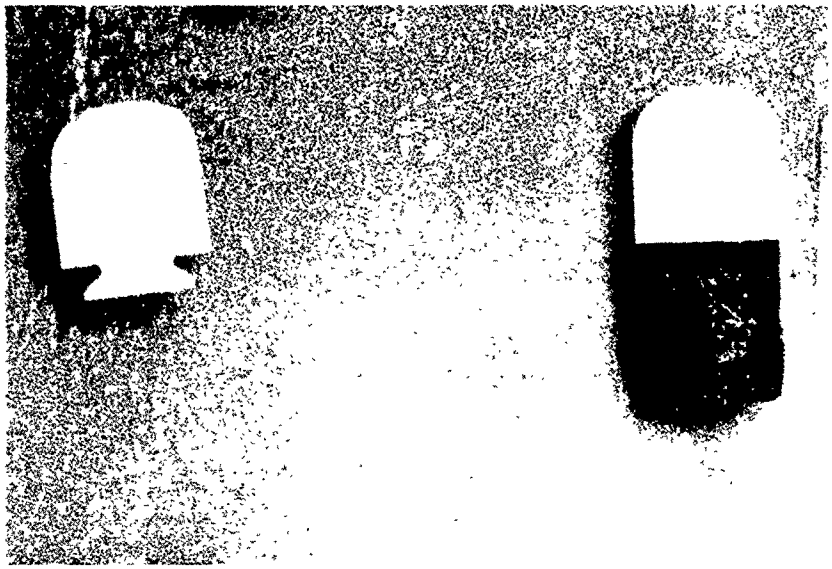

Figure IV.2 Thermal Igniter

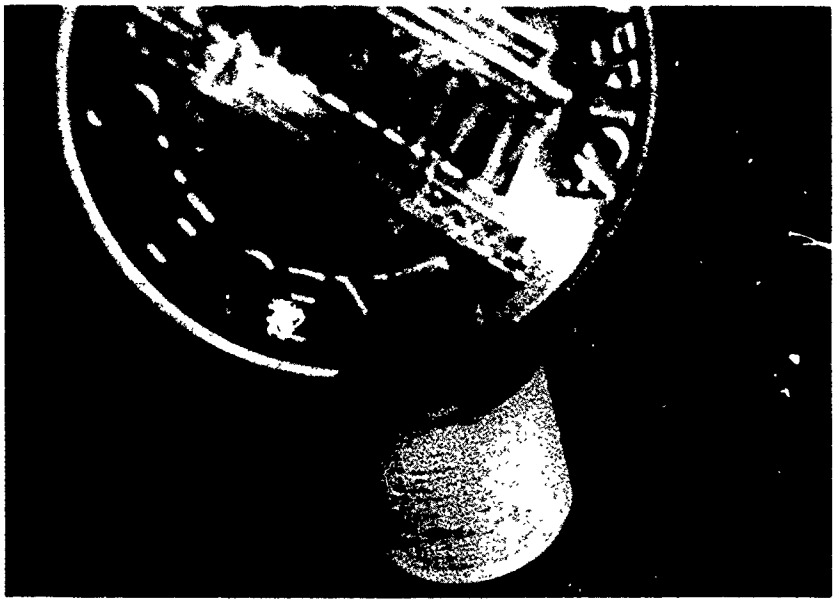

Figure IV.3 Recovered Thermal Igniter

pressure to force the mixture into the mold. Other propellant mixtures were used in the traveling charge such as, potassium nitrate, McCormick-Selph 164 and nitrocellulose. The various mixtures tried did not result in significant improvements in igniting the propellant lining.

The igniter is fired by the cartridge. A recovered thermal igniter is shown in Figure IV-3. 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 is probably insufficient to provide ignition without delay. An added advantage to the thermal igniter is that it supplies some gas on the base of the projectile moving at projectile speeds. It is continuously adding gas to the traveling reservoir.

Mechanical Igniter - Since the thermal igniter was thought to have a long ignition delay time and previous friction tests had indicated immediate ignition, it was decided to develop a projectile that would have a nylon forebody, as a gas seal, and to attach a metallic afterbody that would fire the propellant by friction.

Several of the configurations that have been tested are shown in Figure IV-4. A nylon projectile, a traveling charge and three projectiles using friction rings are shown. The designs were selected for their vibrational characteristics. Cantilever strikers were originally suggested, 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 ring configuration with its very high natural frequencies and limited deflection characteristics provide constant contact and ignition.

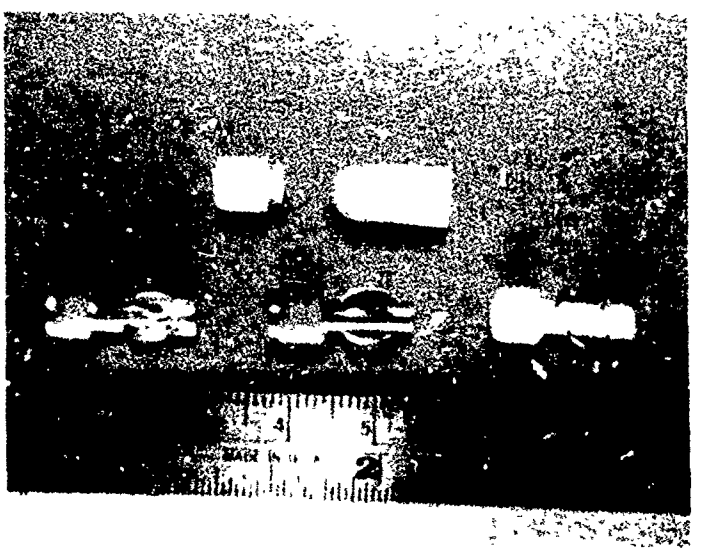

Figure IV.4 Various Projectile Designs

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 maximium stress of the material.

A search for better designs led to the configurations shown in Figure IV-5. These three designs indicated by analysis that they were stronger structurally. The concept was 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 the projectile. The three designs were fired in numerous tests. The configuration of Figure IV-5B proved most satisfactory. The pins of Figure IV-5C would wear down or break, or pull out of the hole. The design of Figure IV-5A proved difficult to manufacture although several were made.

Conclusion - The present status of the projectile design indicates the staple configuration to be the best. It has been suggested that a combination of the staple design and the thermal igniter be tried since both have distinct advantages. No attempt has been made as of yet to manufacture this type.

Propellant Requirements

The propellant used in the launch tube will have to meet certain specifications:

1. The propellant will have to be of a form to facilitate easy coating on the inner surface of the launch tube.
2. The coating must dry to be a smooth, uniform and continuous layer the entire length of the launch tube.

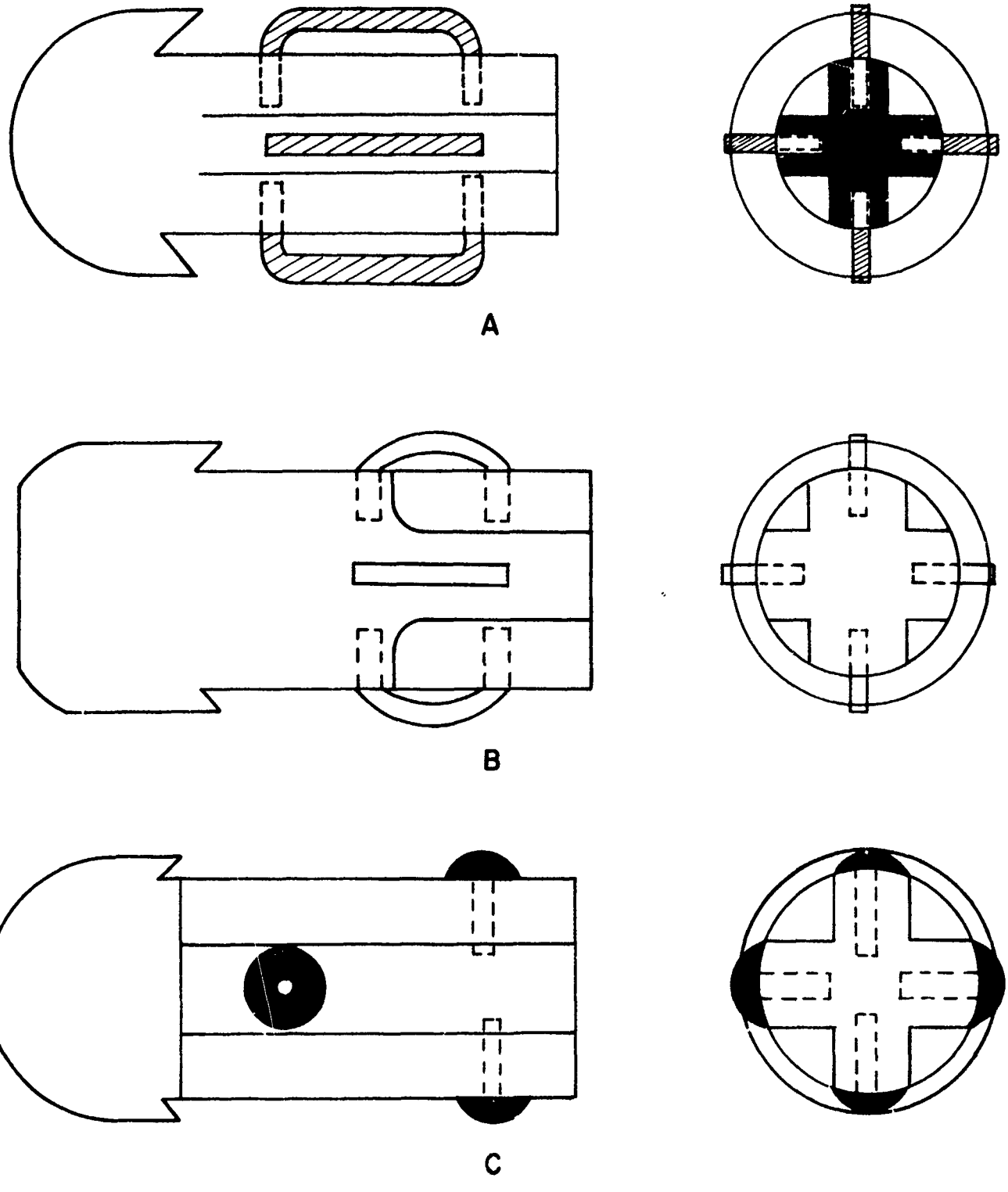

FIGURE IV - 5

PROJECTILE CONFIGURATION

3. The constituents of the propellant will have to lend themselves to being mixed together and being stored for a period of time.
4. The propellant must produce a large volume of gas for a small volume in solid form.
5. The production of the gas should be fast and efficient.

The ignition of the propellant must be accomplished by some method, which will initiate within microseconds after the projectile has passed over the reaction point. As a result the propellant could be ignited by the friction of the passing projectile or by some chemical, mechanical, or thermal igniter trailing the projectile.

The ideal characteristics of a propellant would be one that burns very rapidly without detonating. The rapid burning allows a rapid production of gas but without the problems associated with a detonation. A material which detonates not only produces a high pressure spike which causes structural damage to the tube walls but also can propagate ahead of the projectile if the projectile speed is slower than the detonation velocity. No previous literature had reported on materials that had burning rates between the slow speed deflagration or high rates associated with detonation. Propellants for the hypervelocity gun were developed with burning rates ranging from a 100 to 10,000 inches per second. The burning rate tests were accomplished after the end of the contract period but the report was delayed in order to include the results since this work was initiated under NASA funding. Testing was accomplished at two pressures. Atmospheric testing was used to develop the testing procedure and the initial formulations of propellant Because some tests with this propellant, used in a rocket fuel, had indicated great reductions in burning rate under a vacuum and because the lining is subjected to a vacuum prior to the passage of the projectile, tests were also accomplished under vacuum

conditions. The results of these tests indicated little or no change in burning rate as a function of the pressure change from atmospheric to vacuum regardless of the oxidizer system used. These tests have proven that high burning rate propellants can be developed and that this requirement for the operation of the hypervelocity launcher has been met. A complete report on the results of the propellant testing are included in Appendix A.

Experimental test apparatus was built to test various features of propellants, such as, impact sensitivity, friction sensitivity, heat sensitivity, and burning characteristic, which includes, continuity of flame, complete consumption of the propellant coating, normal burn rate and linear burn rate. Great depth of discussion is presented in Appendix A on the test equipment and experimental results.

Appendix A discusses the effects of:

1. Percentage of binder on burn rates.
2. Percentage of fuel-oridizer on burn rates.
3. Low pressure on burn rates.
4. Propellant curing time on burn rates.
5. Top coats on burn rates.

Ignition Testing - A friction testing device, discussed in the next section, was devised to study ignition. The propellant is coated on a plexiglass disc attached to an electric motor. The propellant is ignited by a simulated projectile held by a rocker arm and contacts the rotating disc with a known force. A high speed camera focused on the contact point and on a mirror, which reflects the view of the contact point on the opposite side of the plexiglass disc, photographs the ignition characteristics of the propellant. A film strip from a typical test is illustrated in

Figure IV-6. The camera shutter was open 67 microseconds with a frame speed of 250 microseconds for this test. Interpretation of these frames indicates that the propellant is igniting, so that it ignites both ahead and behind the striker and that it is occuring in less than 67 microseconds. This is the maximum time because neither the proceeding or subsequent frame has any burning recorded. Although the test was run at room temperature and pressure, the results should not be greatly different than for the propellant in the tube which is at room temperature and a vacuum when the projectile contacts it. The maximum velocity of this device was in the order of magnitude of 100 inches per second. Typical gun velocities, greater than 3,000 ft/sec or 36,000 in/sec can not be obtained with this concept.

Friction Testing - Since the coefficient of friction and the friction characteristics of the propellant were unknown a friction testing device was built. The device consisted of a plexiglass disc attached to an electric motor. A band of propellant was coated on the surface of the disc. An arm supporting a simulated projectile surface was then used to apply a controlled pressure to the propellant. Strain gages attached to the arm were used to determine the perpendicular and tangential forces applied to the propellant by the simulated projectile.

Through high speed photography it was hoped to examine the characteristics of ignition and burning rate. The camera was focused on the striker and a mirror that reflects the view seen through the plexiglass. The result were previously discussed under ignition tests.

The electric motor produced a maximum tangential velocity of 250 feet per second on the outer edge of the disc. Using a higher RPM motor and a large diameter disc to yield greater tangential velocities was not considered feasible due to the small incremental velocity increases versus

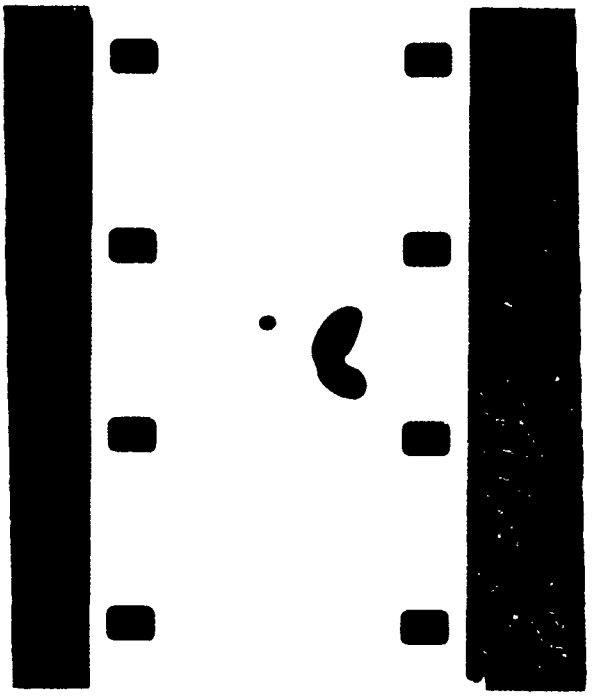

Figure IV.6 Frames of Movie Film of Ignition

the cost of the motor and structural capabilities of the plexiglass disc. Therefore, the coefficient of friction of various propellants was measured up to a velocity of 250 feet per second. The static coefficient of friction was measured first for various propellant mixtures. Then the disc was rotated to yield incremental velocities up to 250 feet per second. In theory the static coefficient is larger than the coefficient of friction between two moving surfaces. The coefficient should decrease parabolically to some asymptotic value provided there is constant contact between the two surfaces. The test data obtained matched this general description. The coefficient became asymptotic before the velocity between the simulated projectile and the propellant reached 250 feet per second. Since the velocity of the projectile in the launch tube could not be simulated, the coefficient of friction for velocities higher than 250 feet per second could not be determined, therefore the value of the coefficient of friction for projectile velocities was assumed to be approximately the asymptotic value obtained at the velocity of 250 feet per second.

V. Experimental Studies

The philosophy of the experimental studies was to advance the work in the laboratory along with the theoretical study. This approach was justified because of the great number of unknown parameters and propellant characteristics. Propellant testing and diagnostic equipment was developed to fill in the voids left by the theory. Very little has been written in the literature about thin film propellants, thus much time and effort was devoted to propellant testing, as described in the previous section. The diagnostic equipment was developed to aid in the study of the reaction within the launch tube. The projectile velocity measuring system could also be classified as part of the diagnostic equipment.

Diagnostic Equipment

Velocity Measuring System - For developmental studies an inexpensive accurate system of velocity measurement was desired that would also indicate projectile integrity. For these reasons a ballistic paper device was developed. Circuits were designed to provide the response time required for accurate measurements and are shown in Appendix B. The basic consideration was to eliminate capacitance from the circuits in order to reduce the RC time delay to a minimum. Three ballistic paper stations were used. The first station was used to trigger the oscilloscope and the other two stations were connected as switches to separate 6 volt batteries in order to indicate large voltage changes when the switches were opened.

For the preliminary tests it was considered necessary to use an oscilloscope to record the voltage changes in order to provide diagnostic information. For more accurate readings an interval counter was developed using integrated circuits in conjunction with decade frequency dividers.

The oscilloscope and the counter were used in conjunction and were found to be quite accurate and reliable. Later the counter was used exclusively, freeing the oscilloscope for other uses.

The ballistic pape_ _ting as yaw indicators have provided excellent information on projectile integrity and tumbling because the holes exactly outline the projectile shape.

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.[27] 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 B.

Two types of strain gages were employed on the launch tube: A foil type, SR-4, Type FAR-03G-12S9 and a semiconductor type, SPB2-12-10006. 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 Oscilloscopes 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 V.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 upward 0.1 cm, 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 gages 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 V-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 V-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 V-1. The pressure development is a runction 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 V-1 shows a jump in trace as previously discussed, whereas in Figure V-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 V-1 and V-2, the results

confirm the burning rate data. Figure V-1 shows a smaller slope with the slower burning propellant and Figure V-2 shows a larger slope with a faster burning propellant.

Discussion of Pressure Determination - 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 dynamics 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.

Interpretation of data recorded on the oscilloscope can yield information as to the ultimate base pressure on the projectile, an indication of the burning rate of thepropellant, the distinction between a projectile passing the station or a flame front passing the station, and the average velocity of the projectile between stations. See Figures V-1 and V-2 for interpretation pointers.

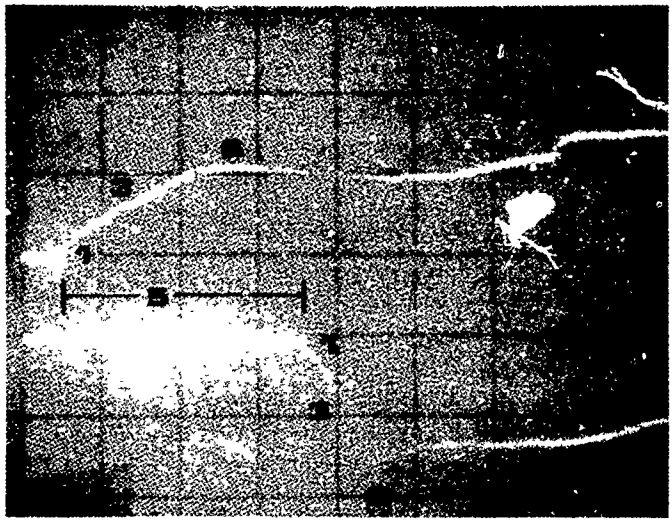

Figure V.1: Gage # 12 and 48 trace with 3 in/sec. burning rate propellant.

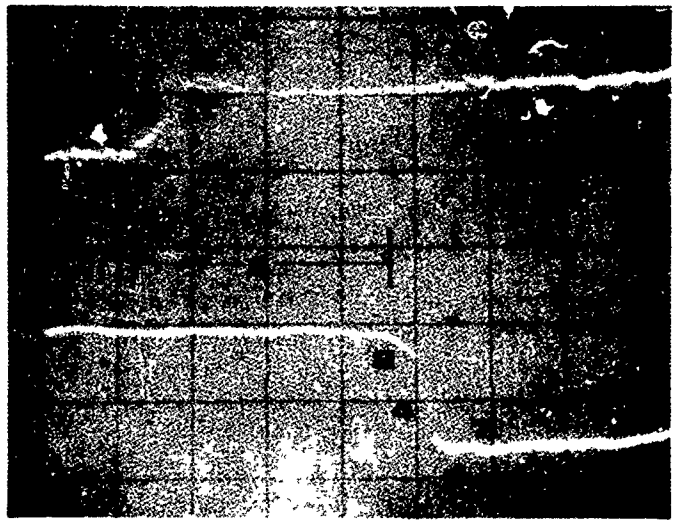

Figure V.2: Gage #12 and #48 trace with 30 in/sec. burning rate propellant.

1. Indicates base pressure on projectile
2. Rounding of trace indicates flame front proceeded projectile
3. Low slope indicates slow burning rate propellant
4. High slope indicates high burning rate propellant
5. Distance indicates average velocity of projectile between gage #12 and #48
6. Indicates ultimate pressure behind projectile
7. Thermal spike reaching strain gage

Experimental Apparatus

Launch Tubes - The constant base pressure concept was used as a design basis for selecting the tubing to be used for the launch tubes. A constant base pressure of 10,000 psi was desired for the .125 caliber tubes and 20,000 psi for the .25 caliber. The propellant lining may generate higher short time pressure as it detonates. A design pressure of 50,000 psi was used to select the tubing thickness. A low carbon steel was chosen that would exhibit good yield characteristics under impact loading. This should provide a safer deformation of the tube due to overpressures rather than the shattering that would be expected from higher strength, less ductile steels. The .125 inch tubes were chosen from Shelby, round, seamless, steel, mechanical tubing - cold drawn AISI-MT-1015 with a nominal inside diameter of .122 inch and a wall thickness of .095 inch. The .25 inch tubing was the same specification with a nominal inside diameter of .250 inch and a .188 inch wall thickness. The steel has a tension ultimate strength of 75,000 psi and a tension yield of 55,000 psi with a 30% elongation in a 2 inch gage length.

Launch System - The projectile is inserted in the adapter section which connects the trigger system to the launch tube. The projectile is held in

place by scotch tape to provide both a vacuum seal and a low pressure rupture disc. The initial velocity and pressure is provided by the use of industrial type power loads containing a nitrocellulose base propellant. Firing of the cartridge is performed by the trigger system of a .22 caliber rifle modified to fit the adapter.

Impact Attenuation - The impact chamber can hold several types of targets such as honeycomb and aluminum plates. This chamber has a vacuum pump to reduce the pressure both in the chamber and the launch tube. The propellant gages are discharged into the vacuum to reduce the effect of the blast. To aid the reduction of the blast effect an expansion chamber is attacted to the front of the impact chamber. The expansion chamber contains a flapper valve which is deflected into the line of flight by the gages trailing the projectile. The purpose of the valve is to protect the velocity measuring stations in the impact chamber from the jet of gas trailing the projectile.

In order to provide a measure of the impact energy and to provide recovery of the projectiles, blocks of honeycomb were used. The layers of foil act as multiple sheets to slow the projectile and capture it. The use of 1.5 mil foil honeycomb was very effective for capturing the projectile intact and relatively undamaged at velocities below 6,000 feet per second. Half inch aluminum plate was also used as impact targets. In this case the energy of the projectile could be ascertained by the depth and diameter of the crater left in the aluminum.

Application of Propellant Lining

An important part of the research was to develop the techniques to apply uniform smooth layers of propellant to the internal walls of the launch tubes.

Early attempts to build up thick layers of nitrocellulose invariably resulted in the lifting or peeling away from the walls after five or six coats had been applied. The thickness that could be built up with nitrocellulose and nitrocellulose aluminum mixtures were between .5 and 1 mil per layer. When the thicker materials containing a larger percentage of solids, such as the perchlorates or RDX, were applied to the tubes it was possible to achieve 1 to 2 mils per layer. When polyrinylchloride was used as a filmogen it was possible to achieve greater thickness per layers and thicknesses up to 15 mils were successfully achieved.

The critical parameter in forming a smooth, uniform thickness layer is the selection of the proper coating plug, geometry, and configuration. Various shapes of coating plugs were tested. It was found that the most efficient shape was a rounded nose plug. The use of a sharp pointed plug seemed to invariably result in irregular deposition on the surface. The diameter of the plugs were chosen to be approximately 10 mils less than the diameter of the tube and reduced in diameter as the thickness built up on the walls. The use of longer plugs (L/D greater than 2) were more effective than the shorter plugs (L/D equal to 1). Apparently the longer plug allows a more uniform flow of material around the plug resulting in a more uniform layer on the walls of the tube.

The propellant is inserted into the tube through the use of a syringe. The coating plug is then inserted behind the propellant and blown through the launch tube with compressed air. The plug was found to center itself in the tube after one or two inches of travel. Coating from opposite ends of the tube each time smoothed the ends out adequately.

The drying process consisted of removing the solvent from the plastic mixture. The solvents that have been used are n-butylacetate, methyl ethyl ketone and acetone. One method of obtaining very rapid drying is to apply

a vacuum to the tube and vacuum dry the solvent. The other is to use an air blowing technique and flow low velocity air through the tube. Generally the vacuum drying technique is more successful and will normally obtain a hard finish in twenty to thirty minutes. The air drying technique usually requires forty to sixty minutes to completely extract the solvent.

Inspection

Inspection of the launch tube is performed after each coating of propellant. The tube is visually checked by shinning a light through it. It is checked for an uneven surface which would indicate peeling. Shadows in the tube indicate a low place in thepropellant coating. Bumps or grains of propellant are also checked. Any of the above blemishes would result in removing the lining and beginning the coating process again. The propellant thickness is measured after each coating with a micrometer and recorded.

Cleaning Launch Tube

Each type of propellant residue requires a different cleaning technique. The many cleaning techniques include: ram rod and brush, ram rod and cotton swab, swab blown by air, MEK, Butylacetate, acetone, water, rust remover and mild acid. It was found that the best combination for cleaning nitrocellulose base propellants was soaking tube in MEK, ram rodding cotton swabs through it and then blowing cotton swabs (moisten in MEK) through it. For the polyvinylchoride base propellants water would remove the propellant residue, and then a few cotton swabs blown through it would finish the job. Great care was taken in making sure no specks of residue were left in the tube. The specks were disastorous in coating. They caused at least bumps in the coating and generally the coating would peel at dirty spots. The tubes were also inspected during the cleaning operation for deformation or scares.

VI. Experimental Results

Experimental results have indicated that high pressure can be generated in a launch tube as a result of the ignition of the liner. Velocities which are above those that would be achieved in an unlined tube have been obtained.

Work on the hypervelocity accelerator was begun in the Summer of 1966. During the course of the summer months the accelerator was designed and a prototype was built. The first system was only a test system, however it proved the velocity could be increased by the use of a propellant lined launch tube. Since much of the work was done in an unknown region where theory has not been developed as yet, much experimentation was done by trial and error. The propellant selection was the greatest of the stumbling blocks to overcome. However, it was decided that the only way to overcome this obstacle was through experimentation.

Experimental test shots were begun in September 1966 with a .125 caliber projectile. The initial test were unlined tubes and were used to check out instrumentation. Velocities obtained from an unlined five foot tube were found to be in the range of 3,200 feet per second. Several lined shot were fired during November and December, however the instrumentation was faulty and unlined shots were continued until April when the velocity instrumentation and triggering system became more dependable. During the Summer months of 1967 many types and combinations of propellant mixtures were tested. By the end of the summer several propellant

mixtures were judged to be acceptable as a basis to work from in refining the propellant compound. Those judged to be acceptable were ammonium perchlorate and potassium nitrate base with a nitrocellulose filmogen.

The next step which was carried out through the remainder of 1967 and into 1968 was to determine what percentages to mix the ingredients of the propellant and test additives which would increase sensitivity or gas production. It was at this time that it was realized a greater coating thickness was desirable, therefore the decision was made to increase the caliber to .25 inches. This also made the manufacturing of projectile somewhat easier. With the .125 caliber tube the greatest coating thickness feasible was 4 mils, however with the .25 caliber, coating thicknesses of 15 mils have been obtained.

During this time the tube coating operation was perfected and propellant test equipment was designed. During 1968 a diagnostic system was designed and built to determine the pressure in the launch tube behind the projectile. It has been determined through the use of the diagnostic system that for a 10 mil propellant thickness, pressures of 15,000 to 20,000 psi can be developed.

One of the greatest advances during 1968 was the results of the burning rate tests. It was found that burning rate greatly depended upon the thickness of the propellant coating. Further, it was found that nitrocellulose retarded the burning rate of ammonium perchlorate and potassium nitrate. A search was then begun for a better filmogen. This was found in polyvinylchloride. This filmogen not only increased the burning rate but also made the tube cleaning operation faster. The burn rate test indicated when McCormick-Selph, a commercial proprietary explosive, was added to the mixture the propellant exhibited burning rates between slow deflagration and detonation of the previously used

propellant. The burning rate depended upon coating thickness, however for 10 mils the burning rate was in the order of 1000 inches per second.

Propellant friction tests and ignition tests were also developed during this time. These tests were not as refined as the burning rate tests and the data is somewhat rough. This is mainly due to the fact that no precise friction or ignition test has been developed by explosive experts.

During 1969 the greatest thrust was made in perfecting the propellant and the design of the projectile. Many projectile designs were tried during the course of that year. The design judged most adequate was principally made of nylon with staples implanted in the aft portion.

The summary of test results are listed in Appendix C. Shots fired for instrumentation check out have not been listed. The listing for each shot gives all the pertinent information that was obtainable.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the research completed to this date, it is concluded that the propellant lined hypervelocity accelerator and the explosively driven accelerator proposed by Physics International are the only current research projects that have promise for providing a breakthrough to achieve greater velocities than the present limited velocities of light gas guns. The research developed methods of providing an internal coating of a launch tube with a fast-burning gas-producing propellant and demonstrated that these techniques could be used for laboratory experiments very readily. A combination of binder and propellant was formulated that would provide a rapid burning internal lining for the launch tube. The major parameters that control the characteristics of the internal propellant lined launch tube were identified and each parameter was controlled experimentally with the exception of the friction ignition system. Because of the experimental difficulty in obtaining relative velocities it was necessary to test the friction ignition system using the launch tube itself. This particular part of the experiment was not adequately instrumented to directly determine the properties. However, studies were made of the friction characteristics at lower velocities.

It was determined that the satisfactory operation of the internal lined propellant launch tube required both the ignition of the propellant immediately behind the projectile passage and the rapid release of gas from the propellant

lining. The initial testing did not have the rapid gas formation characteristics that were developed only during the last few months of testing. The final tests were run during a period of insufficient funding to allow the proper instrumentation and therefore it was not determined whether the gas pressure was adequate or whether the ignition was the reason for failing to achieve desired velocities.

Techniques were developed for instrumentation of the launch tube that allowed an examination of the pressure build up as the projectile passed a given point which could be interpreted diagnostically to evaluate the various parameters. The theoretical investigations indicated that simple one-dimensional or two-dimensional finite difference simulation of the launch tube was not adequate for determining the dynamics of the gas with injection from the wall and jetting occurring at the centerline. A simplified piston theory indicated that the concept had sufficient merit to continue with development. The theoretical work also indicated the need for a better understanding of the mixing characteristics of gas being produced at the innersurface of the launch tube.

It is recommended that this study be continued using two thrusts. One, a better analytical model of the gasdynamic process should be developed either by establishing the mixing characteristics of the boundary between the gas produced from the lining or examination of the problem with a solid thin lining that would form a definite boundary between the gas produced at the wall and the gas in the tube of the liner. The liner approach is a modification of the idea proposed by Physics International of an explosively collapsed tube with the major variation resulting from the fact that the

projectile acts as a timing device for the ignition of the propellant reaction. The experimental research should be continued in order to determine other parameters that are not apparent in mathematical models. It appears to be the only way in which the velocity associated with ignition can be generated in order to study the ignition phenomenon.

The purpose of this research is to provide this nation with the capability of simulating hypervelocity. At the present time simulation of meteoroids of greater than micron size are impossible because of the inability to achieve meteoroid velocity. Also the study of high pressure physics is hampered until such a capability is developed. The major advantage of the propellant lined launch tube is that it provides for a more efficient utilization of the explosive energy within the launch tube making the devices much more suitable for laboratory work.

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Appendix A

An Investigation of the Burning Rates of Thin Films of Some Selected Composite Propellants

AN INVESTIGATION OF THE BURNING RATES OF THIN FILMS OF SOME SELECTED COMPOSITE PROPELLANTS

REPORT HVL -70

Prepared by

MILES LEE SAWYER

Final Report Covering the Period
4 February 1967 Through 10 July 1970

Prepared for

HYPERVELOCITY ACCELERATION LABORATORY

Department of Aerospace Engineering

Texas A&M University

This research was supported in part by
NASA Contract NAS-9-6812 from the Manned Spacecraft Center
Houston, Texas

29 July 1970

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August 1970

APPROVED:

Dr. Charles A. Rodenberger
Principal Investigator
Hypervelocity Acceleration Laboratory

ABSTRACT

An Investigation of the Burning Rates of Thin Films of Some Selected Composite Propellants. (August 1970)

Miles Lee Sawyer B. S., Texas A&M University

Directed by: Dr. Charles A. Rodenberger

This paper is the presentation of the results of research done on burn rates of thin films of some solid composite propellants for application in the Hypervelocity Acceleration Laboratory's propellant lined launch tube.

The chemistry of the propellants generally included a binder, explosive materials, and oxidizer materials. Binders tested included solvent dried nitrocellulose and polyvinyl chloride. Suspended in these binders were mixtures of explosive materials such as RDX, PETN, lead azide, and McCormick-Selph monopropellant (designated as 300,104 and 510,164), and oxidizers such as ammonium perchlorate, potassium chlorate, and potassium nitrate. The propellants studied were in thin layers of from 0.001 inches thick to 0.032 inches thick which were restrained on one surface and tested at both vacuum and atmospheric pressures.

Propellant film thickness was the primary parameter investigated. The effects of vacuum and atmospheric pressures, change of oxidizers, change of binder percentage, top coats, and curing time on the burn rates of the propellant films were also investigated.

Burn rates reported range from 10 inches per second for film

thicknesses of less than 0.005 inches to over 10,000 inches per second for thicknesses of 0.030 inches.

It was found that burn rates of thin films of the propellants which were tested generally increased with propellant film thickness. Propellant age, curing time, or the changing of the test pressure from one atmosphere to a vacuum apparently had no effect on the burn rates. Top coats of nitrocellulose and polyvinyl chloride (in combination with aluminum dust) increased burn rates but not substantially.

ACKNOWLEDGEMENTS

The author wishes to thank Professor A. E. Cronk and Mr. T. A. Noyes for providing their professional guidance when needed and Mr. W. M. Adams who provided both technical and creative services in the development of the electronic instrumentation for this research. A special thanks is offered to Dr. C. A. Rodenberger not only for serving as Committee Chairman but also for providing the author with professional guidance and an opportunity to work and learn throughout most of his college career.

The author would also like to acknowledge the encouragement given him by his parents, his wife's parents and, of course, his wife without whose help this thesis would probably not have been written.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A,B	Functions of heating rate and diffusional mixing rate for Fenn pyrolysis rate equation.
d	Propellant film thickness (FIG 11)
n	Unknown parameter in Fenn pyrolysis rate equation
p	Absolute pressure (atmospheres)(FIG 5)
p.s.i.a.	Pounds per square inch absolute
p.s.i.g.	Pounds per square inch gauge
r	Pyrolysis rate of propellant specimen
r_L	Linear burn rate of propellant film restrained on one surface
A/PA	Ammonia/Perchloric Acid
AL	Aluminum
Atm.	Atmospheres
BA	Butyl Acetate
C	Carbon
G	Glass
HMX	Cyclotetramethylenetetranitramine
L.A.	Lead Azide
Mc/S	McCormick-Selph
MEK	Methyl Ethyl Ketone
NC	Nitrocellulose
O/F	Oxidizer/Fuel

x-104,x-164	McCormick-Selph material 300,104 and 510,164
PETN	Pentaerythritol Tetranitrate
PVC	Polyvinyl Chloride
RDX	Cyclotrimethylenetrinitramine
ST	Steel powder

INTRODUCTION

General

The primary purpose of this study is to investigate the burning properties of a thin film of propellant for application in an hypervelocity accelerator of the type described by Dr. Charles A. Rodenberger.[1] This accelerator makes use of a thin layer of explosive propellant for a major part of its energy input.

In the accelerator the projectile is blown into an evacuated, propellant lined tube at some initial velocity. The projectile, by either chemical or mechanical means, ignites the propellant lining as the projectile passes over the propellant surface. The reaction of the propellant generates high pressure gases which maintain a high pressure against the base of the projectile and accelerates the projectile down the tube. The velocity of the projectile then is a function of how well the projectile can utilize the energy released by the thin film of propellant, and how fast and in what form the propellant releases this energy.

The efficiency and successful operation of this hypervelocity concept is very dependent on the reacting characteristics of the propellant liner. These characteristics include ignition sensitivities and burn rates of the thin layer of propellant exposed to vacuum

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The citations on the following pages follow the style of the AIAA Journal.

conditions.

The propellant liner itself is one or more layers of a composite propellant (oxidizer, explosive, and binder) coated onto the inner walls of the accelerator launch tube. Therefore, it is restrained on one surface (where it is bound to the tube walls) and free on the opposite surface.

The required burn rates of the propellant liner have been estimated by considering the thickness range of the propellant liner, and the required velocity of the projectile. According to Dr. Rodenberger[1]:

> . . .To obtain some indication of the required characteristics of the propellant the problem was examined of a propellant .020 inches thick ignited one caliber behind a .250 inch projectile traveling at 100,000 feet per second and with the assumption that the reaction of the propellant was completed in eleven calibers. This would result in a required reaction rate for the propellant of 250 meters per second.

Therefore the required burn rates of the thin layer of propellant restrained on one side in the tube would be around 10,000 inches per second.

This burn rate range lies above the range of burn rates which are considered to be normal deflagration rates. It also lies below that range normally considered as detonation. Brown[35] in surveying literature and research covering the burn rate range intermediate between deflagration and detonation has stated:

> Deflagrations are burning phenomena whose propagation rates are controlled by transport processes and

> by chemical kinetics. They are characterized by the dependence of the linear burning rate on the ambient pressure, and their reaction rates are low compared to those of detonation. In the condensed phase, propagation rates in void-free materials range from a fraction of a centimeter per second to about 12 centimeters per second at 1000 p.s.i.
>
> Detonations are reactive wave phenomena whose propagation is controlled by shock waves. Theoretical analyses assume that reaction rates are essentially infinite and that chemical equilibrium is obtained. Therefore, the actual propagation rate is considered to be governed solely by thermodynamics and hydrodynamics. The propagation rates of detonations are orders of magnitude higher than those of deflagration, i.e., thousands of meters per second.
>
> There is a gap of several orders of magnitude between the propagation rates of conventional deflagrating explosives such as black powder or double base propellants (cm. per second) and conventional detonating explosives such as TNT or RDX (thousands of meters per second).

It appears then that research directed toward finding a propellant coating for the hypervelocity accelerator with burn rates suggested by Dr. Rodenberger will also be research on propellant burn rates which have not been previously reported for any application.

Since this is the case, the objective of this report will be to present experimental data on some solid composite propellants with burn rates intermediate between deflagration and detonation. The major emphasis will be placed on application to the propellant liner for the hypervelocity accelerator.

Although this report will be on experimental research, the literature on burn rate theories will be reviewed mainly to point out the inapplicability of these theories to intermediate burn

rates. However, some of the assumptions made for the theories may aid in the investigation of these propellant burn rates.

Previous Burn Rate Research

There have been many studies of burn rates of composite propellants but none report burn rates in the range of 10,000 inches per second and none of the previous research was conducted on thin strips of propellant constrained on only one side. Some of these previous studies include:

1. A study[2] of ammonium perchlorate-based propellant in unrestrained rectangular strands with burn rates of from 0.01 inches per second to 3 inches per second.
2. An examination[3] for particle size effects of cylindrical samples of sodium nitrate-based flare compositions with burn rates of about 0.2 inches per second.
3. An investigation[4] for effects of strong mechanical tension on flexible rubber sheet explosives (0.032 inches to 0.10 inches in thickness) with detonation rates in the neighborhood of 7000 meters per second (280,000 inches per second).
4. An investigation[5] comparing "loose-granule" tests to "porous plug" tests using ammonium perchlorate-based propellants enclosed in cylindrical tubes and producing burn rates of from 0.02 inches per second to 0.14 inches per second.
5. An investigation[6] of the effects of several catalytic surfactants on polyesobutene/ammonium perchlorate propellants with strand burn rates of from 0.26 inches per second to 2 inches per second under pressures ranging from 200 p.s.i.g. to 2000 p.s.i.g.
6. An investigation[7] of compressed sheets (thickness of from less than 0.01 centimeters to 0.05 centimeters) of several solid explosives such as PETN, RDX, and lead azide with detonation rates of from 1000 meters per

second (40,000 inches per second) to 5000 meters per second (200,000 inches per second).

These previous experiments have reported on burn rates of several types of propellant samples such as strands, solid cylinders, and some thin films, either completely restrained or unrestrained. There is a definite lack of information available for propellant formulations in thin films restrained on only one surface and having burn rates between 3 inches per second[2] and detonation velocities of 40,000 inches per second.[7]

The research mentioned in this section and some other experiments on burn rates will be reviewed more thoroughly in the literature survey.

Theories of Burning and Detonation

There are several theories of propellant burning and detonation mechanisms from which burn rate predictions are derived. These mechanisms are discussed in detail in the literature survey. These theories base their predictions on assumptions of the size of the reaction zone, the mechanism of propellant decomposition and mixing, and temperature and pressure gradients in or near the reaction zone.

The theoretical studies of propellant reactions generally predict the effects of initial temperature and pressure on burn rates. The theories also give a general view of the effects on non-homogeneity and non-uniformity of propellant composition on propellant burning.

The burn rates predicted by these theories are for high pressure situations. That is, most of the burn rate equations derived are only good for pressures above several atmospheres, which are well above the pressures of the surroundings of the propellant liner before ignition. Steinz, Stang, and Summerfield[2] have developed a numerical method of predicting the burning rate of ammonium perchlorate-based propellants for pressures below one atmosphere but it is complicated and does not intuitively apply to any other than ammonium perchlorate-based solid propellants.

The theoretical equations predict very low burn rates (less than three inches per second) for the propellants they are derived for. These burn rates are well below the range required in the hypervelocity accelerator tube lining. Using the same chemical reaction times and gas diffusion times as presented for the certain chemical formulation in question, the pressure required for burn rates of several hundred inches per second would be in the thousands of atmospheres according to the equations given for burn rates.

This report will present an experimental study of thin films of some solid composite propellants which yield burning rates in the range from 3 inches per second to 10,000 inches per second in pressures at and below one atmosphere.

REVIEW OF THE LITERATURE

General

Most literature available on solid composite propellants has been written for application to solid rocket propellant motors. The specimens tested have been liquids, completely restrained films, completely unrestrained specimens, relatively large solid cylindrical specimens, and some specimens of loose constituents. Burn rates recorded generally fall into categories below 3 inches per second or around detonation velocities (about 200,000 inches per second).

The theoretical research has generally centered around ignition characteristics or the kinetics of the reaction after ignition. This includes studies of flame thickness, temperature, and size and nature of the reaction zone.

Although the burn rates reported are not in a range of burn rates required in the hypervelocity accelerator liner, the literature may yield important relations which will lead to the generation of a fast burning propellant film. The literature may also predict the effects on the burning rate of the propellant liner that results from changing from atmospheric conditions to vacuum conditions in the propellant environment.

It will be important to note in the following section that both theoretical and experimental work, with the exception of part of Steinz, Stang, and Summerfield's research[2], is for high pressure situations (above several atmospheres) and, except for McCormick-

Selph's work with fuse materials, is for low deflagration rates (below 3 inches per second) or for rates associated with detonation (above 40,000 inches per second). This leaves a gap in the knowledge of composite propellants which burn in the range intermediate between deflagration and detonation, especially at pressures less than one atmosphere. Also there is no literature available on burn rate tests of thin films of propellants restrained on only one side.

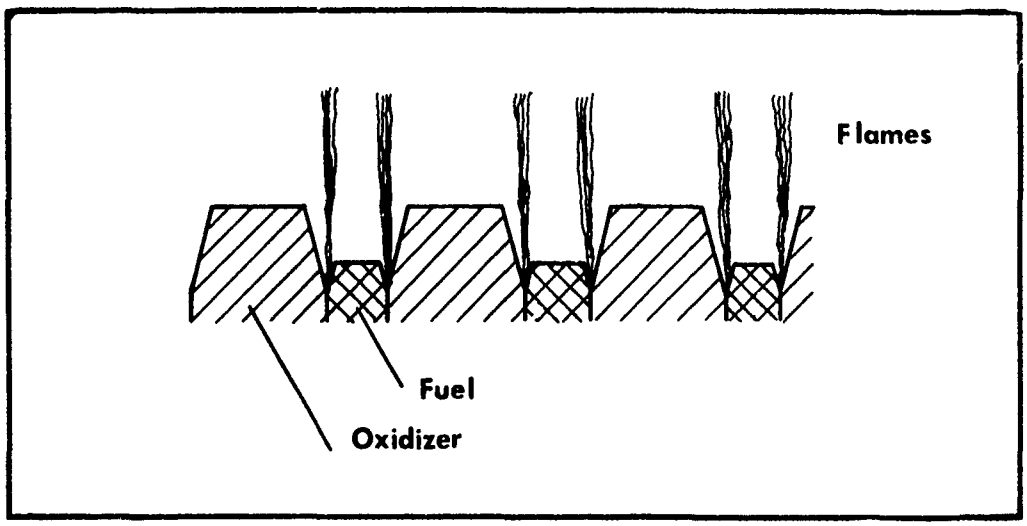
Theories of Solid Propellant Burning

Columnar Diffusion Flame Model

General. In general this theory describes the flame of burning propellants as one in which the fuels and oxidizers are not premixed. It is the type of burning which occurs in the flame of a lighted candle, in the burning of a pan of oil in air, or in the burning of a fuel droplet in oxygen in a rocket motor.[18] (See FIG 2 and FIG 3)

Rice.[20] In 1945 Rice proposed a diffusion flame model assuming that the flame occurred at an interface between the fuel and oxidizer (FIG 1). Rice neglected finite reaction times and assumed that the flame was columnar (not layered) with respect to the propellant surface. This model correctly predicts the effect of particle size on the burn rate but does not predict pressure effects.[2]

Nachbar.[21,22] Nachbar developed a simplified revision of the diffusion flame model by assuming that the propellant specimen consisted of layers of fuel and oxidizer. Nachbar's calculations for burn rates are also independent of pressure.



Rice Model of Diffusion Flame [26]

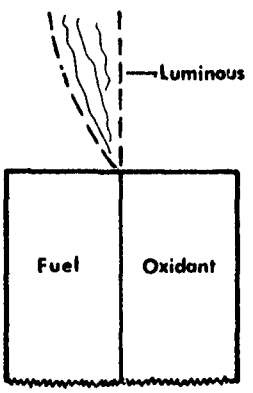
FIG 1

Thermal Layer Theory

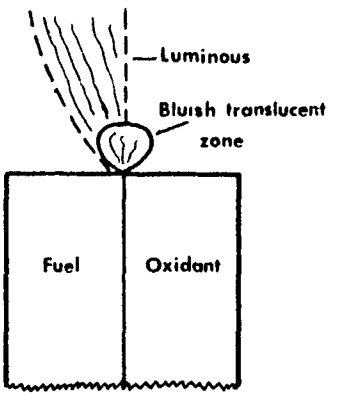
This theory was first proposed by Chaiken[23,24] in 1959 (FIG 4). The original proposal was that the burn rate was linearly dependent on pressure but was not affected by fuel type or fuel-oxidizer ratio. Chaiken attempted to correct this fault[24] by the addition of two variable mixing factors. This complicated the problem since a burn rate cannot be calculated without the knowledge of the values of these two factors. The factors cannot be derived from fundamental principles but must be deduced from experimental evidence.

Crack Theory

Irwin, Salzman, and Anderson[25] proposed that small cracks in the oxidizer surface of solid composite propellants seriously affected the

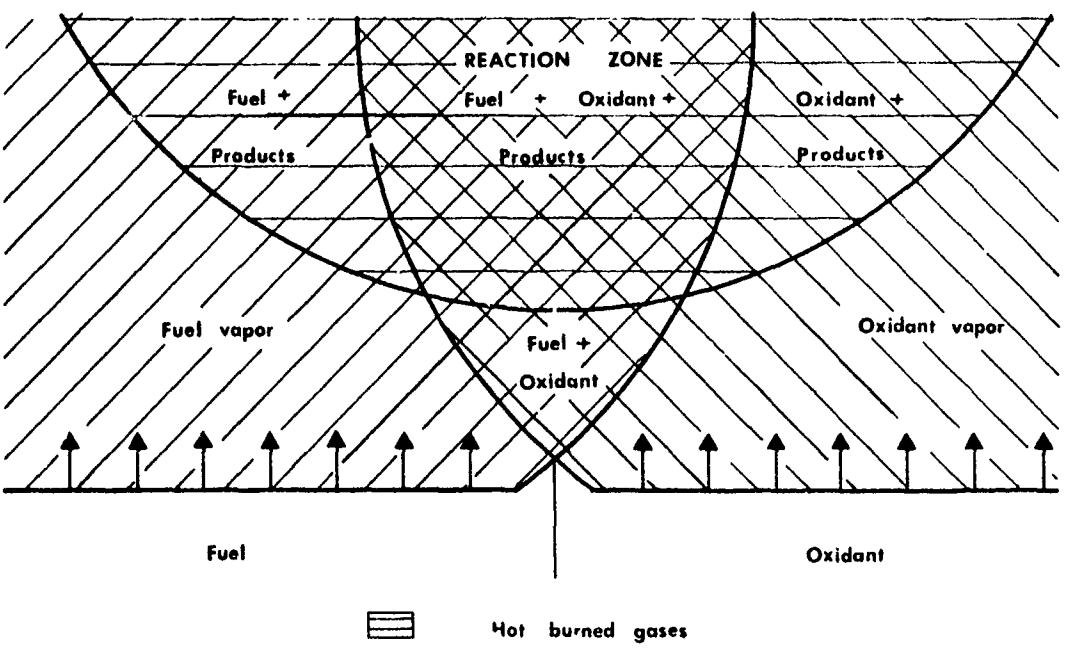


Schematic representation of a two-dimensional diffusion flame at high pressure[27]



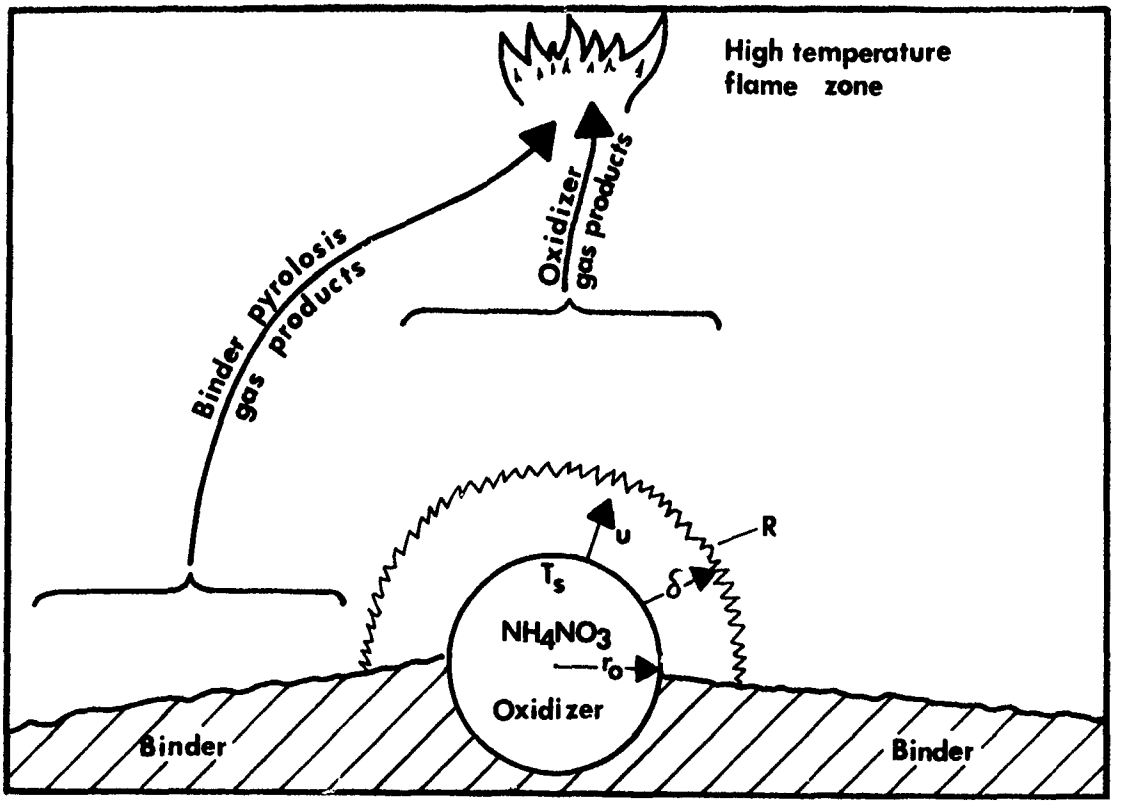
Schematic representation of a two-dimensional diffusion flame at low pressure[27]

FIG 2



Compositional structure of a diffusion flame[27]

FIG 3

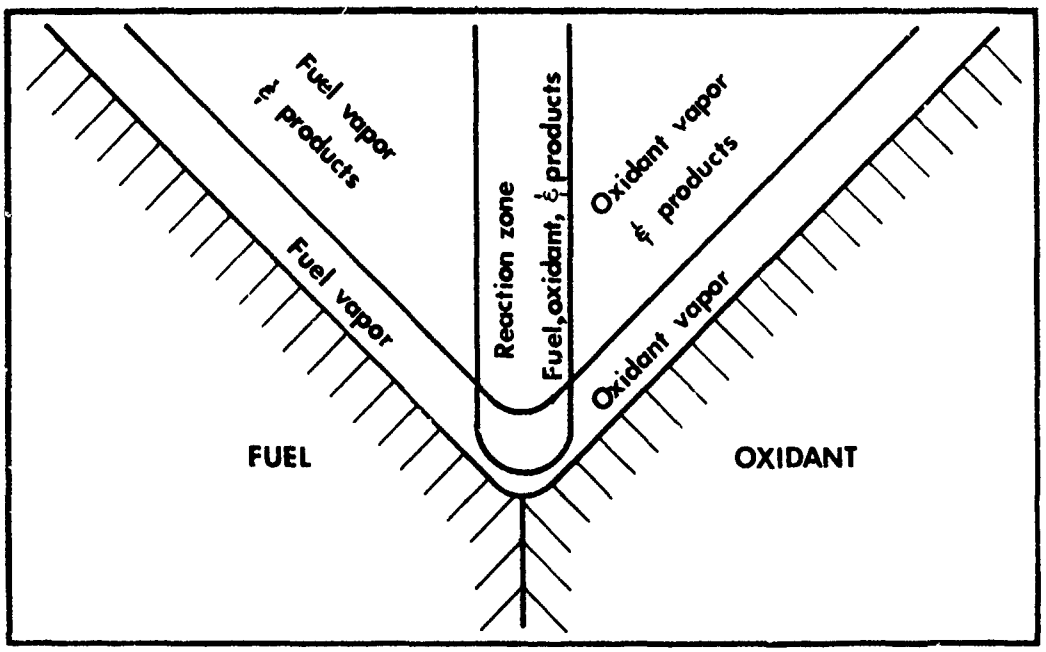


R = Redox reaction flame zone
u = Gas velocity
δ = Thickness
T_s = Surface temperature of oxidizer particle
r_o = Radius of oxidizer particle

Thermal Layer Model of Combustion of a Solid Composite Propellant[23]

FIG 4

burn rate. Under high pressures where the cracks might widen it was theorized that the increased oxidizer surface area would increase burn rates. The causes of these cracks would be the thermal stresses due to the steep temperature gradient in the solid phase at the high pressures. This theory has not been verified experimentally.



Compositional Structure of the Phalanx Flame Model[27]

FIG 5

Phalanx Flame Model

This model (FIG 5) proposed by Fenn[27] has a gas-phase fuel-oxidant flame which exists immediately above the interface between the solid fuel and solid oxidizer surfaces.

The flame stand-off distance is assumed to be a function of the diffusional mixing rate and the reaction rate. The reaction itself is assumed to be sustained by conductive heat transfer through the gas phase.

The burning rate equation derived is

$$\frac{1}{r} = \frac{A}{p} + \frac{Br}{p^{n/2}}$$

where n is some unknown parameter which is arrived at by experiment.

The theory itself is dependent on the assumption that small crevices exist at the interface between fuel and oxidizer. According to Fenn, these crevices are caused by the high temperature in the reaction zone which causes the reaction zone to "bore" into the propellant surface. Hightower and Price[28] have observed experimentally that these crevices probably do not exist.

Powling Model

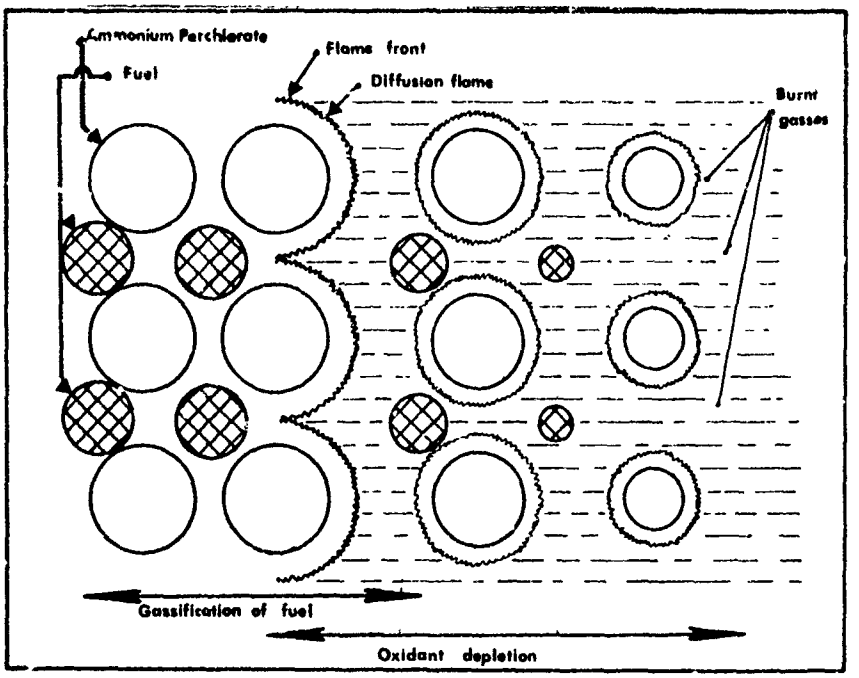
A two-phase reaction for ammonium perchlorate-based propellants was described by Powling[26,29] after he reviewed much of the theoretical and experimental work in the literature (FIG 6).

The first stage according to Powling's theory is a premixed reaction between two primary products of the decomposition of ammonium perchlorate--ammonia and perchloric acid. The second stage is a flame stage with an unmixed reaction between the fuel vapors and the first stage products. Therefore, the assumption that the mixing is diffusional plays a major role in this theory.

Powling's theory does not explain why fuel and oxidizer particle size affects burn rates at low pressures. However, it does provide a possible explanation for some of the burn rate phenomena peculiar to propellant burning at low pressures.

Granular Diffusion Flame Theory

The granular diffusion flame model is a model based on the

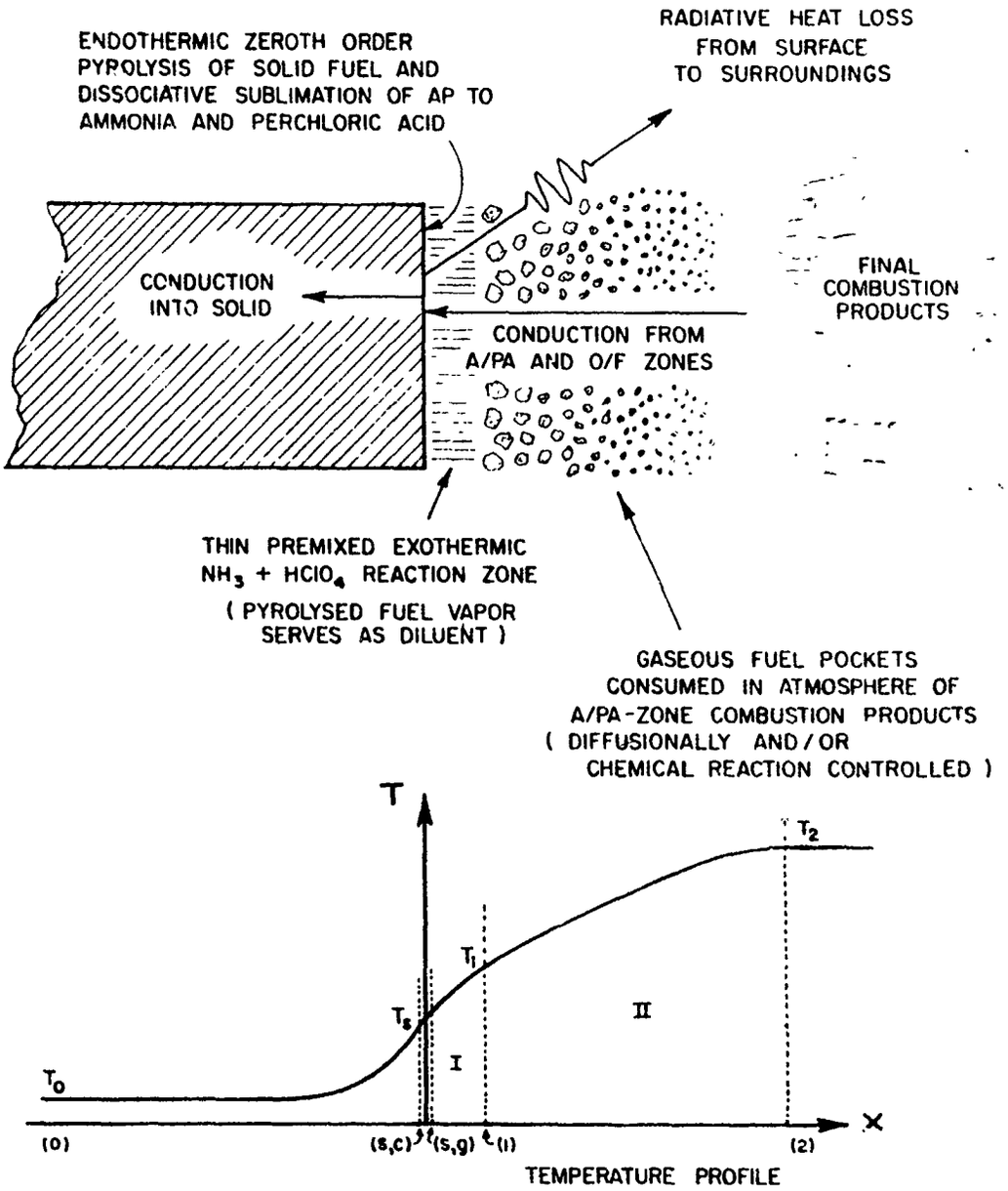


Schematic of Combustion Process of Ammonium Perchlorate According to Powling[26]

FIG 6

Powling theory which has previously been discussed. This model assumes that there are three stages in the decomposition and reaction of the composite propellant (FIG 7). The first is a solid to gas phase where the solid propellant either sublimes from the propellant surface or melts and then gasifies. The next two stages are the premixed ammonia and perchloric acid reaction and the fuel-oxidant reaction as described by Powling for an ammonium perchlorate-based propellant.

This theory is valid in its assumptions for the 2-100 atmospheres range but must be modified for low pressures. In 1969,



TWO-STAGE GRANULAR DIFFUSION FLAME MODEL FOR AMMONIUM PERCHLORATE-TYPE COMPOSITE SOLID PROPELLANTS[2]

FIG 7

Steinz, Stang, and Summerfield[2] undertook to modify the theory to fit sub-atmospheric burn rate data. Their distended flame theory[2] takes into account the variation in surface temperature with pressure.

The experimental work will be reviewed in the following section. The data taken seems to substantiate their revised theory.

Previous Experimental Work on Burn Rates of Solid Composite Propellants

Strand Specimens

Howard and Powling.[6] These researchers have reported on burn rates of some cylindrical strands of ammonium perchlorate-based solid propellants. The work was done to determine the effect of several metal catalysts on the burning rate.

A typical composite propellant tested was

89% Ammonium Perchlorate

10% Polyisobutene

0.3% Pentaerythritol Dioleate

0.4% Ethyl Oleate

.3% metal aerosol

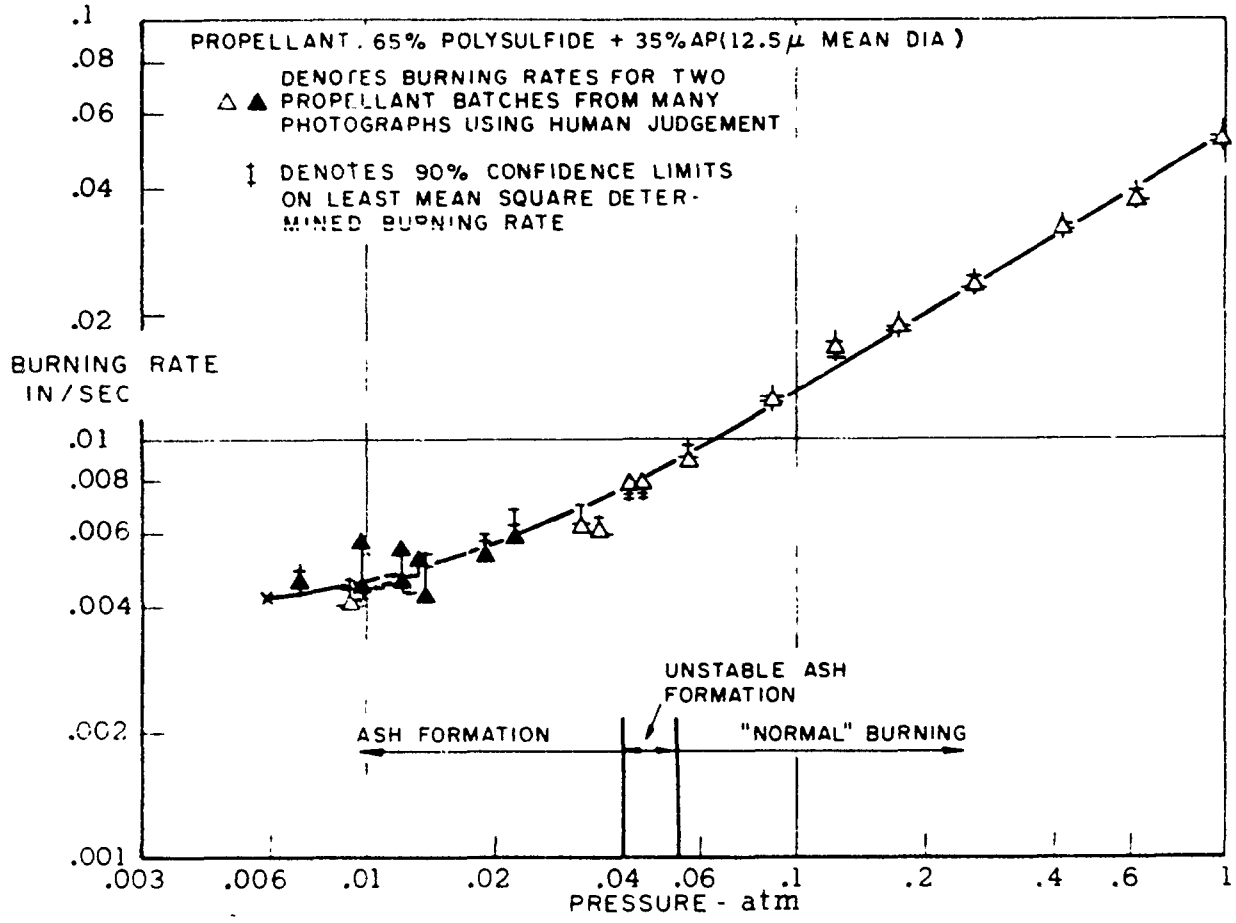
With a catalytic surfactant of copper the resulting burn rates ranged from 0.26 inches per second for a pressure of 2000 p.s.i.g. to 1.25 inches per second for 2000 p.s.i.g.. These burn rates are typical of the other burn rates reported by Howard and Powling.

Steinz, Stang, and Summerfield.[2] This research was done to substantiate the granular diffusion theory after Steinz, Stang, and Summerfield had altered it to predict burning characteristics for sub-atmospheric conditions (FIG 8).

The data taken to support their theory was from burn rate tests of cylindrical strands of ammonium perchlorate based propellants. The strand sizes were from 0.25 square inches in cross sectional area to about 0.6 square inches in cross sectional area. The strands were ignited at about 0.3 atmospheres (228 mm of mercury) and then the pressure of the surroundings of the strand was lowered to the desired level.

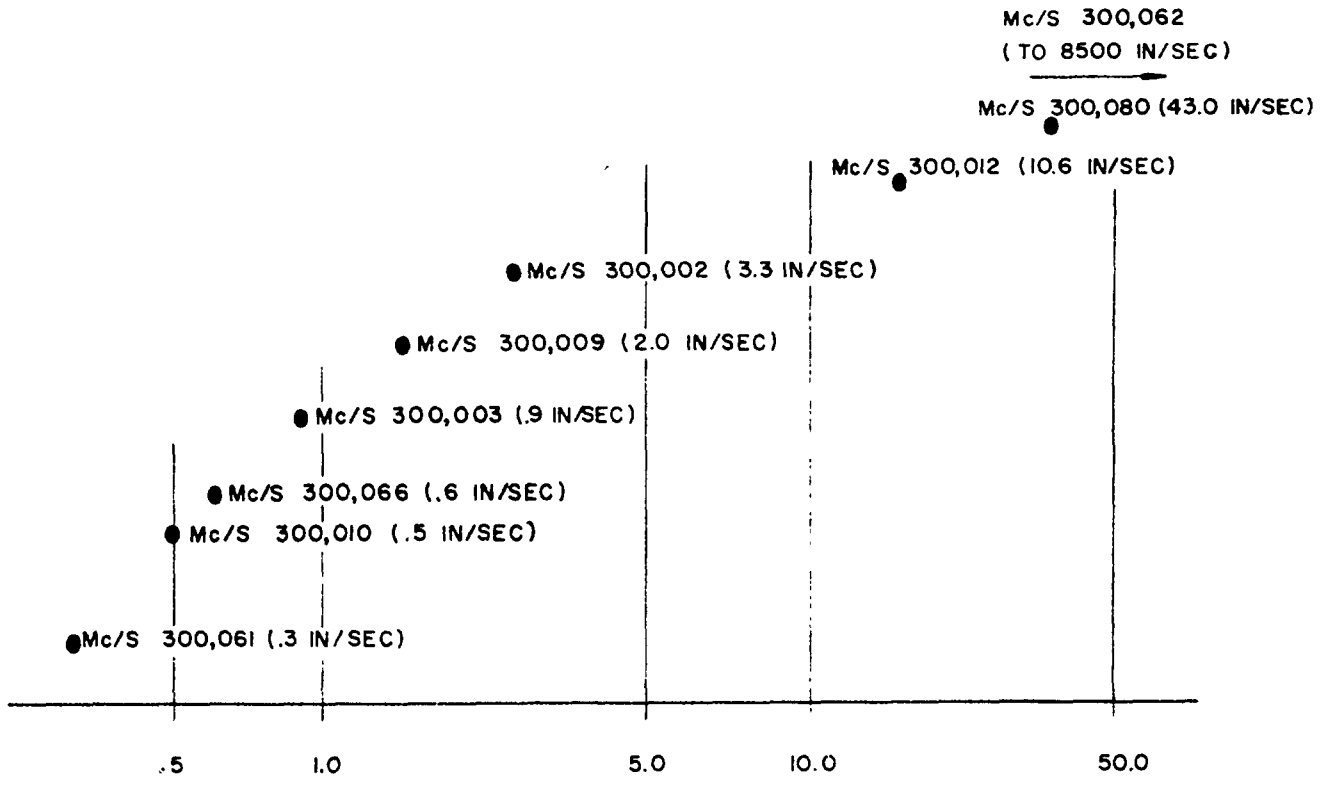
Burn rates were measured using high speed photography. The burn rates ranged from 0.01 centimeters per second (0.004 inches per second) to 0.2 centimeters per second (0.080 inches per second) for pressures of from 0.006 atmospheres (4.56 millimeters of mercury) to one atmosphere (760 millimeters of mercury).

Small column insulated delays. McCormick-Selph[30], a Teledyne company, has produced a fast burning composite material for use in small column insulated delays (fuses). This material is produced for several different linear burn rates depending on adjustments in its chemistry (compounds of hydrogen, boron, oxygen, and nitrogen). A partial listing of the materials by numbers is found in FIG 9. These burn rates are for open air testing of small diameter strands (0.040 inches to 0.080 inches in diameter). Several of these



PROPELLANT BURNING RATES DETERMINED BY TWO INDEPENDENT MEANS OF DATA REDUCTION[2]

FIG 8



DATA SOURCE — Acceptance testing at 70° F. Typical open-air burn rate (lot-to-lot) is reproducible within ±10% of nominal rate shown. Reproducibility within lot is typically ±3%.

Partial Listing Of McCormick-Selph Explosives [30]

FIG 9

numbered materials including McCormick-Selph 510,164 (not shown) have burning rates in the range intermediate between deflagration and detonation.

In normal use these strands are encased in fiberglass sleeving, extruded plastic coatings for insulation resistance, or braid jackets for abrasion resistance. In any case, the material is relatively easy to handle and will adapt to several types of use configurations.

Large Cylindrical Specimens

Howlett.[3] Sidney Howlett, in investigating the effect of particle size of sodium nitrate on burning rates of flare compositions, tested some large cylindrically shaped specimens of fuel and oxidizer.

The chemical composition of a typical test specimen was

38% (by weight) Sodium Nitrate

57% Magnesium granules

5% Laminac binder

The composition was cast in solid cylinders 1.4 inches in diameter and 2 inches long. Burn rates were then determined by the length of time that the flare gave off light. The assumption was made that the flare burned in a plane parallel to the end of the cylinder.

The cylinders with gran 16 magnesium burned in the range of from 0.2 inches per second for a sodium nitrate particle size of 15

microns to 0.15 inches per second for sodium nitrate particle size of 60 microns.

Gurton.[11] Gurton compared the detonation velocities of some cylinders of pressed tetryl for several pressure levels. The cavities that existed in the cylindrical samples were filled with either air or methane gas as indicated in Table 1. T.N.T. and Nitroguanidine were also tested with about the same results.

Liquids

The question concerning the mechanism of ignition by shock of liquid propellants led to an investigation of some thin films of liquid explosives by Baur, Cook, and Keyes.[8] Some of the liquid explosives included nitromethane, dithekite-13, nitromethane-ethyline diamine, 80/20 nitromethane-tetryl, and 80/20 nitromethane trinitro-toulene.

Burning velocity-specimen diameter curves were obtained for the liquids using thin walled polyethylene tubes for explosive containers. The walls of the plastic tubes were six mils thick so the confinement of the reaction was a minimum. The liquid specimens were set with their longitudinal axes vertical and ignited at the upper end.

A light source and a streak camera were used to record the detonation front velocity. As the detonation front progressed down the specimen, the light shining behind the specimen was gradually extinguished and this change in light intensity was recorded on the

Table 1

Ef· · of Pressure on the Velocity of Detonation of Tetryl;

Density 0.9 g.c.c. (after Gurton[11])

Diameter of tetryl cylinder (cm)	Pressure (atm)	Gas filling voids	Velocity of detonation (M.sec)
1.11	0.03	Air	1,460
	1.0	Air	1,420
	14.3	Methane	910
	27.7	Methane	failed
1.91	1.0	Air	1,700
	14.3	Methane	1,890
	21.0	Methane	1,450
	27.7	Methane	1,330
	47.7	Methane	failed
2.39	1.0	Air	2.860
	14.3	Methane	2,330
	17.6	Methane	2,085
	21.0	Methane	1,695
	41.0	Methane	failed

film in the streak camera. From the film the velocity was determined.

The detonation velocities recorded for nitromethane were in a range of from 40,000 inches per second for a diameter of 2.5 centimeters to over 120,000 inches per second for diameters greater than 3 centimeters. For the other explosives the range was higher. Nitromethane-trinitrotoulene detonated at 260,000 inches per second for specimen diameters above 3 centimeters.

Loose Granule and Porous Plug Specimens

An investigation of the deflagration mechanism of ammonium perchlorate-based composite propellants was performed by McAlevy, Lee, Lastrina, and Sumarin[5] using experimental analog techniques. Two types of models were used in this study.

The porous plug model test consists of a porous bed of ammonium perchlorate through which a gaseous fuel was passed and burned at the regressing oxidizer surface. The second model was a loose-granule burner in which the fuel and oxidizer in granular form were mixed and then ignited.

For both models ammonium perchlorate was the oxidizer. For the loose granule burner, polystyrene was the fuel used. For the porous plug burner the fuel was polysulfide.

For the burn rate tests, fuel and oxidizer granules were packed in a stainless steel tube (0.50 inches outside diameter and

0.049 inches in wall thickness). At three points along the tube, fuse wires which were parts of an electric circuit, were inserted. As the burning surface of the propellant specimen reached the wires the circuit was broken. The burn rate was then easily calculated.

For visual burn rate observations a high speed camera was used. The propellant specimens were packed in a pyrex tube (0.57 inches, outside diameter and 0.47 [sic, probably should be 0.047] inches in wall thickness) for these tests.

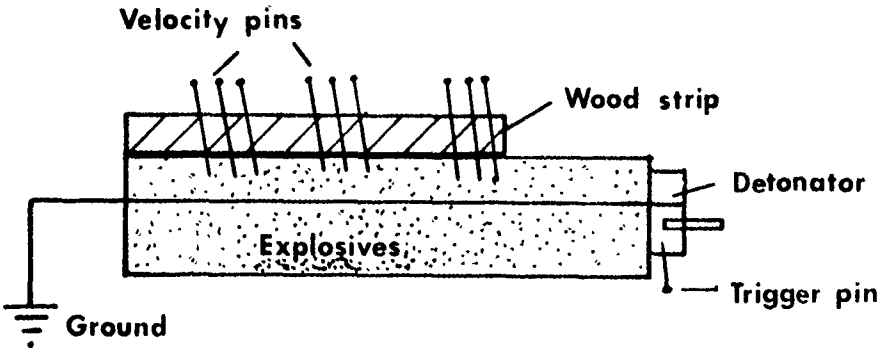
For the porous plug tests the burn rates varied from 0.02 inches per second to 0.04 inches per second for a pressure of 15 p.s.i.a.. Burn rates for the loose granule burner were approximately in the same range as for the porous plug tests.

Rubber Bonded Sheet Explosives

The effect of strong mechanical tension on detonation rates of flexible sheet explosives was investigated in 1965 by Kegler and Schall.[4]

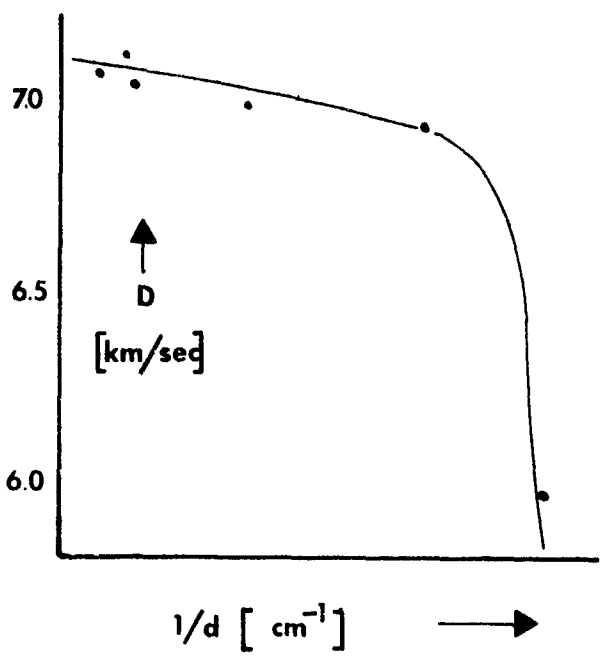
For this investigation rubber was used as the binder for several explosive components including RDX, PETN, and HMX. The greater part of the data taken was with PETN as the explosive component. The explosive content of the sheets was normally 85% to 90%.

The burn rate measuring system was a pin system (FIG 10). As the propellant burns an ionized gas region forms directly above the regressing surface. As this region reaches the gap between "pin-tip" and "ground" (this region is moving with the same velocity as



Pin type velocity measuring system[9]

FIG 10



Detonation rate of PETN sheets (Δ=1.4, 15% natural rubber) as a function of inverse thickness d[4]

FIG 11

the regressing surface) a closed electric circuit is formed and the detonation rate is easily calculated.

Figure 11 shows the thickness effect on the burning rate of a PETN-containing sheet with 15% rubber. The symbol Δ (delta) represents the estimated density of the sheet in grams per cubic centimeter. (In this case 1.4 gm/cm^3). This graph is for an unstretched sheet and shows detonation rates of approximately 0.75 inches. The plot also shows that the detonation rate varies directly with the sheet thickness.

Completely Restrained and Unrestrained Thin Films

Measurements of burn rates of some thin films of propellant in completely restrained and unrestrained configurations have been made by Bowden and Yoffe.[7] Their research was directed toward studying the mechanism of low velocity detonation of explosive thin films such as films of PETN, HMX, lead azide, and nitroglycerin.

The films of explosive were from one mil (0.001 inches) to twenty mils (0.020 inches) in thickness. The confined specimens were mounted between a steel plate and a glass plate. Initiation of the burning was by hot wire. The burning rate was measured by high speed photography.

Table 2[10] shows some of the velocity measurements. The burn rates of the confined specimens were slightly higher. Bowden and Yoffe stated that only this low velocity detonation was observed when burning initiation was by a low intensity heat source

TABLE 2

Detonation Velocities in Thin Films

of Some Inorganic Azides and Fulminates[10]

Material	Unconfined film Initiated by Hot Wire	Confined film Initiated by Hot Wire
LiN_3	decomposition	900 meters/second
TlN_3	explosion does not propagate	1,500 "
AgN_3	1,500 meters/second	1,700 "
$Pb(N_3)_2$	2,100 "	-----
NaCNO	500 "	500
TlCNO	1,000 "	1,250 "
AgCNO	1,700 "	1,900 "
(CuCNO)	(1,100) "	(1,300) "
$Cd(CNO)_2$	1,400 "	1,800 "
$Hg(CNO)_2$	0.05 "	-----

such as a hot wire. The detonations of films of PETN and nitroglycerin are also in this low velocity detonation range.[7]

The results of the tests revealed several interesting factors which are important in any study of burn rates of thin films. For instance, Bowden and Yoffe noted[7]:

> For thin films of a secondary explosive such as PETN, about 0.1 to 0.5 mm thick, the explosion begins as a comparatively slow burning which accelerates until it reaches a speed of several hundred meters a second. When the speed ex-

> ceeds this value the burning passes over into a stable low velocity detonation of 1000 to 2000 m. sec. A number of the more sensitive materials behave in the same way.[10] For example, mercury fulminate ignited by a hot wire may burn with an initial speed as low as 5 cm. sec. Lead styphnate and the organic azides such as cyanuric triazide and trinitrotriazido benzene also burn at a slow rate: the value for cyanuric triazide is 6 m. sec. and for trinitro-triazido benezene is 3 cm. sec. The inorganic azides on the other hand do not burn but detonate very close to the point of initiation within 10^{-7} sec.

The researchers pointed out that the difference in the burning and detonation characteristics of various explosives was due to the complexity of the material. A simple compound will decompose much more quickly and with less energy than a complex compound. The complex explosive decomposition may be marked by several stages of decomposition. The complex material first breaks up into simpler materials and then decomposes to the chemical reaction or detonation.

The physical state of the material must also be considered. There will be a stage of burning where the heat of reaction melts material or causes it to sublime off the material surface. The flame stand-off distance will be determined by whichever of these mechanisms occurs.

Using the findings of other researchers[11] as well as their own, Bowden and Yoffe postulated that certain conditions existed for the transition from burning to low velocity detonation. They stated[7]:

> . . .Thus two conditions are apparently required to transform burning into detonation; the formation of a

> suspension, and the possibility of the explosion of the suspension.

The suspension[12] is a result of high pressure gases in the reacting region being forced into the unburned solid propellant layer. As the intensity or the reaction increases, the amount of gas forced into the propellant also increases. If the ratio of gas to fuel particles rises to a certain level then a suspension is formed which may explode just as coal dust suspended in air can explode.

This mechanism is dependent on pressure. According to Bowden and Yoffe[7]:

> . . .The pressure under which the burning proceeds influences this process reversely--increase of pressure hinders the formation of a suspension but favors its explosion (due to the increased rate of burning of the suspension). Within some pressure interval the combination of these two factors causes an explosion, beyond this interval no explosion occurs.

For a film of PETN, Bowden[7], Williams[13], and Gurton[11] found that at atmospheric pressures the film burn rate was around 1500 meters per second while at pressures above thirty atmospheres the velocity decreased rapidly. At fifty atmospheres the film failed to burn or detonate.[13]

Bowden and Yoffe also pointed out that the burning speed of a film can be changed by mixing very small quantities of inert liquids and solids with the explosive in the film. For example[7]:

> . . .In the case of a mixture like gunpowder, it has been shown that the presence of 1.2% stearic acid can cause a retardation of 800% in the burning speed at

room temperature and atmospheric pressure.

Compressed Sheets

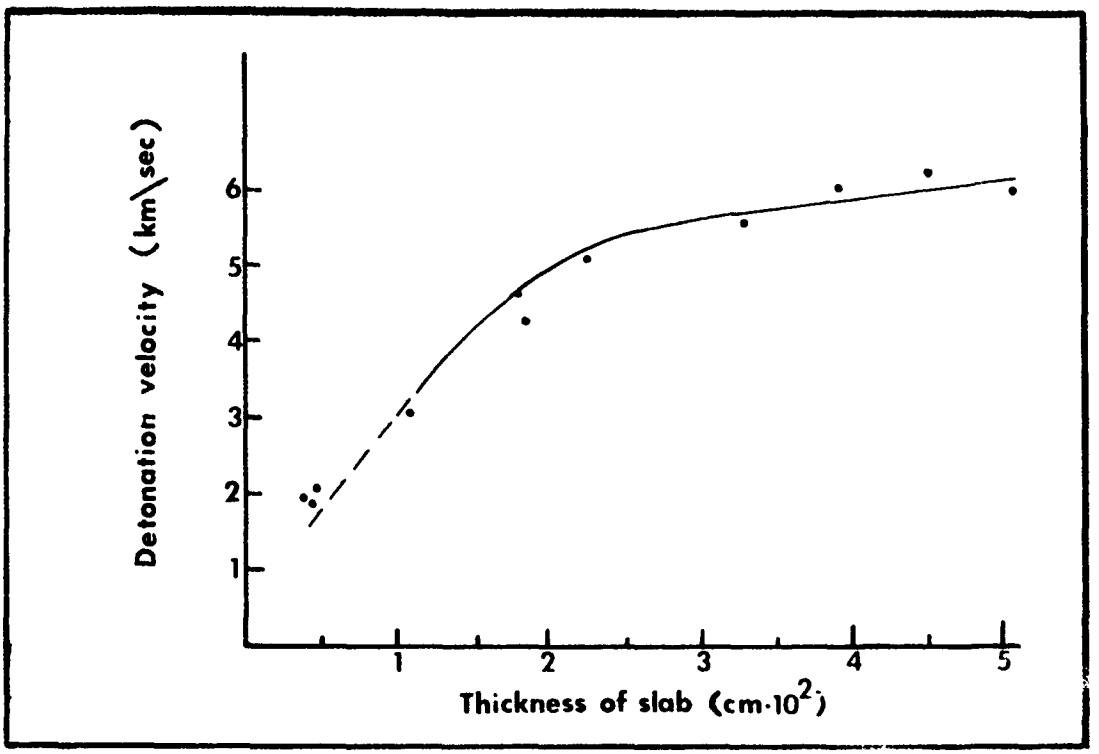
McLarin[14] has reported on the effect of thickness on burn rates of some compressed sheets of lead azide. The results of his study are shown in Figure 12.

Sheets with thickness below 0.02 centimeters (0.0078 inches) show a steady increase in burning velocity for increase in film thickness. The burning rate ranges from two kilometers per second (79,000 inches per second) to five kilometers per second (180,000 inches per second) for thickness increase from 0.005 centimeters (0.0019 inches) to 0.02 centimeters. At this thickness the burn rate levels off at about 5.5 kilometers per second (200,000 inches per second).

The experimental points are shown in the small circles in Figure 12. The line represents a theoretical calculation based on the expanding jet hydrodynamic theory developed by Jones[15]. This theory is based upon the assumption that the reacting gases in the burning of a condensed explosive expand and that the reaction takes place during the expansion. Therefore some of the reaction would take place at a lower effective density of explosive material (a "suspension"[12] of different density).

Summary

Bowden and Yoffe[7] have stated:



Relation Between Detonation Velocity and Film Thickness for Compressed Sheets of Lead Azide[14]

FIG 12

The speed with which a burning spreads in a thin film depends on a number of factors. The heat of reaction of course, is one of the most important. The intensity of the igniting source, the degree of confinement, the surrounding gas pressure, the thermal constants and the size of the solid film all affect the burning speed.[16,17] The structure and decomposition mechanism must also be taken into account.

This summarizes the factors which are covered in the theoretical and experimental work done in the propellant area on burn rates. In studying propellants for burning mechanism there have also been some burn rate studies on thin films. However, these

thin films were either completely confined or unconfined and consisted almost entirely of films of explosive being tested at detonation levels. No work on thin films restrained on only one side and made up of a composite propellant has been reported.

Also, the theories on burn rates and detonation rates have been developed to fit data taken at high pressures (above several atmospheres). Even Stienz, Stang, and Summerfield's[2] low pressure pyrolysis rate equations were derived by revising the granular diffusion theory for high pressure burning rates of ammonium perchlorate based propellants.

The prediction of the effects of low pressures (one atmosphere and below) on the burning of thin films of composite propellants with burn rates in the range intermediate between deflagration and detonation cannot be made from the literature just reviewed. Nor can a prediction of the effects of restraining one surface of the films being tested be made.

The research described in the following section will be directed toward "filling the gap" on the knowledge of some composite propellants which burn in the range between deflagration and detonation. It will also give results of the testing of those composite propellants in thin films restrained on one side and burned in surroundings of one atmosphere and less.

PROPELLANT SELECTION

General

The selection of the composite propellants to be tested in this research was dependent mainly on factors relating to the propellants use in the hypervelocity accelerator tube lining. The propellant used in the hypervelocity accelerator will have to meet certain requirements.

1. The propellant will have to be in a form so as to be coated easily on the inner surface of a steel tube.
2. The coating of propellant will have to be smooth and uniform down the length of the tube.
3. The constituents of the propellant will have to lend themselves to being mixed together and stored for short periods of time.
4. The propellant constituents will have to produce a large amount of gas for a small initial volume in solid form.
5. The production of the gas should be fast and efficient.

The ignition of the propellant will have to be accomplished by some method which would cause the burning or detonation to be initiated soon after the projectile passed over the reaction point. This means the propellant could be ignited by the friction of the projectile or by some chemical or mechanical igniter trailing the projectile.

These are relatively low intensity energy sources for ignition. A repeatable, low intensity source for propellant testing is a hot wire. Although tests for the sensitivity of the propellants inves-

tigated were conducted using impact test devices and friction test devices, the burn rate studies were conducted using a hot wire ignition system. The propellant, therefore, had to be sensitive enough so that burning could be initiated by a hot wire.

Due to the lack of literature on materials demonstrating burn rates in the range of interest (3 inches per second to 40,000 inches per second) the selection of propellants was largely by informed guess. High gas producing, quick reacting explosives were combined with active oxidizers and suspended in a paint-like carrier. The resulting material was coated on metal coupons and tested for impact sensitivity, friction sensitivity, heat sensitivity, and burning characteristics such as continuity of flame, complete consumption of the propellant coating, and, of course, linear burn rate. A more detailed description of tests and test procedures is given in Experimental Apparatus.

After comparing these characteristics of a certain propellant and also comparing lined shots in the hypervelocity accelerator, if they were made, a new variation of the propellant was prepared if suggested by the tests.

Propellants Tested

Nitrocellulose-Based Propellants

Many fuels and explosives were investigated in this research. Some were tested as propellants by themselves as well as in com-

posite propellants with oxidizers and/or metal additives.

The first propellant formulation tested consisted of nitrocellulose dissolved in either methyl ethyl ketone or butyl acetate (commercial solvents). This was a simple propellant in that it was made up of only two constituents and formed a hard thin coating when painted on the steel walls of the hypervelocity accelerator tube.

The nitrocellulose propellant was tested extensively. It was determined that this formulation was either not igniting properly by the friction of the projectile or was being ignited by a flame front behind the projectile. The flame front behind the projectile is from the commercial loaded .22 caliber charge used to give the projectile an initial velocity before entering the lined accelerator tube. This formulation was a good carrier, however, and instead of discarding the nitrocellulose propellant, several variations were tried.

Using the nitrocellulose as a filmogen several other chemicals and combinations of chemicals were tested. These included:

1. Aluminum
2. Aluminum, glass
3. Black powder
4. Black powder, aluminum
5. Potassium chlorate
6. Potassium chlorate, black powder
7. Potassium chlorate, glass
8. Potassium chlorate, glass, aluminum

9. Potassium chlorate, glass, steel powder
10. Potassium chlorate, glass, black powder
11. Potassium chlorate, carbon
12. Potassium chlorate, carbon, glass
13. Potassium chlorate, zinc oxide, sand
14. Potassium chlorate, carbon, sulphur
15. Potassium chlorate, glass, aluminum, carbon
16. Potassium chlorate, lead azide, aluminum, glass, McCormick-Selph 300,104
17. Ammonium perchlorate
18. Ammonium perchlorate, aluminum
19. Ammonium perchlorate, black powder
20. Ammonium perchlorate, glass
21. Ammonium perchlorate, black powder, glass
22. Ammonium perchlorate, black powder, aluminum
23. Ammonium perchlorate, aluminum, glass
24. Ammonium perchlorate, steel powder
25. Ammonium perchlorate, steel powder, glass
26. Ammonium perchlorate, RDX, aluminum
27. Ammonium perchlorate, McCormick-Selph 510,164
28. Ammonium perchlorate, McCormick-Selph 300,104, aluminum
29. Ammonium perchlorate, McCormick-Selph 300,104, aluminum, glass
30. Ammonium perchlorate, McCormick-Selph 300,104, glass
31. Ammonium perchlorate, aluminum, McCormick-Selph 510,164

32. Ammonium perchlorate, aluminum, glass, McCormick-Selph 510,164
33. RDX
34. RDX, glass
35. RDX, aluminum
36. RDX, aluminum, glass
37. RDX, aluminum, sand
38. RDX, sand
39. PETN
40. PETN, glass
41. Sulphur
42. Carbon
43. Lead azide
44. Lead azide, silicagel
45. Potassium nitrate, aluminum
46. Potassium nitrate, carbon, sulphur
47. Potassium nitrate, McCormick-Selph 510,164

The characteristics of these propellants will be discussed in detail in the Experimental Results section.

Polyvinyl Chloride-Based Propellants

Extensive testing of the nitrocellulose-based propellants showed that a new binder material was required to replace the nitrocellulose binder (see Experimental Results). From observations of

the comparison tests of the nitrocellulose propellants (described in Experimental Apparatus and Testing) it was obvious that something in the propellant was inhibiting the reaction of the oxidizer and explosive materials in the propellant. A review of the properties of the nitrocellulose revealed that the mechanism that made it a good binder was also inhibiting the reaction of the propellant. The tough, filmy make-up of the nitrocellulose coating was isolating oxidizer particles and fuel particles from one another.

Of several commercially available binders which would meet the binder requirements as needed to coat the accelerator tube walls, polyvinyl chloride was chosen for testing.

Polyvinyl chloride binder is made up of two constituents--a polymer, Geon 427, and a plasticizer, dioctyl adipate. The coating is not quite as hard as the nitrocellulose coating but tests have shown that the Geon 427-Adipate combination has low heat resistance and does not impede the propagation of the burning of the active propellant constituents.[31] The polyvinyl chloride is a fuel in its own right and will burn when mixed with an oxidizer such as ammonium perchlorate or potassium nitrate though at a very slow rate.

The burn rate data presented in Experimental Results is the result of the tests of the polyvinyl chloride-based propellants.

Some of the materials and material combinations used in conjunction with the polyvinyl chloride binder include:

1. Potassium nitrate, McCormick-Selph 510,164
2. Potassium chlorate, McCormick-Selph 510,164
3. Ammonium perchlorate, McCormick-Selph 510,164

Other Binders

In the process of developing a good propellant liner for the accelerator tube, several other binders besides the two previously mentioned were tested.

Water-based glues. Two water-based glues, methylcellulose and dextrin, were experimented with. These are stored in dry form and then mixed with water to form a paste. Test propellants of these glues were made up of potassium nitrate and carbon, potassium nitrate and aluminum, and commercially prepared black powder.

These formulations did not adhere well to a steel surface and were flaky and brittle when dried. Since these binders would not make a satisfactory coat of propellant on the accelerator tube walls, they were not tested extensively.

Casein glues. A glue commercially manufactured as "Elmer's Glue" was tried and found to be very difficult to work with as it dried very quickly.

The propellant tested with this binder was a potassium nitrate-carbon combination. The glue formed a soft coating which desensitized the coating completely to impact and friction tests. This binder was also ruled out for use in the propellant tests.

EXPERIMENTAL APPARATUS AND TESTING

General

As the preliminary examination of the problem of developing a propellant liner for the hypervelocity accelerator tube progressed, the need for methods of comparing one propellant with another in the lab became apparent. Coating the tubes was both tedious and time consuming. Also, it was not always possible to contribute the failure or success of a shot in the lined accelerator tube to the propellant properties alone. The examination of the propellant lining before and after the shot was difficult and was based on visual observations.

Some of the properties assumed to be of prime importance in comparing various propellant formulations before using the propellant in the accelerator tube lining were impact sensitivity, friction sensitivity, and sensitivity to open flame. Also, the physical properties of the propellant coating such as smoothness and uniformity of thickness were observed and compared.

After reviewing some of the literature available on thin films of propellant it was determined that the linear burn rate of the propellant lining in the accelerator tube and the effects of the initial vacuum conditions on the linear burn rate of the lining may also be of importance. The linear burn rate of the propellant was later proven to be of great importance to the operation of the

hypervelocity accelerator by a two dimensional mathematical model of the accelerator devised by Ferrata[32].

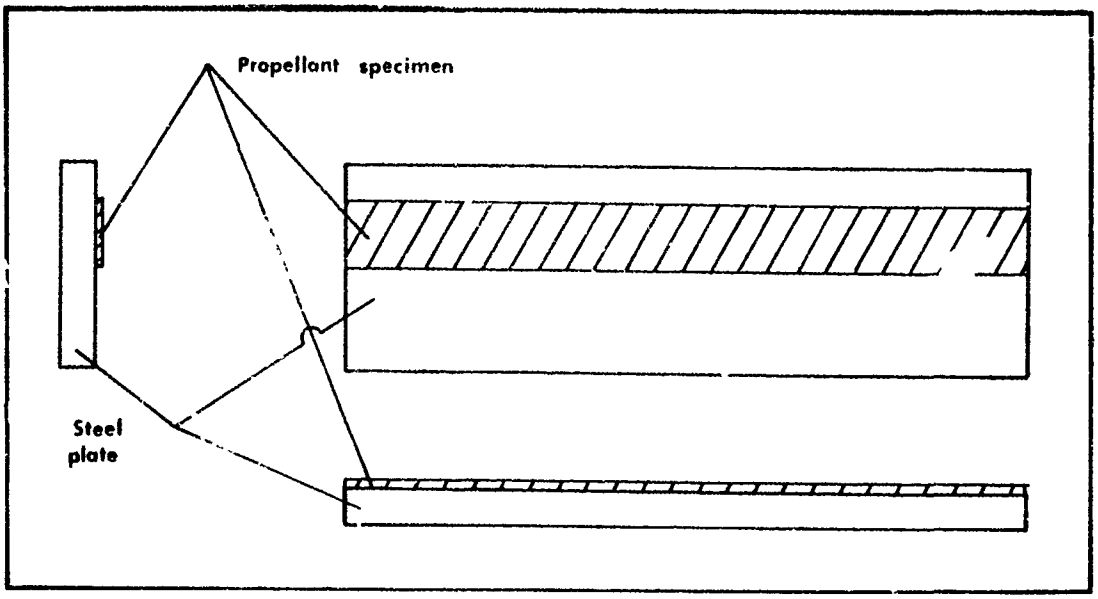
Due to the lack of previous work on thin films of propellant restrained on one side and tested in surroundings of one atmosphere or less, a special chamber and velocity measuring system had to be devised for this research. This apparatus will be described in detail in the next section. Following the next section, will be a description of a normal burn rate test and an impact sensitivity test which were used to a limited degree in the laboratory.

The last section deals with the comparison tests of impact sensitivity, friction sensitivity, direct heat sensitivity, and the physical propellant coating properties such as smoothness and uniformity of thickness.

Linear Burn Rate Measurements

Propellant Specimen

Specimen description. To be able to draw some analogy between the results of the comparison tests and burn rate tests and the action of the propellant liner in the hypervelocity tube, the propellant test specimen had to be as near like the propellant liner as possible. The specimen developed was a thin strip approximately eight inches long, one-half inch wide and of variable thickness depending on the requirements of the hypervelocity accelerator (Data is presented for thicknesses ranging from 1 mil [0.001 inches] to



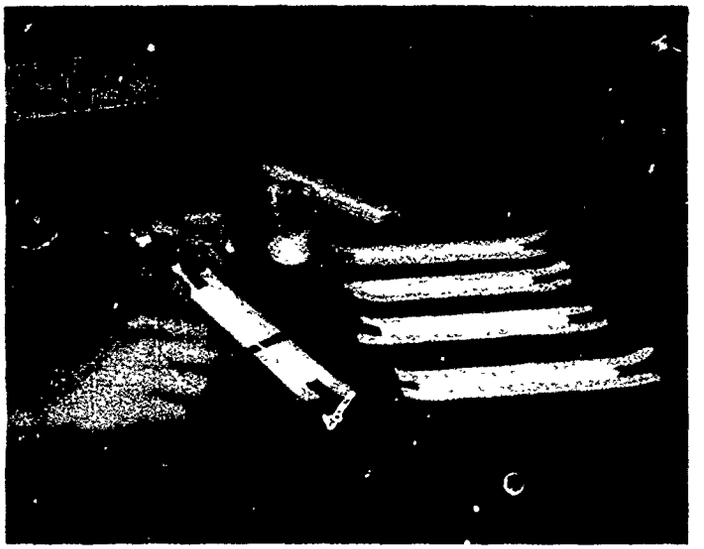
Linear Burn Rate Test Specimen

FIG 13

30 mils.). (See FIG 13)

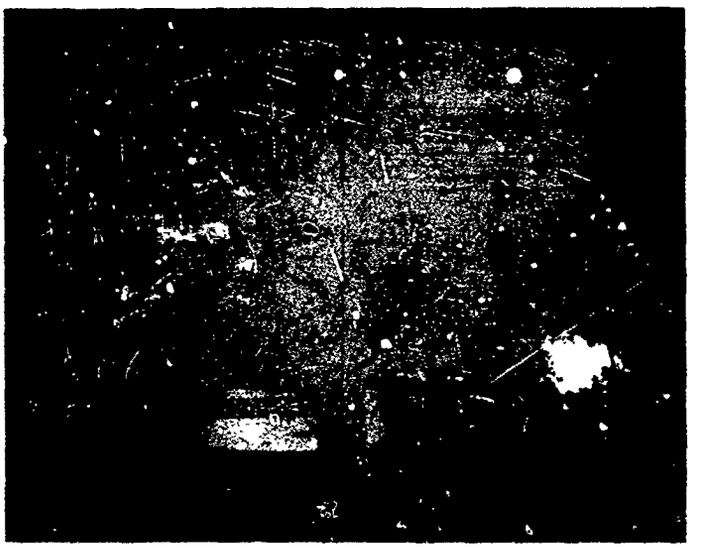
Specimen construction. The film is coated onto a polished steel plate which is approximately two inches wide, eight inches long, and one-fourth inch thick. Two strips of masking tape are put down on the plate one-half inch apart. The number of layers of tape used will determine the thickness of the propellant strip.

The propellant is poured into the space between the strips of tape and is leveled and smoothed (FIG 14). After sitting for a certain period of time (over one-half hour) the strips of tape may be removed. The specimen is checked for surface defects, and uniformity of thickness. The thickness of the strip is measured and recorded along with the other pertinent information such as



Casting a propellant strip.

FIG 14



Finished specimen.

FIG 15

propellant batch number and coating age (See FIG 22). The specimen is then ready for burn rate tests (FIG 15).

Photodiode-Electronic System

In a previous attempt in the hypervelocity lab at measuring burn rates in thin films of nitrocellulose, small diameter fuse wires placed at several points along the strip of propellant were used to determine the burn rate. However, not enough heat was generated by the burning film to melt the wires or change their resistance to an electric current, so the burning rates could not be recorded. Other known methods of measuring burn rates such as the pin method (FIG 10) would be difficult to apply to thin films of propellant restrained on one surface.

This left high speed photography as the one "tried and tested" means of measuring fast linear burn rates of thin films. However, the primary disadvantage of high speed photography is the delay due to film developing and the time to analyze the frame by frame measurements. Due to the numerous variations and combinations of propellants that needed to be tested, the use of high speed photography for each burn rate measurement would have been cumbersome.

This led to the development of a new concept for burn rate measurement. This concept was based on the knowledge that there was a visible reaction zone at or just above the surface of a burning thin film as the flame front passed down the length of the film.

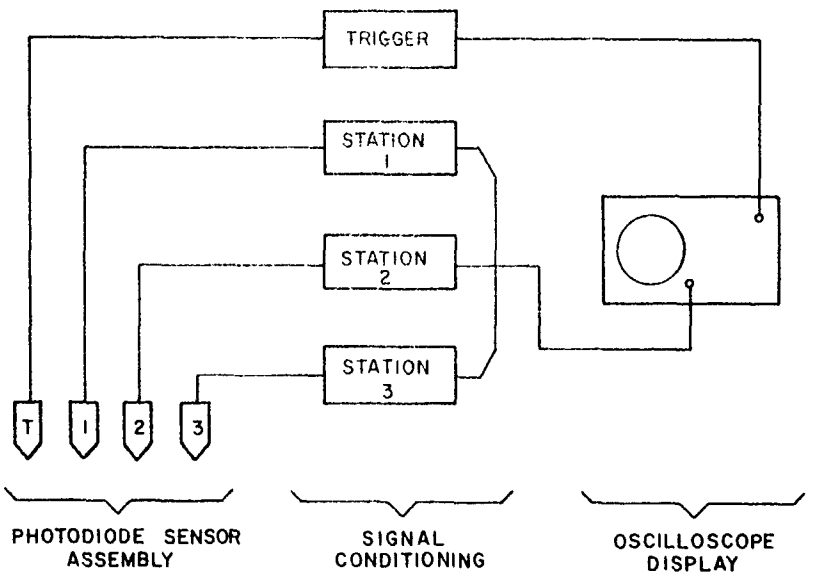
A light sensor, which could see the light from the reaction zone, could signal when the flame front passed by the sensor.

Initial experiments with photodiodes showed that they were sensitive enough to give a response when only a short, low intensity light pulse was projected on them. Using these photodiode sensors and the electronic circuit signal conditioners (FIG 17) which relay the photodiode responses, a test system was devised.

This system is made up of four photodiodes--a trigger station and three velocity measuring stations (FIG 16, FIG 18, and FIG 19). The responses of the photodiodes as they see light are to change the voltages in their signal conditioners. The circuits transmit this response in the form of a voltage step to the oscilloscope whose vertical trace position is governed by the voltage inputs.

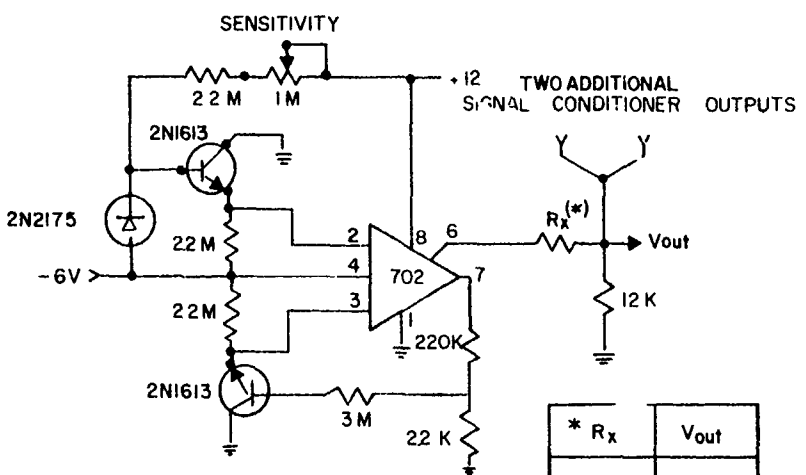
The trigger inputs a signal which is used to start the trace on the oscilloscope. The second photodiode's (station one) response is transmitted to the oscilloscope and is displayed as a volt displacement (vertical axis) of the trace. The third photodiode's (station two) response to seeing light is a three volt displacement (vertical axis) on the oscilloscope trace. The fourth photodiode's (station three) response yields a five volt displacement on the vertical axis of the oscilloscope trace.

With this system it is possible to decipher exactly which photodiode is responding, or which combination of photodiodes are responding at the same time. (See FIG 20 and FIG 21)



BLOCK DIAGRAM - PHOTODIODE LONGITUDINAL BURNING RATE DATA SYSTEM

FIG 16



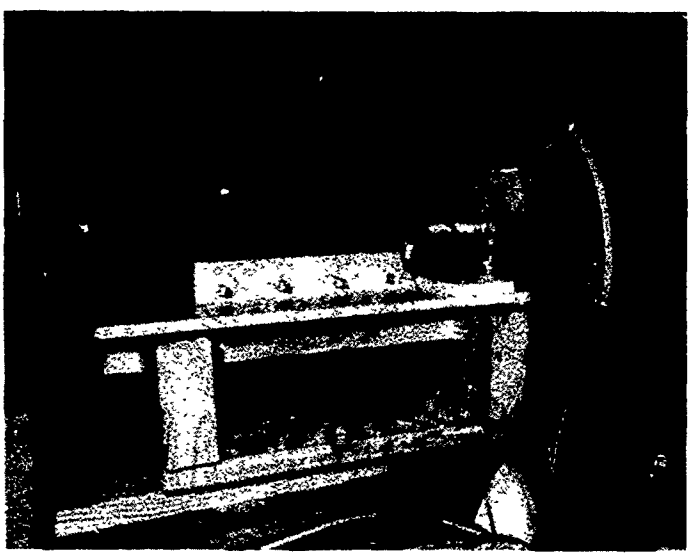
* R_x	V_{out}
47 K	1 V
15 K	3 V
10 K	5 V

SCHEMATIC DIAGRAM - PHOTODIODE SIGNAL CONDITIONER

FIG 17

Photodiode longitudinal burn rate data system

FIG 18



Instrument tray and photodiode velocity measuring system

FIG 19

5 V/CM

① ② ③

INDIVIDUAL STATION OUTPUT SIGNALS

FIG 20

5 V/CM

STATION 1

STATION 1 & 2

STATION 1, 2 & 3

STATION 2 & 3

STATION 3

COMPOSITE SIGNAL OUTPUT

FIG 21

HVL PROPELLANT TEST

Test Number 062370006

COATING: Surface Coated Polished Steel

Coating Width 0.5 in. Coating Date 6-23-70 (3 hrs)

No.	Coating	Sample	Measurement aft/base			Thickness			Avg.Thickness
1	$KClO_3$;Mc/S 510,164;PVC	18	.285 .258	.285 259	.286 .261	.027	.026	.025	.026
2									
3									
4									
5									
6									
7									

Remarks

Total 26 mils

Drying Method air

TEST: Type: Vac Ignition Technique Hot wire

Pressure 5 torr

Scope

Sweep Speed 0.5×10^{-3} sec/cm

Upper Trace Analog #1

Sensitivity 5 volts/cm

Lower Trace Velocity

Sensitivity 5 volts/cm

Results:

	Readings		Velocity
T - 1		=	
1 - 2	1.0cm	=	4000 in/sec
2 - 3	1.0cm	=	4000 in/sec
1 - 3	2.0cm	=	4000 in/sec

Remarks: by: M.L.J.

Sensor	Trigger	1	2	3
Spacing (in)	Ref.	2	2	2
Dist. from Propellant	.5	.5	.5	.5
Height	.125	.125	.125	.125
Collimator Aperture	Open	.065	.065	.065
Collimator Length	0	.45	.45	.45
Position Degree	0	0	0	0

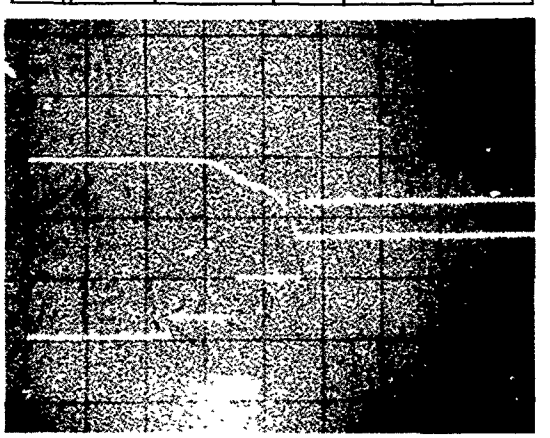
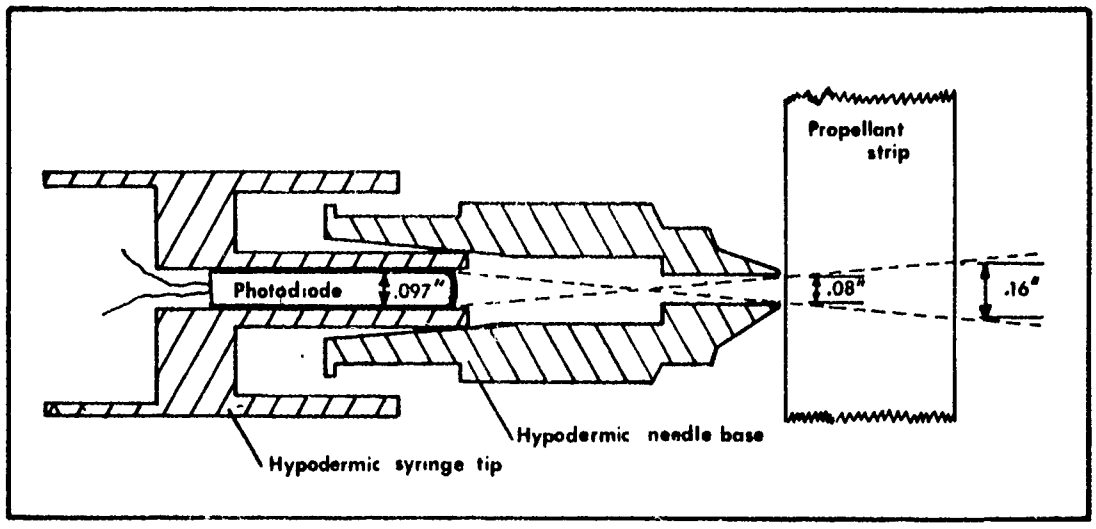


FIG 22

The point of ignition of the propellant film is located in front of the trigger diode. When the propellant ignites, the light emitted from the reaction zone hits the trigger diode and the response of the diode starts the oscilloscope trace. As the flame front progresses down the propellant film, stations one, two, and three see light and respond. The resulting oscilloscope trace such as the one pictured in FIG 22 then gives the time record of the position of the flame front.

The photodiodes are located exactly two inches apart and the velocity measuring stations are collimated by the use of hypodermic needle bases (FIG 23). The photodiodes themselves are cemented inside the metal tip of a hypodermic syringe. The syringe needle bases are then easily put on and taken off for cleaning. Figure 23 shows the collimation of a photodiode velocity measuring station with a number eighteen size needle (drilled to 0.065 inches inside diameter). As shown in the figure, it is possible for the collimated photodiode to see only a very small diameter area across the propellant film. This indicates that the response of the photodiode is due to an intense light source, the flame front, passing through this area.

Using the oscilloscope trace for measuring the elapsed time for the flame front to pass from station to station and the known distance between each station (two inches), the linear burn rate of the propellant film may be calculated.



Collimation of Photodiode Line of Sight

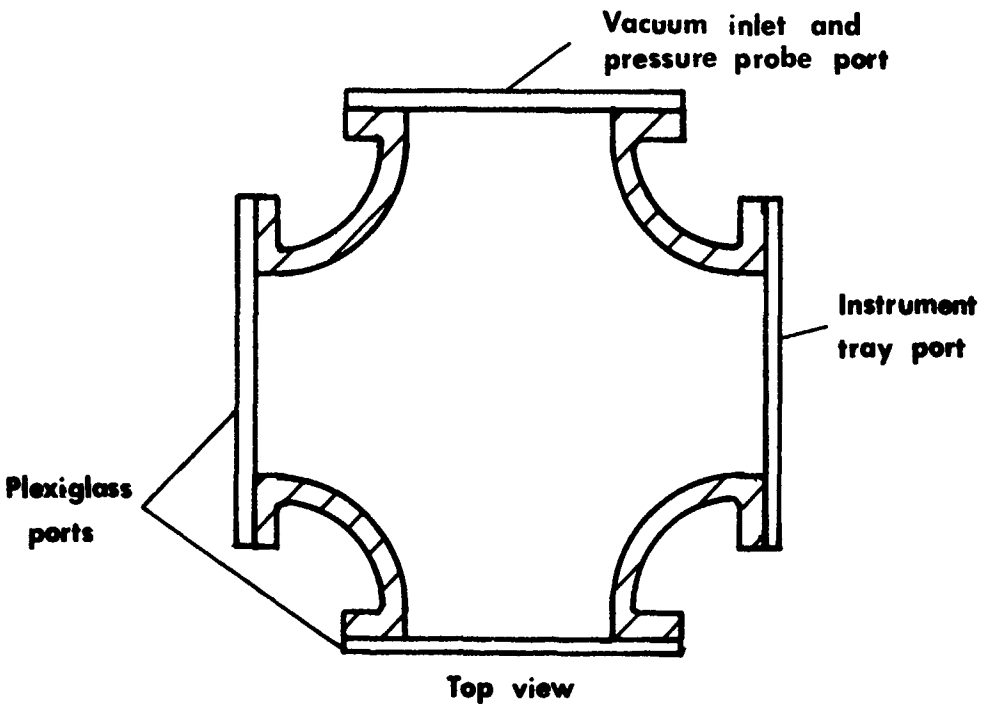
FIG 23

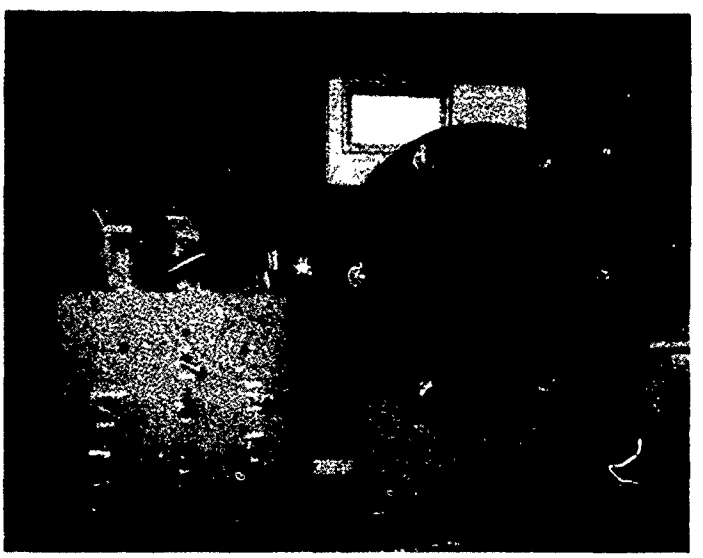
Test Chamber

For vacuum tests a unique vacuum chamber was constructed. The chamber is basically a cast iron, right angle pipe union (FIG 24). This chamber has four large ports for instrumentation and event viewing purposes.

An instrument tray on which the photodiode holders are mounted was constructed to be permanently attached to one of the port covers. Therefore it is only necessary to unfasten this one port from the chamber in order to remove all the instrumentation contained in the chamber (FIG 19).

Two of the remaining three port covers are plexiglass plates for visual observations and for taking high speed movies of the





Linear burn rate test vacuum chamber.

FIG 24

burning in a vacuum. The fourth port is covered by a metal plate through which passes the suction hose outlet and the pressure gage probe.

Vacuums of about five torr (five millimeters of mercury) are attained regularly for test purposes in this chamber.

Test Procedures

The propellant specimen, after first being measured and visually inspected is placed on the instrument tray such that the near edge of the propellant strip is 0.5 inches from the photodiode face. The hot wire probe is put into position such that the ignition point will be directly opposite the uncollimated trigger photodiode.

The instrumentation is checked to assure that the photodiodes are responding and that the response is being relayed to the oscilloscope trace in the desired manner. The tray and port cover are then clamped into place. For vacuum tests the tank is evacuated to approximately five torr (five millimeters of mercury) and the propellant fired with the hot wire.

The chamber is then vented and the instrument tray removed from the chamber. Visual observation of the tray, chamber, and the specimen plate are made and then the plate is removed and cleaned.

The results of the oscilloscope trace are recorded and plotted on appropriate graphs.

Normal Vector Burn Rate Tests

General

Although the linear burn rate tests described previously were the most important tests of this research, other tests for propellant burning characteristics were devised in an effort to learn more about thin films of propellant. One of these tests[33] was developed to measure the normal vector burning rate of the propellant film.

The objective of this study was to determine the rate of burning of a film of propellant through its thickness and attempt to correlate this burn rate with the horizontal vector burning rate already being measured.

Propellant Tests

Propellant specimens. The propellant specimens were ten to fourteen mil thick layers of a propellant being tested for horizontal vector burn rates. The propellant was:

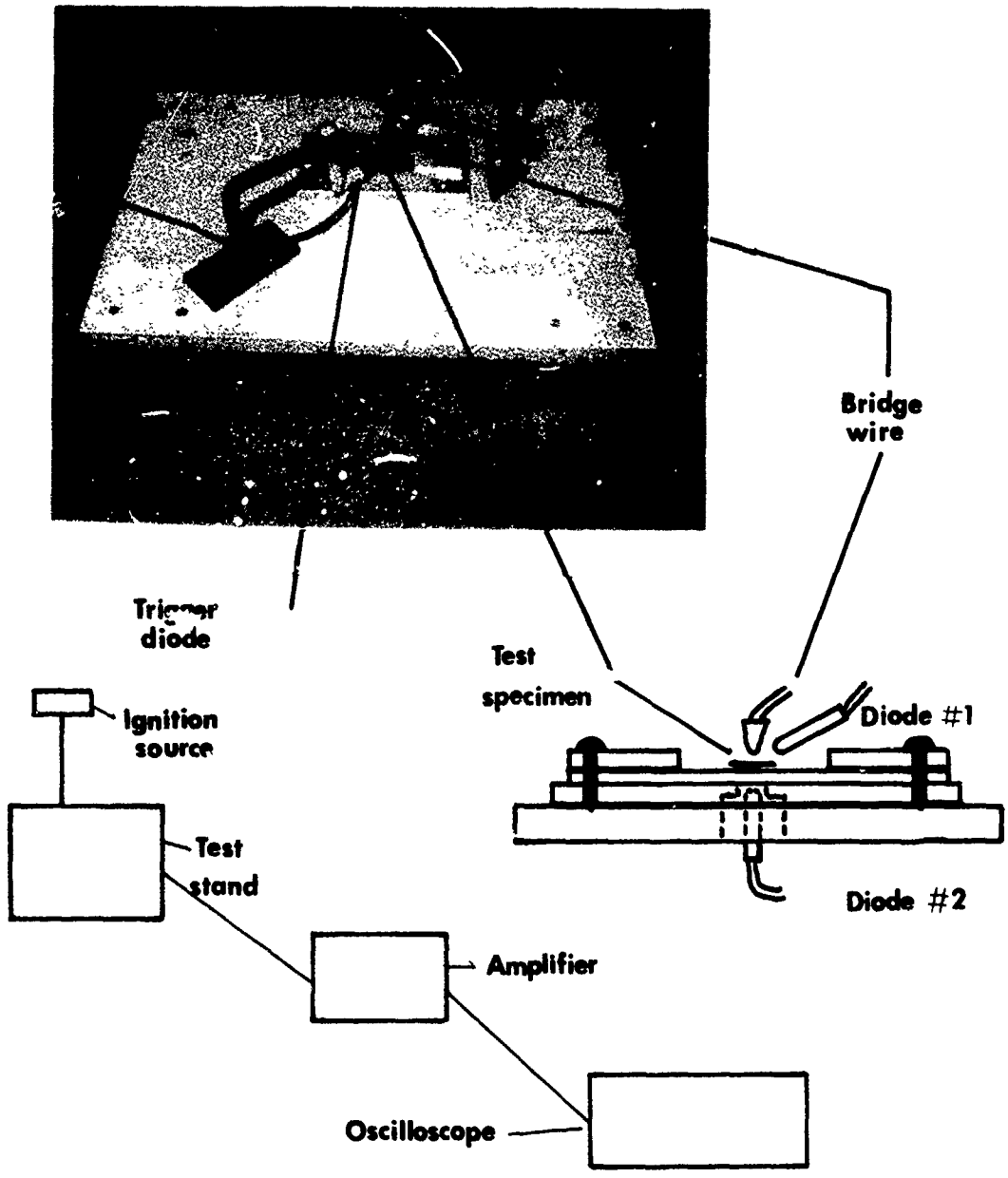
45% Potassium Nitrate

45% McCormick-Selph 510, 164

10% Polyvinyl chloride

The propellant was coated on a glass slide and allowed to dry a maximum of five hours.

Test apparatus. The test specimen was set in a special holder, propellant side up (FIG 25). Implanted in the holder directly below



Experimental system for measuring normal vector burning rate

FIG 25

the lower surface of the glass slide was a photodiode looking up through the glass at a point on the lower surface of the propellant specimen. Directly above this point on the upper surface a hot wire igniter was placed. Another photodiode was located near the hot wire and was looking directly at the point of contact between the wire and propellant. The response of the photodiodes was relayed by the signal conditioners previously discussed (FIG 17), to an oscilloscope.

Test procedure. As the propellant was ignited on the upper surface by the hot wire, the upper photodiode was to respond to this light by triggering the trace of the oscilloscope. The flame front would then burn down through the thin layer of propellant until it reached the glass surface. At this point, the lower photodiode would respond to the light emitted by the flame front. These two responses would give the time period for burning through a certain specimen thickness and therefore yield a normal vector burning rate.

Test Results

The test results according to Conley were inconclusive. No repeatable burn rate measurement was established because of the inherent unreliability of the tests as they were conducted.

Conley pointed out that there was no method available at the time to determine how long the propellant burned from the time of ignition until the upper photodiode responded. Also due to the intensity of the hot wire igniter, a true burning rate, free from the

singularity of having the hot wire in contact with or very near to the propellant surface is not available. Existing literature points out that the intensity of the igniter will have a great bearing on the rate of reaction of the propellant immediately surrounding the igniter. After ignition the free-burning reaction zone is sustained by the conduction of its own heat into the unburned propellant ahead of the reaction zone.

Another unanswered question was whether the lower photodiode actually saw the flame front when it responded or if it actually saw light from the upper surface penetrating through the propellant film. Conley proposed that there was some light penetrating the propellant layer but that there was no way of measuring the actual amount of light, the time history of its intensity, or the source (hot wire or propellant reaction zone).

The conclusion for this test was that the measurement of the normal vector burning rate would take extremely sensitive, accurate instrumentation or very high speed movie cameras. It was felt that due to the complexity of this problem, more useful information could be gotten from the linear burn rate tests so the normal vector burn rate tests were not pursued further.

Impact Energy Sensitivity Test

General

An impact sensitivity device[34] was designed and built to mea-

sure the sensitivity to impact of specimens of a thin film of propellant such as the specimens being tested for linear burn rate. This test was to be analgous to the common weight drop test which is used to compare impact sensitivities of explosives. The drop test, however, is difficult to apply to the testing of thin films due to the increased accuracy required. The drop weight must hit a small but exact area with a uniform pressure impulse on every test. The drop tests for explosives are usually done on large specimens where errors of several inches are negligible.

A more rigid system than a free falling weight was required so that the size of the impact area could be controlled more accurately. Also some adaptability of the test apparatus was required so that the impact tests could be varied and so that accurate instrumentation might be applied.

Propellant Tests

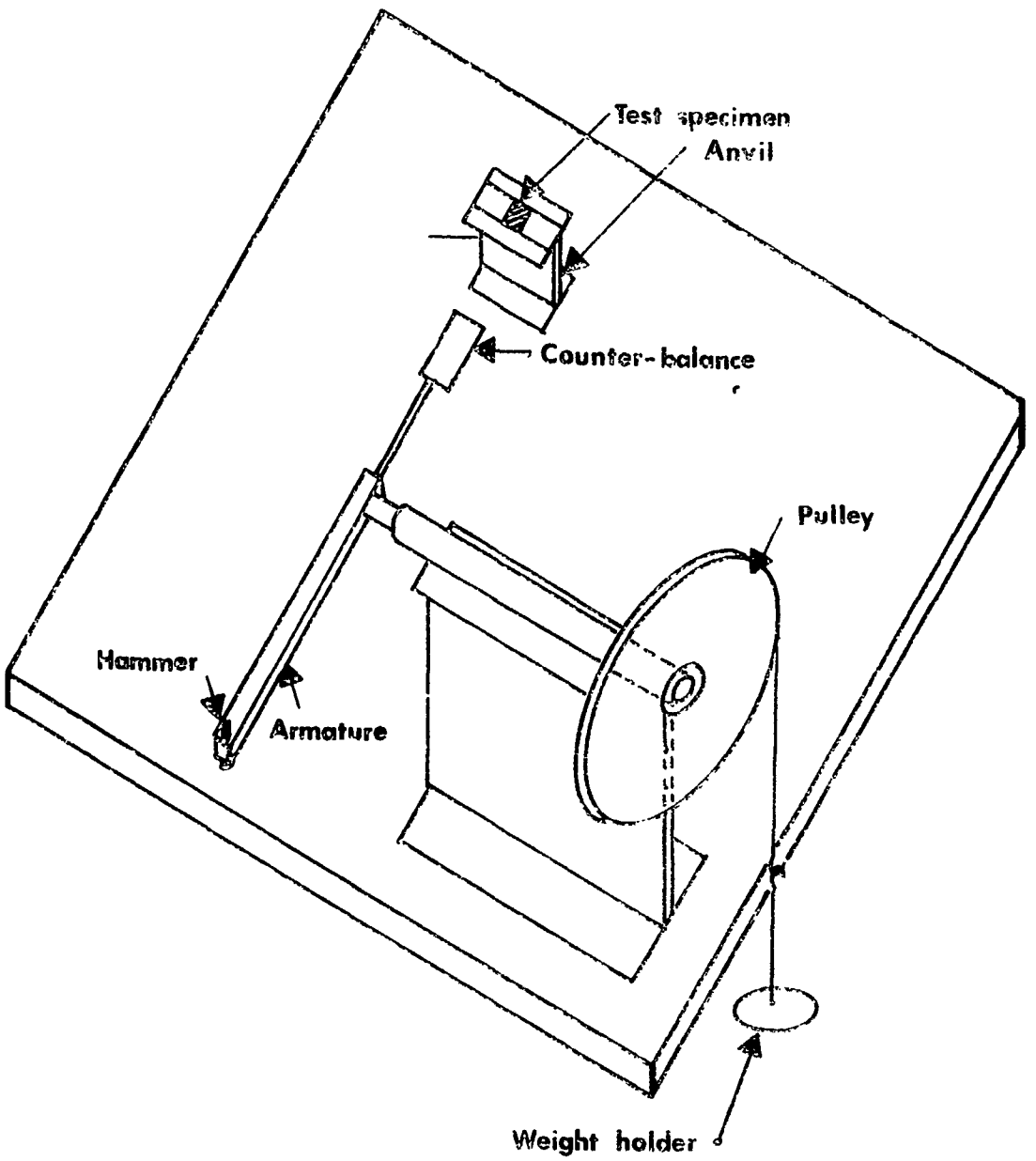
Propellant specimens. The specimens tested were thin layers of a propellant being tested for linear burn rates. The propellant was:

45% Potassium nitrate

45% McCormick-Selph 510,164

10% Polyvinyl chloride

The propellant was coated in a thickness of five mils onto polished steel plates. The film drying time ranged from two hours to thirty



Test platform-
Impact energy sensitivity test.[34]

FIG 26

hours. (This was one parameter studied).

Test apparatus. The testing system devised to meet the requirements set forth earlier consists of a pulley-armature apparatus driven by a drop weight (FIG 26). The contact area is located on the free end of an armature which is rigidly fixed at the opposite end to a large diameter pulley. A weight suspended from the outer perimeter of the pulley supplies the energy for turning the pulley-armature mechanism.

The propellant specimen is located in a position so as to be struck squarely by the contact area on the free end of the armature. The velocity of the contact area is dependent on the angle turned through by the pulley and the weight that is suspended off the edge of the pulley.

Test Results

Linnen pointed out that not enough data was taken to draw concrete conclusions. However, the data that was taken indicated that the age of the propellant film does affect its sensitivity to impact. The propellant films which dried the longest were detonated by the hammer impact of lowest energy.

This test, if refined and instrumentated properly, would be an excellent test for comparing impact sensitivities of propellant specimens, especially thin films of propellant. The device could also be used to study ignition delay times of the propellant coatings. However, due to the priority placed on the linear burn

rate research, work with this apparatus was discontinued.

Comparison Tests

General

The first tests for comparing propellants before use in the lined hypervelocity accelerator tube were based on sensory perception. The results are emperical relations between one propellant and another propellant or group of propellants. The tests were very useful and some are still used due to their simplicity and applicability.

The tests were made for friction sensitivity, impact sensitivity, and direct heat sensitivity of propellant films. Also noted were any special results of coating and testing of the propellant film. These special results included any abnormalities observed in the propellant, propellant coating, reaction of the propellant, and products of the reaction of the propellant.

Test Description

Propellant specimen. The propellant specimens consisted of many combinations of explosives, oxidizers and additives and often were composed of several layers of different propellants. The propellant films were laid on polished steel plates in large patches of uniform thickness. Thicknesses varied depending on the physical characteristics of the propellants and the desired results of the

test. The films were usually from one mil to thirty mils in thickness.

Friction sensitivity. The friction sensitivity of a propellant specimen was judged from the reaction of the specimen to having strikers pulled across its surface with some normal force. The strikers represented the projectile surface contacting the propellant lining in the accelerator tube.

Four materials were used for strikers for each specimen. They were steel, wood, aluminum, and nylon. The strikers were shaped such that a blunt surface contacted the propellant. The strikers were dragged across the propellant surface and the relative amount of force needed to cause some reaction (if any) in the propellant was recorded.

Impact sensitivity. This test was conducted using a hammer with a smooth, slightly convex striking surface. The propellant specimen was impacted with the hammer and the relative amount of force needed to fire the propellant (as opposed to some common propellant) was recorded.

Direct flame. For this test the plate on which a given propellant specimen was coated was heated by open flame on the surface opposite the propellant film. The amount of time to reaction was noted and the physical appearance of the propellant during heating was noted.

A similar specimen was then placed in the flame with the propellant surface being directly exposed to the flame. Time to

reaction and propellant film appearance were also noted here.

Interpretation of Test Results

The interpretation of the tests just described would be difficult to present with numbers or with concrete conclusions. The tests were conducted on propellants of which little was known at the time. The propellant films were in a configuration which had not been previously reported.

The observations made during these tests did lead to the development of several different types of solid composite propellants used in the hypervelocity tube lining. Due to these tests, for instance, aluminum was added to the nitrocellulose propellants. As a result of the friction sensitivity test, glass and sand were added to make the propellant more sensitive to friction.

The comparison tests were the only means of comparing propellants until the burn rate tests were devised. They also provided the means by which the propellants could be improved or at least changed by some scientific method while there was still some uncertainty about the action of the propellant constituents in the propellant liner.

High Speed Movies

Some sixteen millimeter, high speed movies were made of several burn rate tests in atmospheric conditions and vacuum conditions.

The movies were made with a Fastax Category IV movie camera capable of film speeds up to 5,000 frames a second using Fastax 4X Reversal type film. The movie films were used to visually observe and study the entire burning sequence from ignition to depletion of the burning of the propellant strip.

EXPERIMENTAL RESULTS

General

The discussion of the results of the experimentation just described may be naturally divided into two areas both chronologically and physically. The research done on nitrocellulose propellants was completed before the summer of 1969. Since that time the polyvinyl chloride-based propellants have been investigated.

The burn rates of the nitrocellulose propellants are inferred from the comparison tests. This is due to the fact that the reactions in the nitrocellulose film which was coated on the steel specimen plates would not propagate after ignition over the entire specimen when tested at atmospheric pressures.

The linear burn rate tests began soon after the polyvinyl chloride propellants were developed. These propellant's reactions did propagate and therefore linear burn rate tests could be made.

Nitrocellulose Propellants

Nitrocellulose and Solvent

The nitrocellulose formed a thick, honey-like mixture when dissolved in either methyl ethyl ketone (MEK) or butyl acetate (BA) (10% nitrocellulose by weight). This mixture coated steel surfaces with a hard thin (less than one mil) coating.

The tests for impact sensitivity and for friction sensitivity

showed that the coating was relatively inactive. Only areas directly under the steel hammer surface would react when impacted. No reaction resulted from the friction tests with steel, nylon, wood, or aluminum strikers.

The specimen did not burn in the open flame when coated on the steel plate it did burn when completely free on all surfaces. The flame was not intense and did not produce a large gas volume.

After reviewing these observations and the results of lined shots in the hypervelocity accelerator it was decided that the nitrocellulose propellant was not producing the desired action in the accelerator propellant liner.

Metal Additives

Although the nitrocellulose mixture alone was not producing the desired effects in the accelerator liner, it was still an excellent carrier and produced smooth, hard coatings which were desired. Aluminum dust (shiny) was added to the nitrocellulose carrier to improve its explosive characteristics without changing its coating properties. The best combination was about one part aluminum to two parts nitrocellulose by weight.

These propellant specimens were tested and found to be generally more active than the nitrocellulose alone. However, these propellants still would not strike by friction with the nylon, wood, or aluminum strikers.

The steel powder was added in the same amount by weight as the aluminum dust but the greater density of each steel particle caused the coating to run when coated on a vertical plane. The reaction to impact and friction was about the same as the aluminum propellants. Due to the importance of having a smooth coating on the accelerator tube walls, the propellant with the steel additive was not used for any lined accelerator shots.

Abrasive Additives

As the addition of powdered aluminum increased the reaction of the propellant without increasing its sensitivity to impact and friction substantially, it was decided to approach the ignition problem by adding some inert abrasive materials to the propellants.

Fine sand was added in small amounts (one part sand to five or six parts aluminum by weight) but the sand particles were not small enough. The friction tests revealed that spots where the sand particles were located would either react in the immediate vicinity, or the particle would dislodge. The particle would then be dragged for some distance underneath the striker, separating the striker surface from the propellant.

Ground glass with much finer particle size than the sand was mixed into the propellant in the same proportions as the sand. This propellant gave a smooth coating and possessed greater sensitivity than did the previously described formulations.

The steel striker caused a reaction in an area about the width of the striker down the length of the specimen. It was observed that the propellant had reacted intermittently down the length of the specimen as the fringes of the reaction area were very uneven. The aluminum and wood strikers also produced greater reaction from friction tests than previously attained. The nylon striker still produced little reaction in the propellant. This indicated that the glass was increasing the friction energy input considerably.

Lined shots in the hypervelocity accelerator using aluminum, wooden, and nylon projectiles indicated that the propellant was igniting too quickly and was slowing, stopping or destroying the projectiles in the tube. This pointed out the need for more accurate evaluation of the ignition and burning characteristics of the thin layer of propellant.

Oxidizers

In an attempt to make the propellant release more gas at reaction, oxidizers such as ammonium perchlorate, potassium chlorate, and potassium nitrate were added to the aluminum-nitrocellulose propellant in about a one to one ratio by weight with aluminum.

Without the abrasive additives, these propellants were no more active than the propellants with only aluminum and nitrocellulose. However, with the addition of ground glass, the propellants exhibited the same sensitivity as the aluminum-nitrocellulose propellants with

the glass additives except that the reaction seemed to produce a much greater volume of gas.

Propellants containing nitrocellulose, oxidizer, and ground glass only were relatively insensitive. The aluminum dust apparently was important to the reaction of the oxidizer.

Shots in the lined accelerator with these propellants resulted in complete firing of the propellant liner, but also slowed, stopped, or destroyed the projectiles being fired.

Addition of Explosives

Much experimentation was done on propellants containing explosives in an effort to develop a greater gas producing propellant liner. The graininess of the explosives also allowed the removal of a certain amount of the inert abrasives from the propellant formulation. This created a propellant which was as sensitive to friction as the previous propellants and produced a greater amount of gas after ignition of the propellant liner. Black powder (commercial and laboratory made), RDX, PETN, and lead azide were all tested by themselves and in various combinations with oxidizers and metal additives. With the exception of black powder, all these explosives made a more active, greater gas producing propellant from the previously tested propellants.

The black powder propellants were no more sensitive to impact and friction tests than the glass-oxidizer-aluminum combination but

did exhibit greater propensity for burning in the direct heat test.

Of the explosive combinations tested RDX appeared to produce the greater increase in sensitivity and gas production. However, even the reaction of propellants with explosive additives would not propagate past the point of impact of the hammer or the path of the friction test devices. The propellants still refused to react to friction when struck with nylon or wood and very little reaction was realized from striking the propellant with aluminum.

The lined shots made in the accelerator with the explosive propellants yielded loud gun reports and apparently more gas release but did not give projectile accelerations of any consequence.

McCormick-Selph Explosives

Brown[35], in his survey of explosive materials stated that McCormick-Selph had developed some proprietary commercial explosives which were apparently the only materials exhibiting reaction rates between slow deflagration and detonation at the time of his report (1967). Two of these materials designated Mc/S (McCormick-Selph) 300, 104 and Mc/S 510, 164 were used as additives to the nitrocellulose propellants.

The propellants tested with these additives were combinations of oxidizer and explosive and combinations of oxidizer, explosive, and aluminum. These propellants were also tested in coatings with more than one layer and different propellants in each layer.

All of these propellant combinations appeared to react more consistently with the impact test. The strikers caused more propellant to react and made more uniform paths of reaction on the propellant strip. Even the nylon striker caused some reaction in the specimens.

It was often noted that the propellant containing the McCormick-Selph explosives would propagate partially from under the hammer impact area or from the striker path. The greater the concentration of the McCormick-Selph material, the more often this phenomena was observed.

Also when multilayered coatings were tested, it was observed that the McCormick-Selph layer, if on top, would react with little energy input while the layers below remained unaffected.

Shots made in the lined accelerator tube were more productive than before. Higher velocities and higher tube pressures were recorded. A typical propellant combination which gave good comparison tests and also good lined shots in the accelerator consisted of:

30% (by weight) Nitrocellulose

50% Ammonium perchlorate

5% McCormick-Selph 510, 164

15% Aluminum

Although better comparison tests and good lined accelerator shots resulted from the addition of the McCormick-Selph explosives it appeared that some aspect of the propellant formulation was hindering its reaction. Literature available and contacts made with

McCormick-Selph indicated that the Mc/S material used should be able to sustain a burning reaction, once initiated, without any external energy input.

After reviewing the properties of the solvent dried nitrocellulose that was being used as a carrier and binder, it was decided that the propellant problem was mechanical. The nitrocellulose was a good binder because it dried in films. The films surrounded and isolated particles of any additives. This phenomena of separating the explosive particles from the oxidizer particles while still making a hard thin coating of propellant was inhibiting the reaction of material combinations which should have been highly active and whose reactions would have been normally self-supporting once initiated.

This observation led to a change in propellant binder and consequently to the linear burn rate research.

Polyvinyl Chloride Propellants

General

The polyvinyl chloride propellants are the propellants currently being tested in the hypervelocity accelerator. Linear burn rate tests, normal vector burn rate tests, and the impact energy tests which were described in the section on experimental apparatus were conducted on the PVC (polyvinyl chloride) propellants.

The PVC binder was chosen as an alternative to the nitrocellulose binder which, as has been explained, was inhibiting the re-

actions of the propellant constituents. The polyvinyl chloride being used is a combination of Geon 27 (63% by weight), a commercially distributed polymer, and Dioctyl Adipate (37% by weight), a commercially distributed plasticizer.

Analysis of the results of the burn rate tests showed that regardless of other parameters being varied, the longitudinal burn rate was dependent on the thickness of the film of propellant. The burn rates generally increased with increase in film thickness.

Coating Characteristics

The PVC coat·s were not as hard or as thin as the nitrocellulose coatings. The thin propellant layers which were coated on the steel test plates and the coatings on the accelerator tube walls could be applied smoothly and dried quickly (within one half hour). The propellant was easy to mix and stored reasonably well.

The Effects of Low Pressures on Burn Rates

The change in pressure of the surroundings of the propellant specimens from atmospheric pressure to a vacuum (five millimeters of mercury) had no apparent effect on burn rates. This conclusion is supported by information received from McCormick-Selph to the effect that they had observed no adverse effects of vacuums on reactions of their explosive materials.

The Effects of Propellant Curing Time on Burn Rates

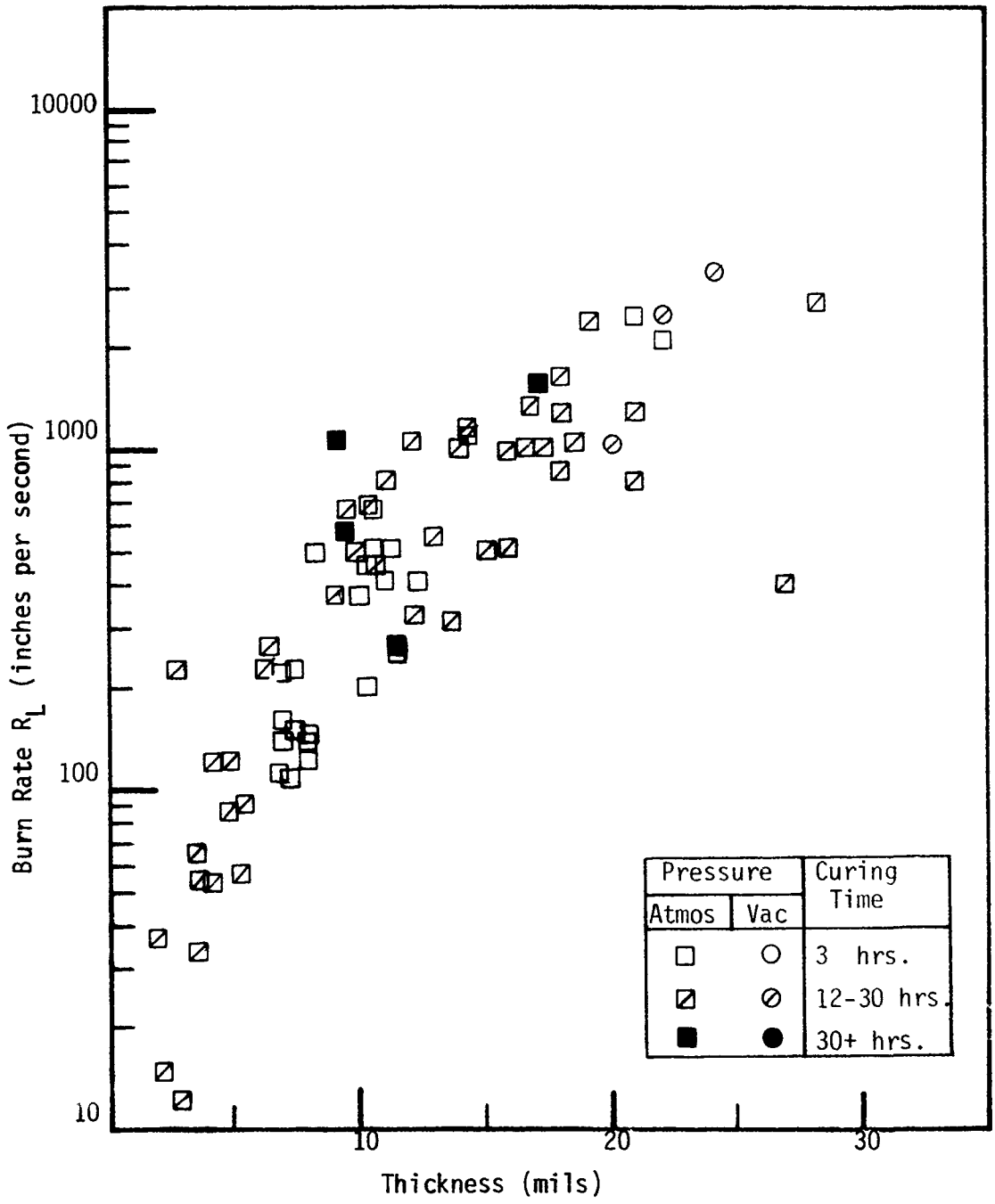
Although mixture age and propellant coating age were recorded and graphed as separate parameters, these apparently had little effect on either vacuum or atmospheric burn rates as can be determined from Figures 27 and 28. These are graphs of different propellant combinations for which burn rate tests were made.

The burn rates for propellant A (FIG 27) which consisted of equal parts of Mc/S 510,164 and potassium nitrate in 10% PVC ranged from several inches per second for thickness below five mils to 2000 inches per second for a twenty-five mil thickness. Propellant B (equal parts of Mc/S 510,164 and potassium nitrate in 15% PVC) burn rates (FIG 28) range from 500 inches per second for a ten mil film thickness to 8000 inches per second for a film thickness of twenty-two mils. Burn rate data on propellant B is more scattered.

Further tests were made on a propellant similar to propellant B but containing potassium chlorate instead of potassium nitrate. These points are plotted in Figure 28. There are very few data points but the potassium chlorate propellant did not do as poorly in a vacuum as had been predicted based on discussions of previous test results with McCormick-Selph representatives.

The different coating ages are noted in the graphs but there is apparently no effect of coating age on the burn rates of thin films of these certain propellants.

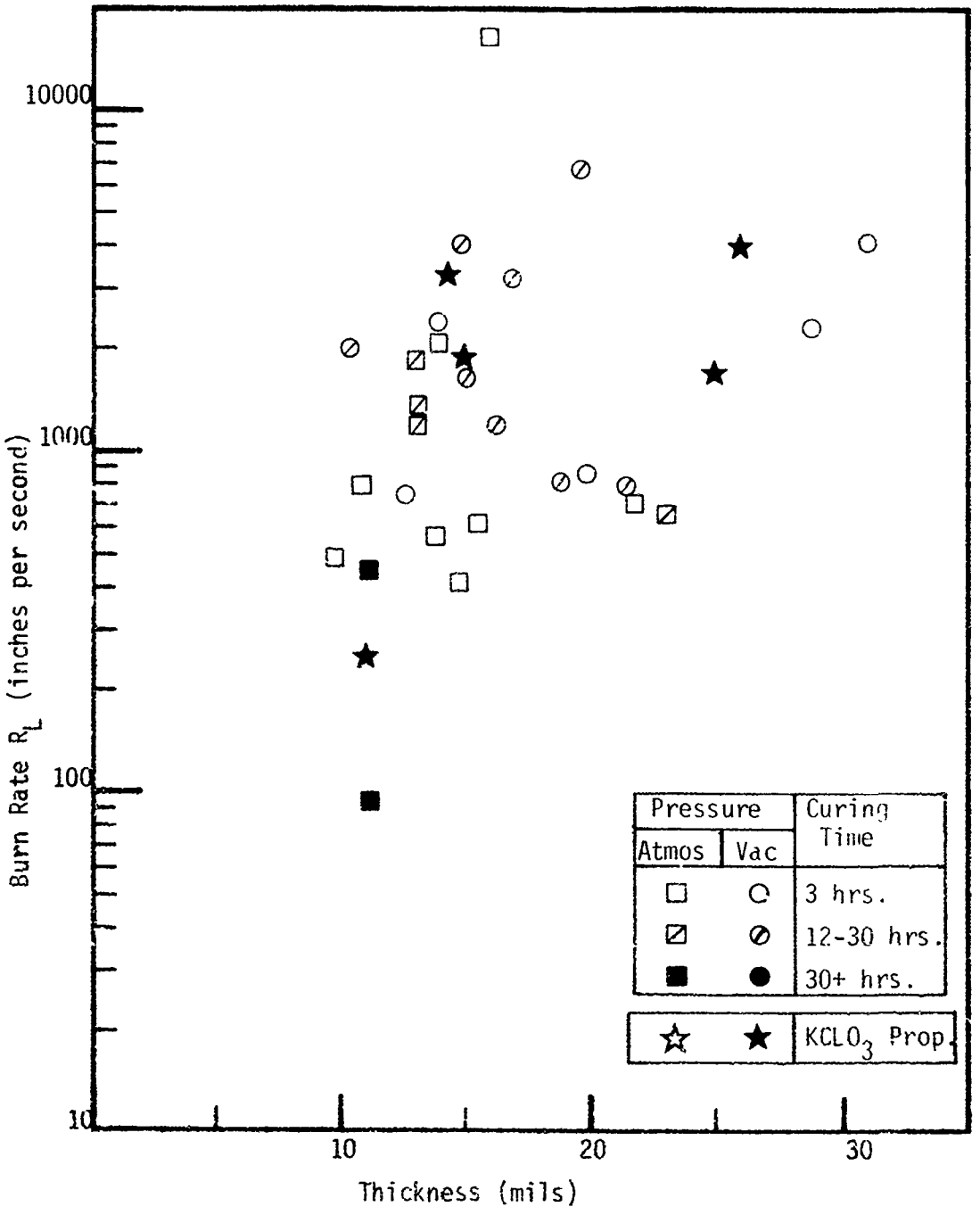
The physical appearance of the propellant strip also was not



Propellant A - 45% Mc/S 510,164, 45% KNO_3, 10% PVC

Burn Rate Dependence on Film Thickness - Propellant A

FIG 27



Propellant B - 42.5% Mc/S 510,164, 42.5% KNO_3, 15% PVC

Burn Rate Dependence on Film Thickness - Propellant B

FIG 28

affected by long drying periods.

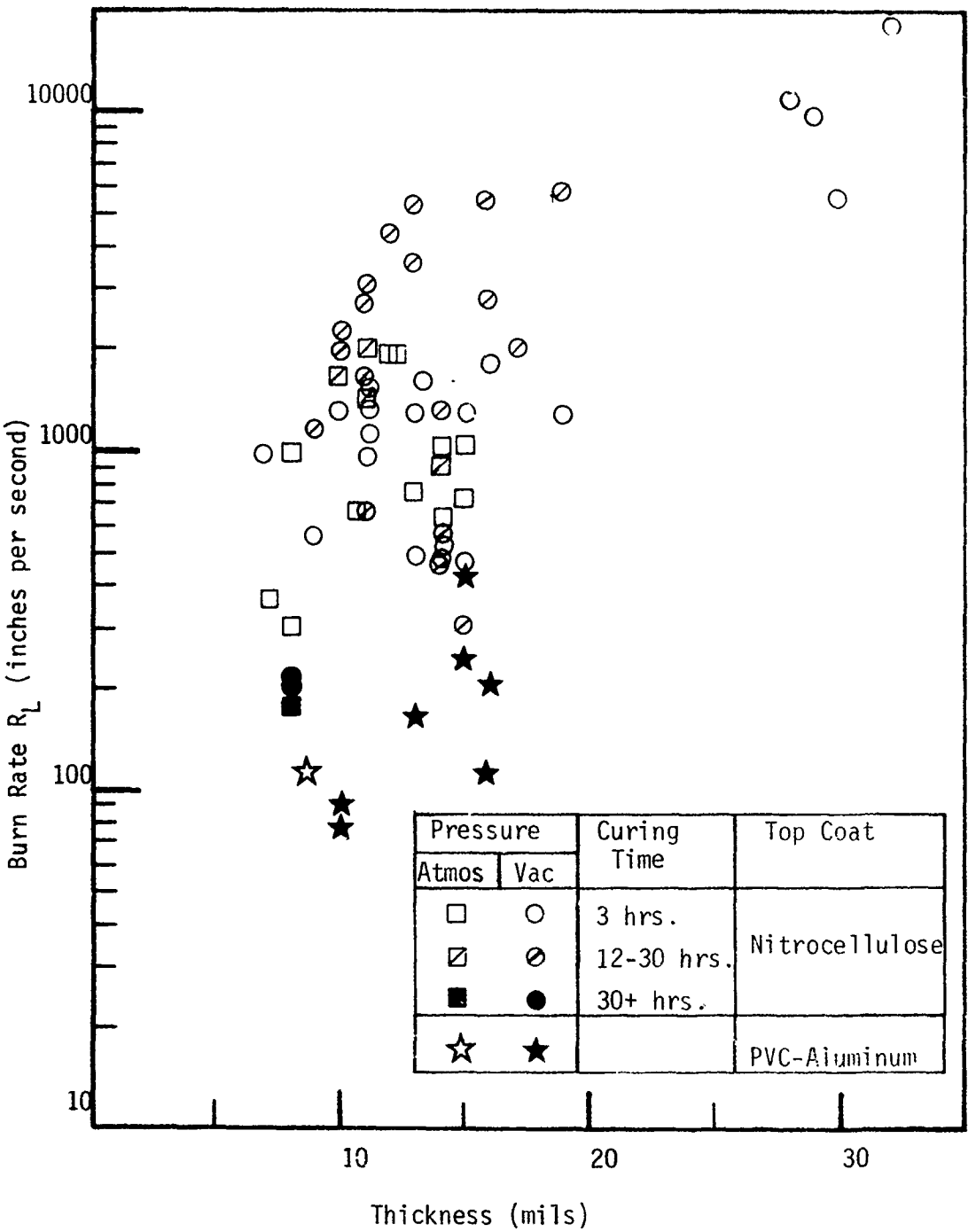
The Effects of Varying Binder Content on Burn Rates

Propellant A is 10% PVC binder by weight. Propellant B is 15% PVC binder. It appears from Figures 27 and 28 that propellant B may possess the greater potential for high burn rates at a given thickness. Propellant A averages approximately 800 to 900 inches per second for a film thickness of fifteen mils while propellant B averages slightly over 1000 inches per second for the same film thickness. With the lack of a large amount of data on propellant B this may be an unfair evaluation of the difference. Propellant B however does exhibit some high burn rates in the ten to fifteen mil thickness range while propellant A remains consistently below 2000 inches per second for this thickness range.

The Effects of Top Coats on Burn Rates

Figure 29 shows the results of coating over the top surface of some dried films of propellant B with both nitrocellulose and PVC containing aluminum dust. These tests were very interesting since Physics International[36] has proposed using a collapsible inner liner surrounded by a propellant layer inside a rigid tube as a possible method of obtaining hypervelocity accelerations.

The effects on the coating itself were surprising. The nitrocellulose top coat did not increase the propellant film thickness and often decreased it. No sure explanation for this phenomena



Effects of Top Coats on Burn Rates of Propellant B

FIG 29

has been provided. The nitrocellulose might possibly be penetrating the PVC coating and, in drying, compresses the PVC layer.

The aluminum-PVC top coat was more flexible than the nitrocellulose. Fragments of the unburned top coat were found after several tests using the aluminum-PVC top coat. This top coat also shrinks the propellant film.

The burn rates measured for the propellant strips with overcoats were generally higher than for propellant tests without the top coat. The burn rates for thicknesses of ten mils to fifteen mils were generally in a range from 1000 inches per second to 4000 inches per second. Several shots were above 5000 inches per second for this thickness range. For a thirty mil thickness burn rates of 10,000 inches per second were observed. These high burn rates were for the nitrocellulose top coat.

The data from aluminum-PVC top coat tests fell at the bottom of the data range in the 100 to 500 inches per second area.

The nitroceilulose overcoat may be increasing the burn rates of the propellant film by partially confining the film on the surface opposite the steel plate. This would keep the reaction zone slightly closer to the propellant surface. However, the shrinking of the PVC propellant by the nitrocellulose top coat also caused a problem in coating lined accelerator tubes. This top coats pulled the PVC propellant from the walls of the lined tubes to such an extent that no advantage could be taken of the increased burn rates.

The PVC top coat appeared to be promising as an inert coating to

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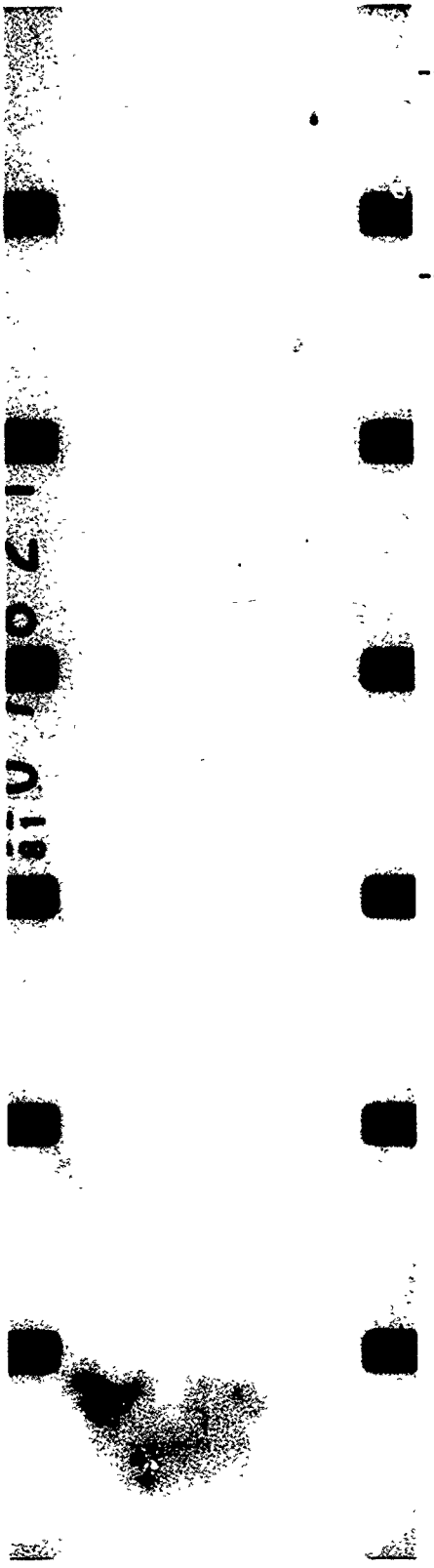
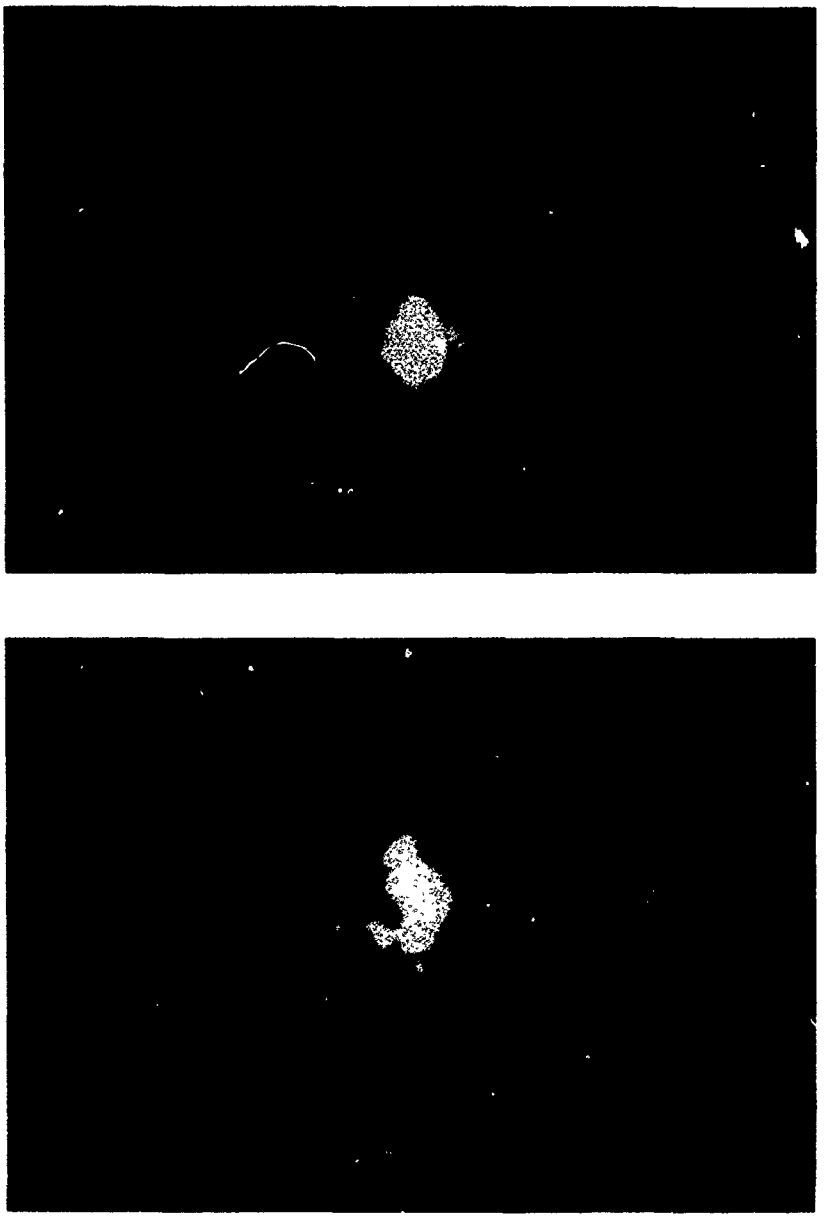


-- Ignition of Specimen by Hot Wire

-- Reaction Zone Burning Along Propellant Specimen

High Speed 16mm Movie of a Film of Propellant B Burning in a Vacuum

FIG 30



Separate Frames of High Speed 16mm Movie of the Burning of a Thin Film of Propellant A at Atmospheric Pressure

FIG 31

act as a flexible tube inside the accelerator propellant lining.

The Effects of Different Oxidizers on Burn Rates

This area was not completely investigated but the results of the tests that were made are worthy of being mentioned. Some burn rate tests were made with a propellant similar to propellant B except that the potassium nitrate was replaced by potassium chlorate.

Information received on some McCormick-Selph experiments indicated that the Mc/S explosives in combinations with chlorates reacted poorly in a vacuum. However, the few burn rates measured in the Hypervelocity Laboratory were almost as high as the propellant B burn rates. The burn rate of one twenty-six mil specimen was 4000 inches per second (FIG 28).

High Speed Movies

Several high speed movies were made of the burning of a propellant specimen. Some difficulty was encountered in filming the high speed reaction in the vacuum chamber due to poor lighting and a slight change in the burning characteristics of the film in a vacuum. It was difficult to isolate a definite flame front in the movies that were made in the vacuum.

The film strip in Figure 30 illustrates the hot wire ignition and possibly displays a reaction zone traveling down the length of the specimen. Due to the graininess of the film and the lack of sufficient illumination of the propellant film and velocity

measuring stations it is difficult to determine exactly what this zone represents. The burn rate recorded on this test of propellant B was 4000 inches per second for a 15 mil thick specimen.

The pictures in Figure 31 are single frames of a film strip taken of a relatively slow burning (fifteen inches per second) thin film of propellant A. The film thickness was mils and the test was at atmospheric pressure The horizontal line just below th bright flame zone is the surface of the steel plate. The small bright spots in the background are the needle base collimators of the photodiode stations.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In the beginning the primary task of this research was to develop a fast burning propellant film for the lined hypervelocity accelerator launch tube. This developed into a research program for investigating thin films of propellants with burn rates in a region not previously reported.

Several important conclusions may be drawn concerning the burning rates of thin films of the propellants tested in this research.

1. The longitudinal burn rate is mainly dependent on thickness ranging from several inches per second for film thicknesses of less than five mils up to the neighborhood of 10,000 inches per second for thirty mil film thickness.

2. There is little or no variation in burn rates between propellant tests in atmospheric pressure and propellant tests in vacuum pressures.

3. There is no effect of the length of curing time of the propellant coating or of the age of the propellant mixture on burn rates.

4. A nitrocellulose layer coated over the propellant film will increase its burn rate but will destroy the bond between the propellant film and a steel surface.

5. The McCormick-Selph explosive apparently will react in propellant formulations with potassium chlorate though not as well as with potassium nitrate.

No concrete conclusions can be made concerning the effects of the change in percentage of polyvinyl chloride on burn rates. The experimental evidence indicates that propellant B (the mixture with 15% PVC by weight) may be capable of producing higher burn rates than the 10% PVC propellant. However, the amount of data taken is not great enough to warrant drawing a sure conclusion.

Recommendations

It is obvious from the scope of this report that there are many unexplored areas in the field of burn rates of propellants. The burn rates reported here are in the range between deflagration and detonation and in an area where apparently the only other work done was by McCormick-Selph in developing pyrotechnic fuse delays.

Brown[35] has listed many uses for propellant formulations which would burn in the range intermediate between deflagration and detonation. Among these are explosively-actuated tools, chaff ejectors, gas generators, metal forming and welding, single-grain gun propellants, high acceleration rockets, and bursters for materials which a detonation would destroy. These are reasons enough for a more complete search for and investigation of propellant formulations which fit in that burn rate region.

For application in the lined hypervelocity accelerator tube there are several recommendations for further study which could be made:

1. More refined and more complete tests for longitudinal burn rates would possibly result in an accurate control over the burn rates of the propellant liner.

2. The refinement of the impact energy test might yield an accurate method of studying the delay time to ignition by impact of propellant films.

3. The addition of a high pressure test vessel for high pressure burn rate tests would give more information on the reaction of the propellant liner in the accelerator tube and a give a greater capability for testing burn rate theories.

4. The feasibility of using an inert, collapsible inner liner in the propellant lined accelerator tube could be studied using the present burn rate facility used for studying the effects of top coats on the burn rates of the propellant film.

5. A better capability for making good, high speed movies of the fast reacting propellant films in the vacuum tests might reveal some interesting changes that take place in the burning of the propellant film in a vacuum.

6. An examination of burn rates of thin films resulting from the constant input of energy down the length of the specimen may give results more closely related to the burning phenomena of the propellant liner in the hypervelocity accelerator launch tube.

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APPENDIX A

RANDOM SAMPLING OF COMPARISON TEST RESULTS

RANDOM SAMPLING OF COMPARISON TEST RESULTS
Y(yes) ; N(no)

No.	Propellant Coating (by parts)	Impact Test	Friction Test				Direct Flame	Comments
			Nylon	Wood	Aluminum	Steel		
1	20 NC;30 $KCLO_3$;20 G	Y	N	N	Y	Y	N	
2	10 NC;10 $KCLO_3$;10 G;5 AL; 5 C	N	N	N	N	Y	N	Less active than #1
3	20 NC;70 $KCLO_3$;40 G;70 AL;10 C	N	N	N	N	N	N	
4	20 NC;40 NH_4CLO_4;50 ST;20 G	Y	N	N	Y	Y	N	
5	97 NC;50 AL;20 G	N	N	N	N	N	N	
6	1 NC;1 ST;1 NH_4CLO_4	Y	N	N	N	N	N	
7	1 NC;3 NH_4CLO_4;1 G	Y	N	Y	Y	Y	N	Very loud report on impact.
8	1 NC;1 NH_4CLO_4;1 G	N	N	N	N	Y	N	
9	1 NC;1 NH_4CLO_4;1 Black Powder;1 G	Y	N	N	N	N	Y	
10	1 NC;1 $KCLO_3$;1 Black Powder;1 G	Y	N	N	N	N	Y	
11	a) 20 NC;30 $KCLO_3$;20 G,30 AL b) NC	Y	N	N	Y	Y	N	
12	1 NC;1 G;1 ST;1 $KCLO_3$	Y	N	N	Y	Y	N	
13	1 NC;1 G;3 NH_4CLO_4;.5 AL	Y	N	N	Y	Y	N	Very loud report on impact.
14	1 NC;1 G;3 $KCLO_3$;1 AL	Y	N	Y	Y	Y	N	Strikes well with wood.
15	a) NC b) 1 NC;1 C;1 AL;3 $KCLO_3$ c) 1 NC	Y	N	N	Y	Y	N	
16	a) NC b) 1 NC;1 $KCLO_3$ c) NC d) NC e) 1 NC;1 AL;1 G	Y	N	N	N	Y	N	
17	a) NC b) 1 NC;1 AL;1 G;3 $KCLO_3$ c) 1 NC;1 C;2 $KCLO_3$,.5 G	Y	N	N	N	Y	N	

No.	Propellant Coating (by parts)	Impact Test	Friction Test				Direct Flame	Comments
			Nylon	Wood	Aluminum	Steel		
18	a) NC b) 1 NC;.3 G c) 1 NC;1 $KCLO_3$ d) 97 NC;3 AL e) 97 NC;3 AL	Y	N	N	N	Y	N	
19	a) NC b) 1 NC;1 G;1 AL;3 $KCLO_3$ c) 1 NC;	Y	N	N	N	Y	N	
20	a) NC b) 3.5 NC;2 PETN	Y	N	N	N	N	N	
21	a) NC b) 3.5 NC;2 G;2 PETN c) 1 NC;1 $KCLO_3$	Y	N	N	N	Y	N	
22	a) NC b)1 NC;1 G;1 AL c) 1 NC;1.5 C	Y	N	N	N	Y	N	
23	a) NC b) 1 NC;1 $KCLO_3$ c) 1 NC;.3 G	Y	N	N	N	Y	N	
24	a) NC b) 1 NC;2 $KCLO_3$;.7 AL;.3 C;.25 G	Y	N	N	N	Y	N	No effects due to carbon.
25	a) NC b) 1 NC;2 $KCLO_3$;.75 AL;.25 C; .5 G	Y	N	Y	Y	Y	N	Low glass content
26	a) NC b) 1 NC;1 C;2 $KCLO_3$;.5 G	Y	N	N	N	N	N	
27	a) 1 NC;2 NH_4CLO_4;.5 AL;.1 G b) 1 NC;3 L.A.	Y	N	N	N	Y	Y	Burns after continous heating.
28	a) 1 NC,2 NH_4CLO_4;.5 AL;.1 G b) " c) 1 NC;3 L.A.	Y	N	N	N	Y	Y	

No.	Propellant Coating (by parts)	Impact Test	Friction Test				Direct Flame	Comments
			Nylon	Wood	Aluminum	Steel		
29	a) 1 NC;2 NH_4CLO_4;.5 AL;.1 G b) " c) "	Y	N	N	N	Y	Y	Less sensitive than 28.
30	1 NC;1.5 NH_4CLO_4;.5 x-104; .5 AL;.1 G	Y	Y	Y	Y	Y	N	Good striking characteristics.
31	1 NC;1.8 NH_4CLO_4;.2 x-104;.5 AL	Y	Y	Y	Y	Y	N	Same as 30.
32	a) 1 NC;2 NH_4CLO_4;.5 AL;.1 G b) " c) 1 NC;1.5 NH_4CLO_4;.5 x-10'; .5 AL;.1 G	Y	N	N	Y	Y	Y	Top coat struck leaving lower coat
33	a) 1 NC b) " c) 1 NC;1 RDX d) 1 NC;1 RDX e) 1 NC;.25 G f) 1 NC;1.5 NH_4CLO_4;.5 x-104 .1 G	Y	N	N	N	Y	Y	Same as 32
34	a) 1 NC b) " c) 1 NC;.25 G d) 1 NC;1.8 NH_4CLO_4;.2 x-104; .5 AL	Y	Y	N	Y	Y	Y	
35	a) 1 NC b) " c) 1 NC;.25 G	Y	N	N	N	N	N	
36	a) 1 NC;1 RDX b) 1 NC;1.5 NH_4CLO_4;.5 x-104;.1 G	Y	Y	Y	Y	Y	Y	
37	a) 1 NC;1.8 NH_4CLO_4;.2 x-104;.5 AL b) 1 NC;1 RDX c) 1 NC;1.5 NH_4CLO_4;.5 x-104;.5 AL; .1 G	Y	Y	Y	Y	Y	Y	
38	a) 1 NC;1.8 NH_4CLO_4,.2 x-104;.5 AL b) 1 NC;1 RDX c) 1 NC;1.8 NH_4CLO_4;.2 x-104;.5 AL	Y	Y	Y	Y	Y	Y	

APPENDIX B

SUMMARY OF LINEAR BURN RATE TESTS

SUMMARY OF LINEAR BURN RATE TESTS

No.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
1	10/1/69	Atmos.	3.67	45%	45%	10%	51.3		51.3	
2			3.67				64.5		64.5	
3			6.3				222		222	
4	10/3/69		3.0							
5			1.67				37		37	
6			1.67							
7			2.67				22.6	8.45	12.3	
8			3.3				22.6	72.8	34.8	
9			2.0				15.1		15.1	
10	10/8/69		6.3				200	400	267	
11			9.0				294	500	370	
12			9.0							
13			6.3							
14			2.67				222	222	222	
15			9.3				667	667	667	
16	10/10/69		11.0				667	1000	800	
17			12.67				645	487	556	
18			16.67							
19			14.3				1250	1000	1110	
20			10.3				1000	536	690	
21			12.0				714	2220	1080	
22			15.0					500	500	
23	10/14/69		16.67				1820	1110	1380	
24			18.3				1000	1050	1025	
25			19.0				2850	2000	2350	
26			18.3				4000	1110	1740	
27	10/15/69		10.0				645	400	495	
28			10.67				445	445	445	

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
29	10/15/69	Atmos	11.3				333	1000	500	
30			11.67					253	253	
31			10.67				667	400	500	
32			20.3							
33			12.3				445	364	400	
34	10/17/69		12.0						333	
35			11.3							
36	10/20/69		11.67							
37			11.3							
38			11.3					267	267	
39			9.3				500	690	580	
40			12.0							
41	10/21/69		7.0							
42			8.0				339	91	144	
43			8.3					488	488	
44			7.6					143	143	
45			7 0				83.5	166	110	
46			7.3				222		222	
47			7.0				153		153	
48	10/22/69		7.3				105		105	
49			8.0				116	170	137	
50			8.0				125		125	
51			7.0				137		137	
52			8.0							
53			7.3							
54			7.0				220		220	
55	10/23/69		4.0				53		53	
56			5.0				58	55	57	

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
57	10/23/69	Atmos.	4.6	45%	45%	10%	122		122	
58			5.3				91		91	
59			4.6				89		89	
60			5.0							
61			4.0				122		122	
62	10/24/69		10.3					200	200	
63			11.0				400		400	
64			10.0				500	286	362	
65			10.0				500		500	
66			10.6				667		667	
67			10.3				445		445	
68			10.3							
69	10/28/69		27.0				400		400	
70			18.0				1120	1480	1270	
71			18.0				667	1140	843	
72			16.0					500	500	
73			32.6							
74			21.0				1000	667	800	
75			21.0				2200	890	1270	
76	10/29/69		14.3				1000	1330	1140	
77			16.6						1000	
78			16.0						976	
79			13.6					313	313	
80			14.0				1000	1000	1000	
81			17.3				1000		1000	
82	1/29/70	Vac	13.5							
83			10.0							
84			10.0							

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
85	1/29/69	Atmos.	14.2	45%	45%	10%				
86		Vac.	15.6							
87			11.0							
88			19.8							
89	2/4/70	Atmos.	18.0							
90			21.0				2700	2272	2470	
91		Vac.	23.0							
92			22.0							
93			22.0							
94			24.0							
95			16.0							
96	2/11/70	Atmos.	17.0				1144	2222	1509	
97		Vac	20.0							
98			14.0							
99			24.0				3000	3846	3345	
100			22.0				2150	3080	2530	
101		Atmos.	28.0				5400	1820	2730	
102		Vac.	20.0					1330	1330	
103	2/12/70	Atmos.	22.0				1980	2140	2060	
104		Vac.	21.0							
105		Atmos.	16.0	42.5%	42.5%	15%	16670	16670	16670	
106			19.0							
107			20.0							
108			10.0				548	455	490	
109			22.0				817	615	701	
110	2/13/70		15.0				218	3840	412	
111			14.0				294	5500	559	
112			11.0				780		780	

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
113	2/13/70	Vac.	11.0							
114			13.0							
115			11.0							
116			12.0							
117	2/18/70		15.0							
118			15.0							
119			15.0							
120			17.0							
121	3/11/70	Atmos.	12.0							NC
122			12.0				2000	2000	2000	
123		Vac.	9.0							
124	3/11/70	Atmos.	11.0				2500	2000	2222	
125			10.0				2500	1250	1666	
126		Vac.	11.0							NC
127			11.0				2000	1428	1666	
128			11.0							
129			11.0						667*	
130			13.0				1250		1538*	
131		Atmos.	14.0				2000	2500	2222	
132		Vac.	14.0				3333		2222*	
133		Atmos.	12.0						2222*	NC
134		Vac.	15.0							
135	3/12/70		13.0				20000	2000	3636	
136			16.0				20000	3333	5770	
137			19.0				40000	4000	6153	
138	3/16/70		12.0				6666		4444*	
139			11.0				4000		3076*	
140			9.0							
141			10.0				5000		2222*	

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
142	3/13/70	Vac.	10.0	42.5%	42.5%	15%	3333		2000*	
143			11.0				3333		2857*	
144		Atmos.	11.0				2500	1000	1428	
145	3/16/70		15.0				1111	1000	1052	
146		Vac.	15.0				2000	1000	1333	
147			13.0				5000		1666*	
148			14.0				1111		1052*	
149	3/17/70		12.0							
150			17.0				2500	1666	2000	
151	3/18/70	Vac.	12.0						NC	
152			11.0						1111*	
153		Atmos.	13.0				769	769	769	
154		Vac	11.0				1666		1428*	
155			11.0				1428		952*	
156			11.0				1426		1539*	
157			11.0				714		1000*	
158	3/20/70		14.0							
159		Atmos.	14.0						508*	
160		Vac.	14.0					1333	923*	
161			130							
162			15.0						307*	
163			14.0						470*	
164			14.0						571*	
165	3/23/70	Atmos.	14.0				478	909	625	
166			15.0				666	833	740	
167		Vac.	14.0				455	833	585	
168			15.0				434	588	500	
169			14.0						500*	

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
170	3/23/70	Vac.	13.0	42.5%	42.5%	15%			500*	
171			14.0					526	500*	
172	3/31/70		8.0							
173		Atmos.	8.0				166	200	182	
174		Vac.	8.0						200*	
175			8.0							
176			8.0						222*	NC
177			9.0							
178			8.0							
179	4/1/70		8.0							
180		Atmos.	7.0					1000	375*	
181		Vac.	7.0							
182			8.0						222*	
183		Atmos.	11.0					667	286*	
184		Vac	19.0				1333	1333	1333	
185			13.0				4000	800	1333	
186	4/2/70		7.0				1000		667*	
187			9.0							
188			10 0				1333		1000*	
189			9.0				571		242*	
190		Atmos.	8.0					307	343*	
191			8.0				1000		276*	
192		Vac.	9.0							
193	4/3/70	Vac.	32.0				20000	20000	20000	
194			28.0					16667	11764	
195			30.0				10000	4000	5714	
196			29 0				10000	4000	5714*	
197	4/10/70	Atmos.	7.0							

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
198	4/16/70	Vac.	6.0	42.5%	42.5%	15%				
199		Atmos.	6.0							
200	4/24/70		17.0							PVC-AL
201		Vac.	13.0							PVC-AL
202	4/27/70	Atmos	12.0							
203			11.0				61.5	210.5	95	
204			11.0				444		81*	
205			10.0							PVC-AL
206			10.0						108	
207		Vac.	10.0							
208			11.0							
209		Atmos.	10.0							PVC-AL
210			14.0							
211	4/28/70	Vac.	11.0							
212			10.0						81.6	
213			10.0					86.9	88.3	
214	4/29/70		17.0				8000	2000	3200	
215			16.0				833	2000	1176	
216			13.0						166	PVC-AL
217			16.0				117.6		105	
218			15.0						240*	
219			15.0				500	400	444	
220			16.0				200	222	210	
221	6/17/70		10.3				2000	2000	2000	
222			15.0				1600	1740	1665	
223			14.67				4000	4000	4000	
224		Atmos.	13.0				1250	1429	1335	
225			13.0				1250	1000	1111	

SUMMARY OF LINEAR BURN RATE TESTS CONTINUED

NO.	DATE	PRESSURE	FILM THICKNESS (mils)	PROPELLANT			VELOCITY (in/sec)			TOP COAT
				KNO_3	Mc/S 510,164	PVC	1-2	2-3	1-3	
226	6/17/70	Atmos.	13.0				1250	3330	1819	
227		Vac.	20.0				578	1539	852	
228			19.67							
229			21.0				953		953	
230			19.6					6670	6670	
231		Atmos.	23.0				909	513	655	
232		Vac.	18.7				900		714	
233	6/18/70		30.0				1379	1429	1404	
234		Atmos.	15.67				769	527	624	
235		Vac.	29.0				2000	2860	2350	
236			12.67				556	1111	741	
237	6/23/70		8.0	$KCLO_3$ for KNO_3						
238			11.0				174	444	250	
239			14.3				3333		3333	
240			15.0				20000	1000	1900	
241			25.0				1740		1740	
242	6/25/70		26.0				4000	4000	4000	
243			7.0							
244			10.67							

VITA

Miles L. Sawyer was born 27 May 1947 in Llano, Texas to Sue G. and James C. Sawyer. He graduated from Burnet High School in 1965. In 1966 he married the former Mary C. Lucksinger and they have two children--Robert, age 3 years, and Catherine, age 3 days. In August 1969 he received a B. S. Degree in Aerospace Engineering from Texas A&M University. After completing R.O.T.C. requirements at Texas A&M University he received a Commission in the United States Air Force. While at Texas A&M University he was a member of the Corps of Cadets, the American Institute of Aeronautics and Astronautics, Sigma Gamma Tau, and Tau Beta Pi. He is presently attending Texas A&M University on a Graduate Assistantship. His permanent mailing address is 509 North Pierce Street, Burnet, Texas 78611.

The typist for this thesis was Pam Allen.

Appendix B

Hypervelocity Laboratory Instrumentation

APPENDIX B

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^{o} 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.

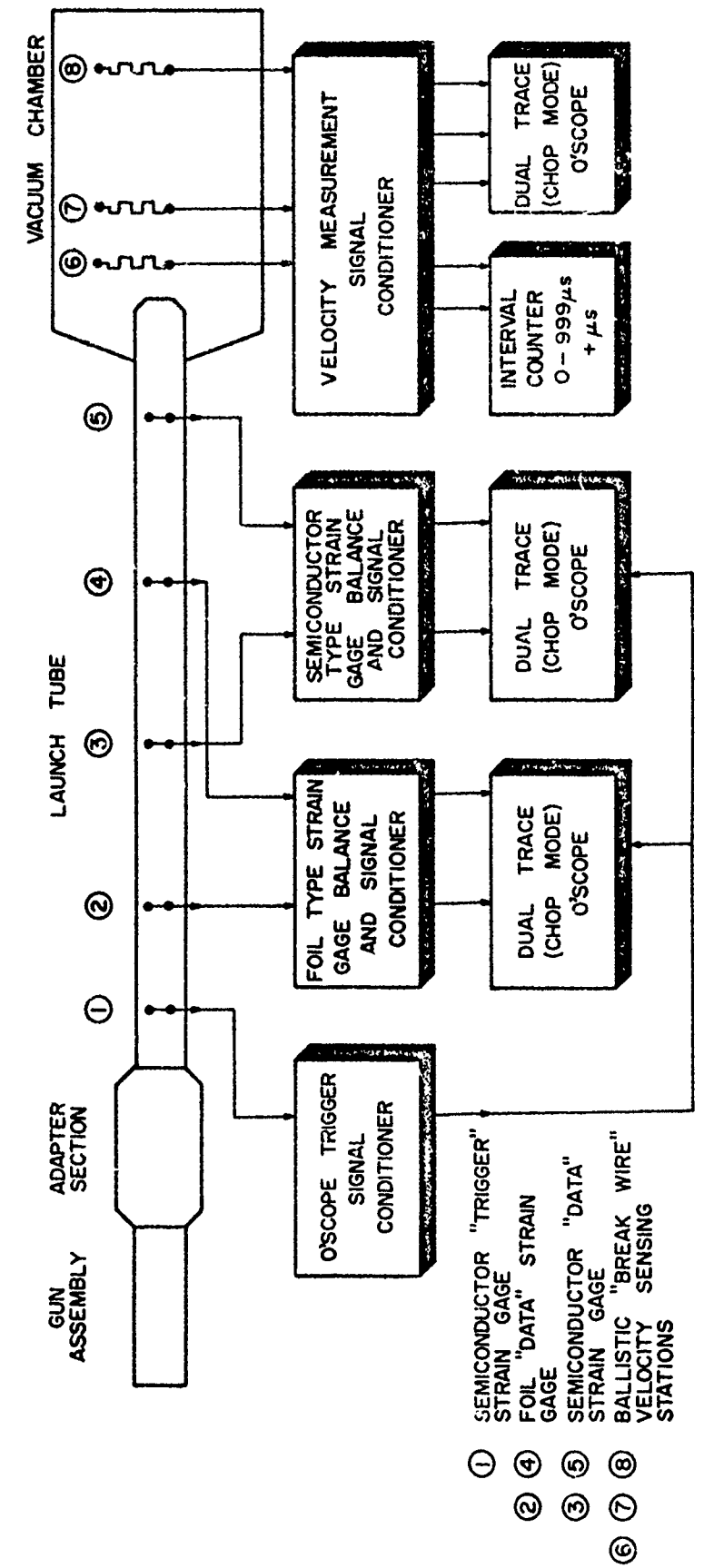


FIGURE-1 HVL INSTRUMENTATION - GENERAL LAYOUT

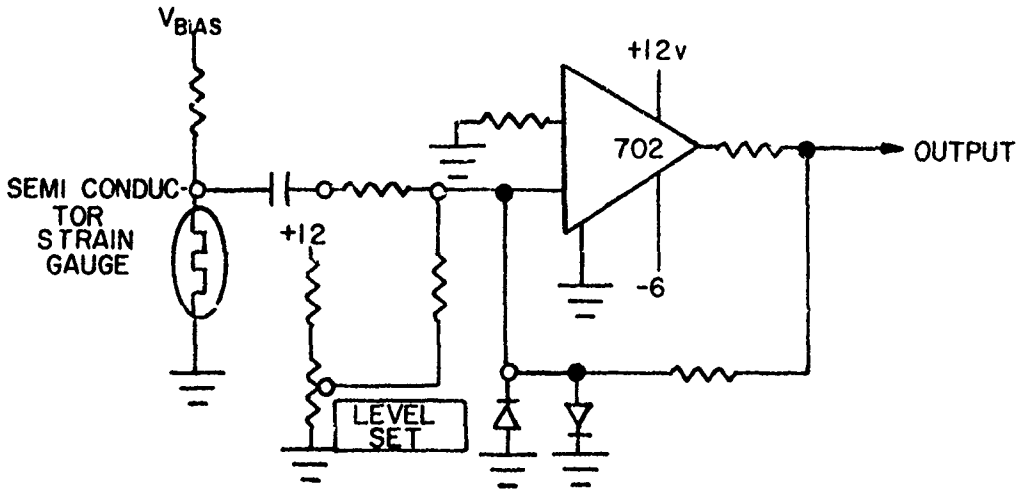


FIGURE 2 TRIGGER SIGNAL CONDITIONER

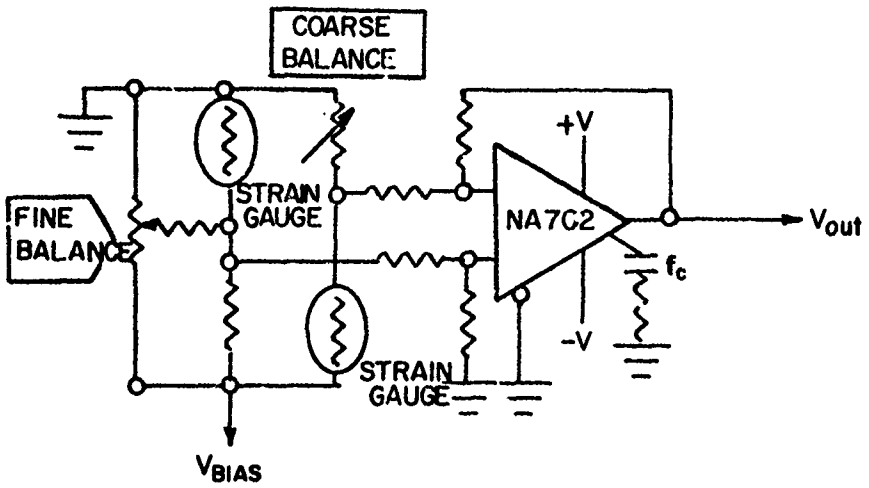


FIGURE 3 FOIL TYPE STRAIN GAUGE BALANCE & SIGNAL CONDITIONER

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 spacing 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

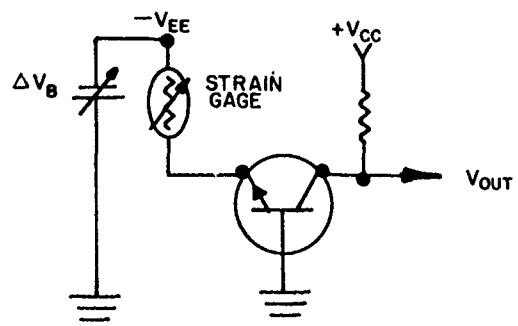


FIGURE 4 SEMICONDUCTOR STRAIN GAGE BALANCE & SIGNAL CONDITIONER

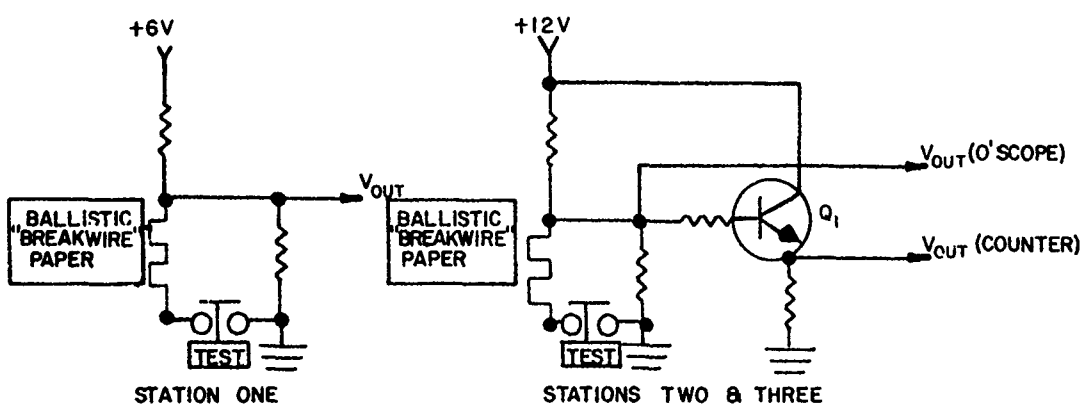


FIGURE 5 VELOCITY MEASUREMENT SIGNAL CONDITIONER

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

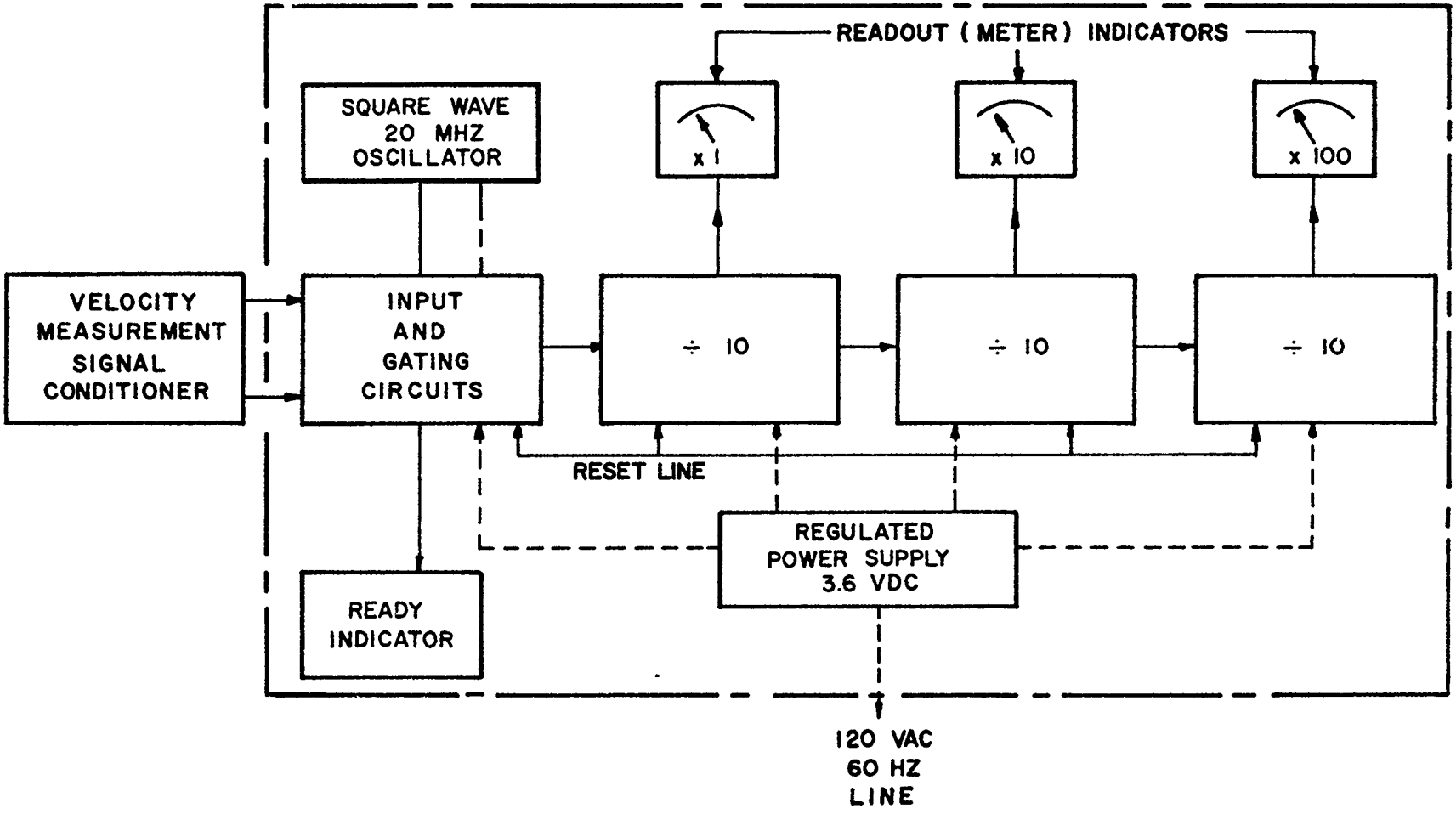
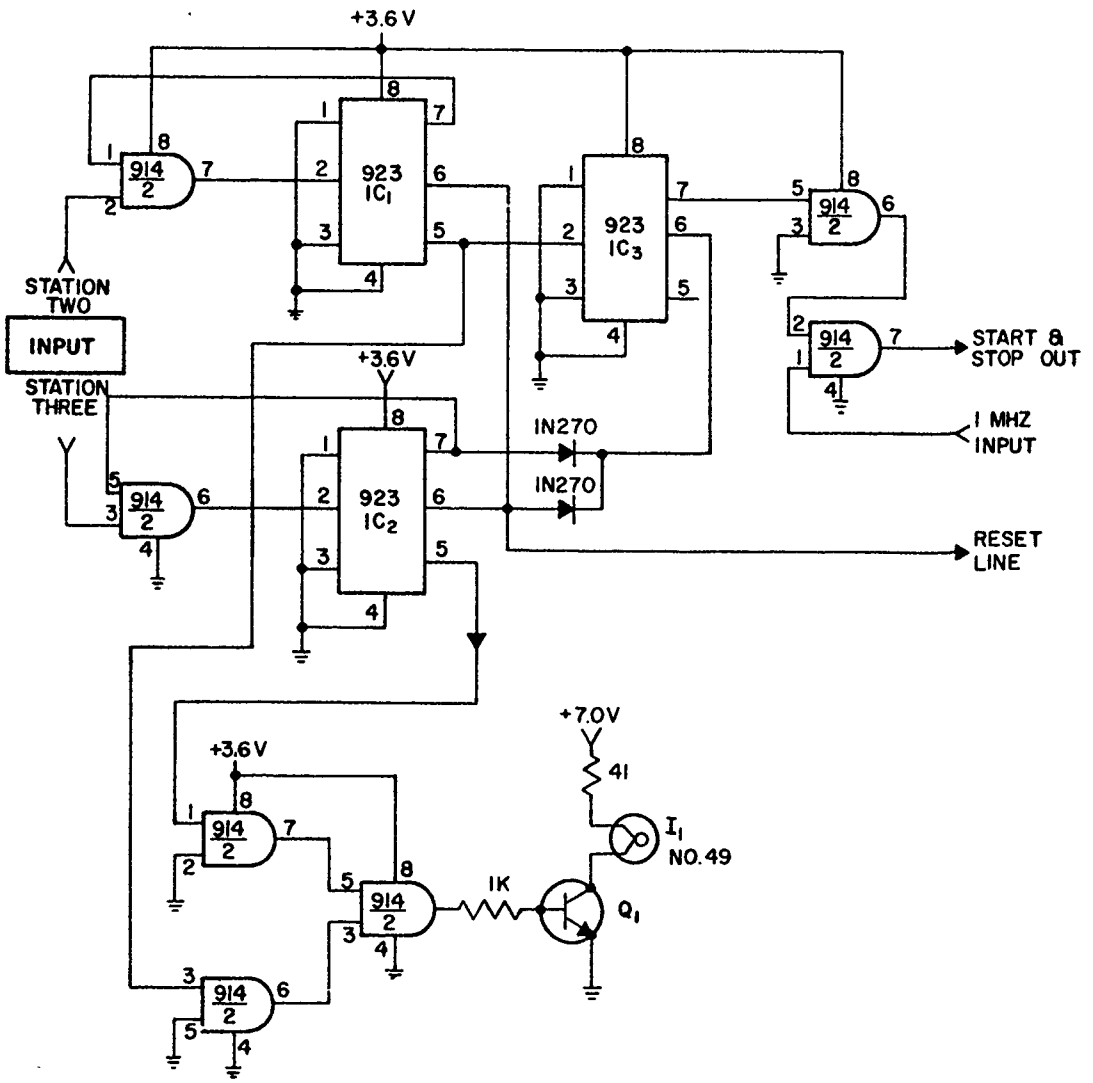


FIGURE - 6 INTERVAL COUNTER - SYSTEM BLOCK DIAGRAM



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

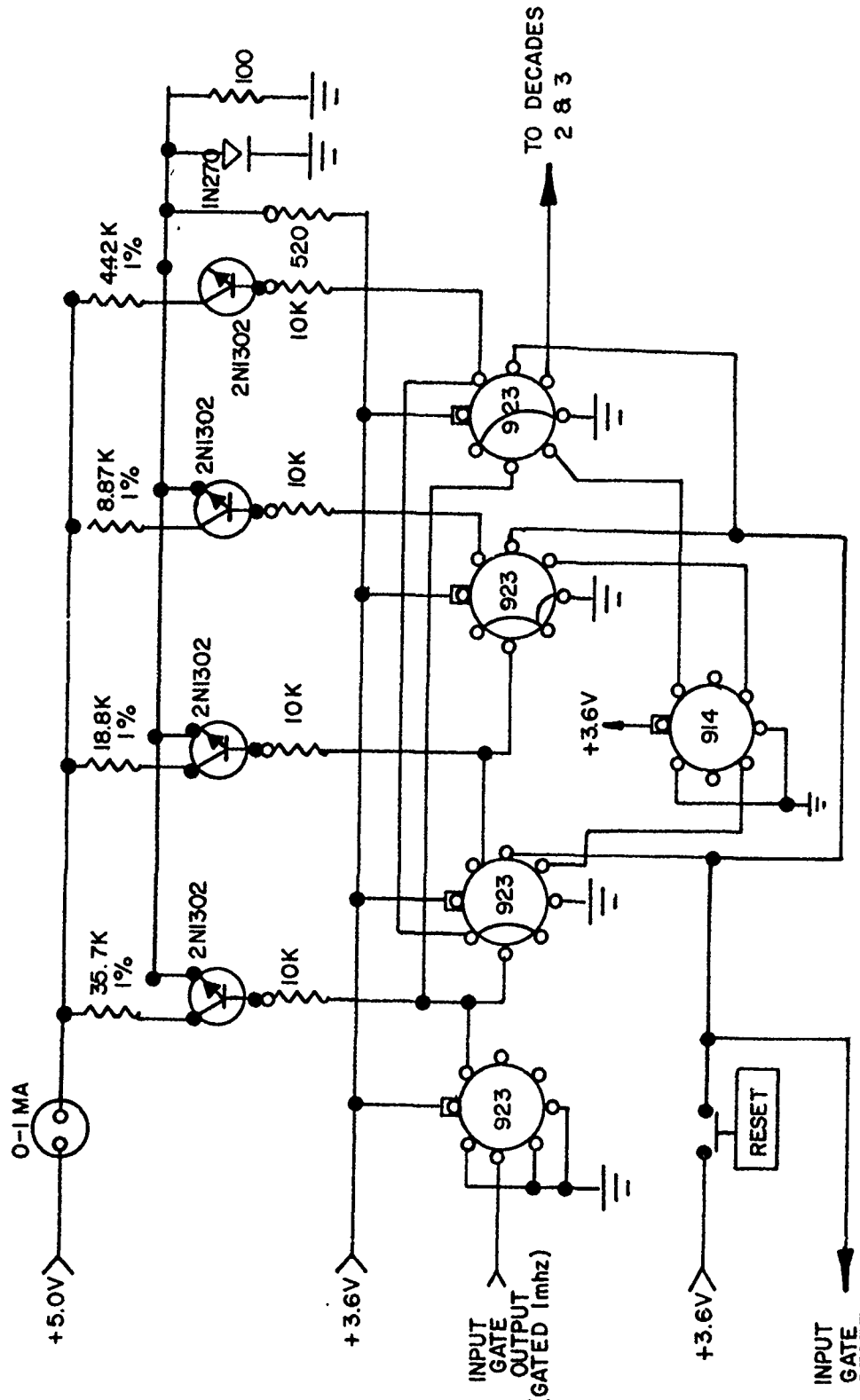


FIGURE 8 VELOCITY MEASURING SYSTEM - ÷ 10 DECADE & METER READOUT SYSTEM

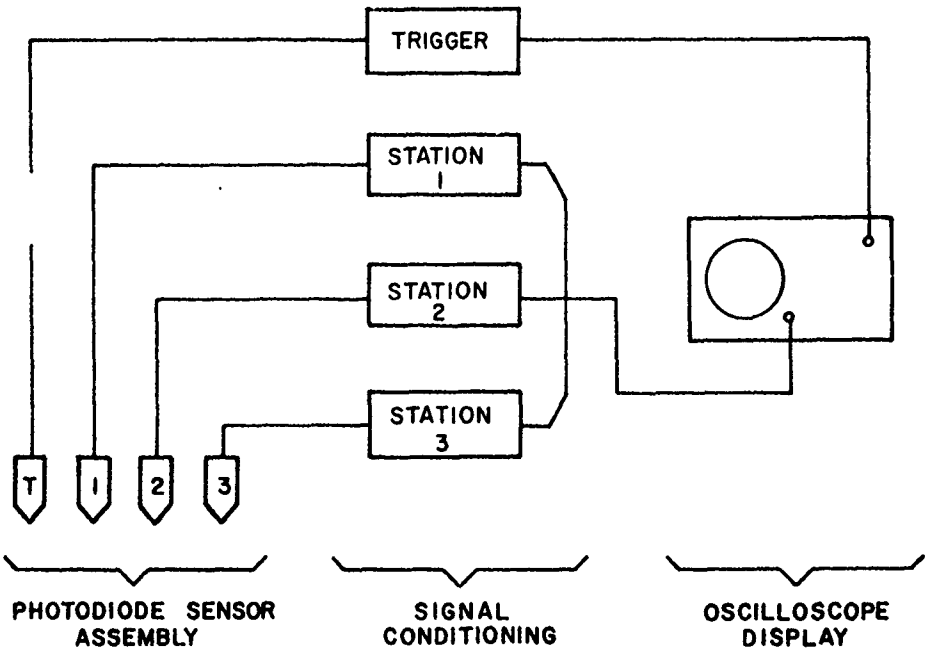
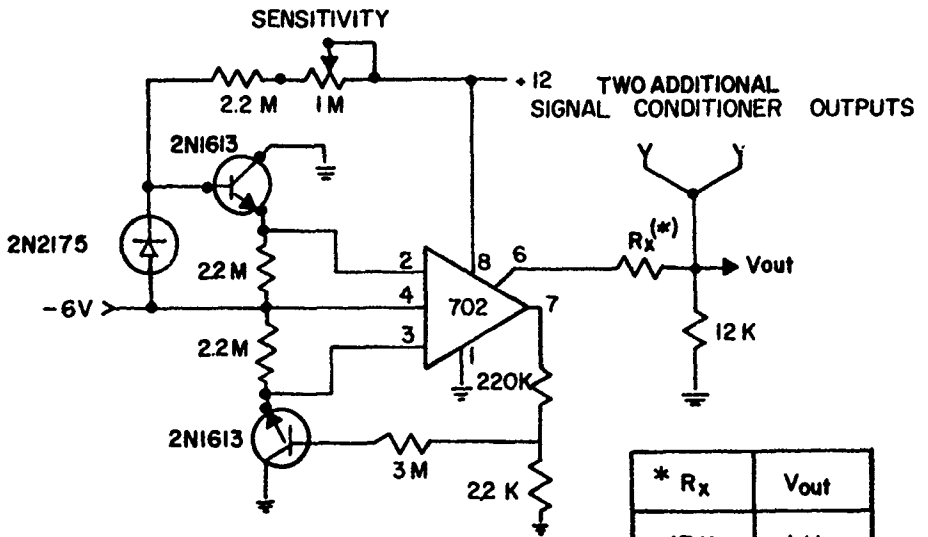


FIGURE 9 BLOCK DIAGRAM - PHOTODIODE LONGITUDINAL BURNING RATE DATA SYSTEM



* R_x	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.

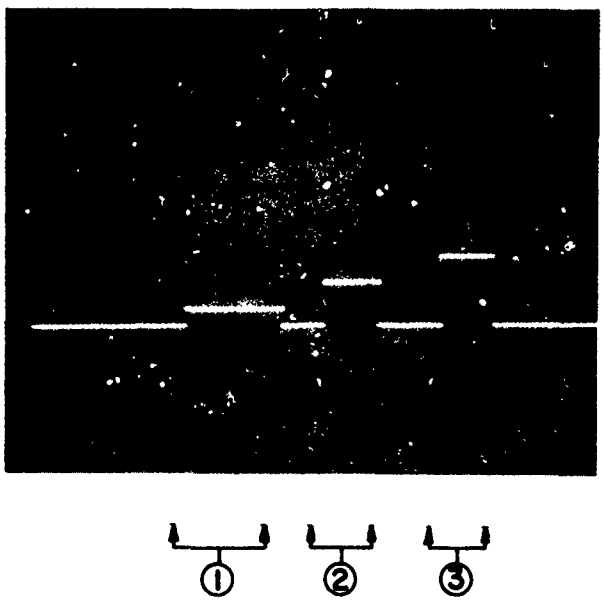


FIGURE 11 INDIVIDUAL STATION OUTPUT SIGNALS

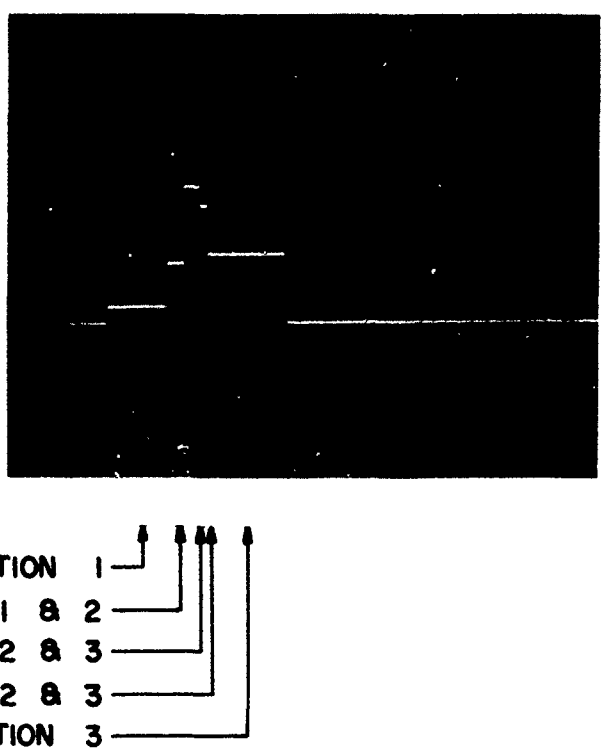


FIGURE 12 COMPOSITE SIGNAL OUTPUT

Appendix C

Summary of Results September 27, 1966 to May 5, 1970

SUMMARY OF RESULTS

DATE	VEL fps	TANK PRESS psi	COATING THICKNESS mil's	BASE COAT *	PROPELLANT % COATS	PROPELLANT %	PROJECTILE SPECIFICATIONS LENGTH in	PROJECTILE SPECIFICATIONS DIA in	PROJECTILE SPECIFICATIONS MASS gr	PENETRATION LAYERS	PENETRATION DIA in	COMMENTS
Aug 1	6600	10	1.5	4a	1	50% NC, 50% RDX	129	119	02			
Oct 2	5400	9	1	1c	2	50% NC, 50% RDX	247	247	1455	20+ through all		
Oct 3	5200	13	2	1c	2	50% NC, 50% RDX	25	.24	.1458			
Oct 3	5400	13	3	1b	2	50% NC, 50% RDX	.232	243	.1491			
Oct 4			3.5	1b	5	60% NC, 40% RDX	.229	243	1509			
Oct 4	4100	10	1.5	1b	3	66% NC, 33% RDX	.241	.241	.1492			
Oct 5		13	1.5	1d	2	60% NC, 40% RDX	247	243	1439			
Oct 6	4620	13	3	1d	2	60% NC, 40% RDX	.247	243	1497			
Oct 6	3500	13.5	2.2	1d	1 1	55.6% NC, 44.4% RDX 60.0% NC, 40.0% RDX	.243		.1453			
Oct 9	2871		2.2	1d	2	55.6% NC, 44.4% RDX	.251	.2435	.1425			
Oct 11			1.5	1d	2	50% NC, 50% RDX	.247	241	.1364			
Oct 10		12	2.3	1d	2	60.0% NC, 40.0% RDX	.253	.243	.1468	through all		
Oct 12	4227 counter	13	2.3	1b	1	22.3% NC, 66.8% RDX, 11.1% glass	.229	243	.15			
Oct 13		9	2.3	1b	1	22.3% NC, 66.8% RDX, 11.1% glass	.249	.243	.1521			
Oct 13			2	1b	1	22.3% NC, 66.8% RDX, 11.1% Al	236	243	.1527			
Oct 17		8	1.6	1b	1	22.3% NC, 66.8% RDX, 11.1% Al	.259	.243	170	56		
Oct 17			1.2	1b	1	21.7% NC, 65.3% RDX, 10.9% Al, 2.17% glass	.221	.2425	.1453	36		
Oct 17			2.5	1b	1	22.3% NC, 66.8% RDX, 11.1% Al	.198	242	127			Tube did not ignite
Oct 18		8	2.5	1b	1	21.7% NC, 65.3% RDX, 10.9% Al 2.17% glass	2275	2425	1463	47		
Oct 19		9	3	1b	1	22.3% NC, 66.8% RDX, 11.1% Al	2370	2415	517	43		
Oct 18		12	3	1b	1	22.3% NC, 66.8% RDX, 11.1% Al	216	.2435	.1484	41		
Oct 19		11	3	1a	1	20% NC, 60% RDX, 10% glass, 10% Al	.252	241	.328	52		Wires in base
Oct 18	3120	10	3	1a	1	20% NC, 60% RDX, 10% glass, 10% Al	.433	.242	.241	49		Nitro on Tab
Oct 20	2311	8.5	3	1a	1 1	20% NC, 60% RDX, 10% Al, 10% glass 24.4% NC, 73.2% RDX, 2.6% glass	240	.2415	1925	41		
Oct 24	4299 counter	8	3	1a	3 1	20% NC, 60% RDX, 20% Al 20% NC, 60% RDX, 10% Al, 10% glass	252	.241	.201	44		
Oct 25		9	3.5	1a	3 1	20% NC, 60% RDX, 20% Al 20% NC, 60% RDX, 10% Al, 10% glass	.248	.2435	.1532	14		
Oct 25	2444	10	3	1a	3	22.2% NC, 66.8% RDX, 5.5% Al, 5.5% glass	.619	242	.3874	60 through all		Nitro on
Nov 1		8	4.2	1g	2	21.8% NC, 65% RDX, 10.8% Al 2.1% glass	518	.243	.368	36	70	Traveling Charge Projectile Adapter slid back 1/4 inch. Plasma interfered with trace
Nov 1		8	4	1g	2	21.8% NC, 65% RDX, 10.8% Al 2.1% glass	502	243	3556	38	70	Adapter slid back 1 inch Plasma interfered with trace Traveling Charge Projectile
Oct 12	4227	13	3	1d	1	22.3% NC, 66.8% RDX, 11.1% glass	229	.243	.15			Loud noise, projectile destroyed Blast deflector charred
Oct 13		9	2.3	1d	1	22.3% NC, 66.8% RDX, 11.1% glass	249	243	154	27		Loud report projectile destroyed
Oct 13			3.2	1d	1	22.3% NC, 66.8% RDX, 11.1% ass	.236	.243	1527			Al odor, Lo[illegible]
Oct 13	5648	11					245	243	1505			Through expanded HC & ½ compressed HC
Oct 17	4670 3249	8					227	241	178			Tube did not fire

*a 84% Butyl Acetate, 12% Nitro Cellulose, 4% Aluminum
b 93% Nitro Cellulose 7% Aluminum
c. 43% Butyl Acetate, 43% Aluminum, 14% Nitro Cellulose
d 81% Butyl Acetate 11% Nitro Cellulose, 8% Aluminum
e. 84% Butyl Acetate, 9% Nitro Cellulose, 7% Aluminum
f 81% Butyl Acetate, 11% Nitro Cellulose, 8% Aluminum
g 97% Butyl Acetate 10% Nitro Cellulose, 3% Aluminum

SUMMARY OF RESULTS CONTINUED

DATE	VEL	TANK PRESS	COATING THICKNESS	BASE COAT	PROPELLANT %		PROJECTILE SPECIFICATIONS			PENETRATION		COMMENTS
	fps	psi	mils		COATS		LENGTH in	DIA in	MASS gr	LAYERS	DIA in	
Oct 17		N	3	1d	1	22.3% NC, 66.8% RDX, 11.1% glass	.259	.243	.170	56		Tube from last shot, Loud noise Tube fired Scope & counter did not record.
Oct 17		10	2	1d	1	21.7% NC, 65.3% RDX, 10.8% Al, 2.17% glass	.221	.2625	.1453	38		Loud Scope did not record
Oct 17			2.5	1d	1	22.3% NC, 66.0% RDX, 11.1% glass	.198	.242	.127			Propellant did not ignite HC not used, galvanized steel used
Oct 18	3267 3282 counter	11					.198	.242	.1273			Tube did not ignite
Oct 18		8	3	1e	1	21.7% NC, 65.3% RDX, 10.9% Al 2.17% glass	.2375	.2625	.1463	47		Loud Noise Plasma interfered with trace Aft part of projectile damaged
Oct 18		9	1	1e	1	22.2% NC, 66.8% RDX, 11.1% Al	.2370	.2615	.1577	43		Test to see if counter affects scope Trace began on second station line Loud noise
Oct 18	4200 3400 counter	11		1e	1	22.2% NC, 66.8% RDX, 11.1% Al	.207	243	.1211	35		Tube did not fire
Oct 18		12	1	1e	1	22.2% NC, 66.8% RDX, 11.1% Al	.216	.2635	.1484	41		Plasma interfered with trace
Oct 19		11	3	1e	1	20% NC, 60% RDX, 10% Al, 10% glass	.251	.241	.328	32 nylon 2 wires		Nylon and Wires. Wires separated from base, wires, 8" from nylon impact, through 2 layers of NaC
Oct 18	3120 counter	10	3	1e	1	20% NC, 60% RDX, 10% Al, 10% glass	.433	.241	.241	69		Nylon with HC attached Some NC on projectile after impact
Oct 20	3313 counter	8.5	3	1e	1 1 1	20% NC, 60% RDX, 10% Al, 10% glass 24.4% NC, 73.3% RDX, 2.4% glass 60% NC, 20% Al, 20% NH_4ClO_4	240	2415	.1925	41		Tube did not ignite Final coat did not coat complete tube, about 2" concave end (last coat) uncoated
Oct 24	4700 counter	8	2.3	1e	3 1	20% NC, 60% RDX, 20% Al 20% NC, 60% RDX, 10% Al, 10% glass	252	.241	.2011	44		Very loud, gun & adaptor blown off shell extruded, projectile in good shape
Oct 25		9		1e	3 1	20% NC, 60% RDX, 20% Al 20% NC, 60% RDX, 10% Al, 10% glass	.248	.2435	.1532	14		Very loud, shell extruded, paper packing around gun ignited by flame blast. Flat base projectile
Oct 25	2444 counter	10	3.1	1e	3	60% NC, 40% RDX, 10% Al, 10% glass	491	.242	.3624	63		NC on projectile, tail broke off, not found, tube did not fire, some NC went through last paper & into NC 1"
Oct 27		8	1.7	1e	2	21.7% NC, 65.3% RDX, 0.8% Al, 2.17% glass	.202	.242	.1248	36		Loud blast
Oct 30		8	1.7	1a	2	21.7% NC, 65.3% RDX, 10.8% Al, 2.17% glass	.238	240	.2162			Tube set over weekend. Very loud, adaptor & gun blown off, projectile did not go thru 3rd station. Al projectile lost
Aug 1	6990 5976		5	2a	1	50% NC, 50% RDX	121	.1185	.0179	15		Projectile blackened on base
Aug 2	6000 5976	10	2.5	2a	2	50% NC, 50% RDX	.134	1185	.0208	14		
Aug 2	6000 5976	12	2	2a	1	50% NC, 50% RDX	139	.1185	.0208	15		
Aug 3	6998 5958	12	1	1a	1	45% NC, 45% RDX, 10% S	.134	.1185	.202	15		SO_2 odor
Aug 3	5951 4987 counter	9	5	1a	1	45% NC, 45% RDX, 10% S		.1185	.0256			Tube clean after shot IPL - 10
Aug 8		9	1.5	1a	1	25% NC, 75% RDX	.1205	1185	0343			Aluminum projectile Loud report, backfire Barrels damaged 3rd station
Aug 7			2	1a	1	25% NC, 75% RDX	.124	117	.0131			IPL-10 Wood projectile
Aug 8			2	2a	1	18% NC, 54% RDX, 28% Sand	.126	.1165	.040			Aluminum projectile, Backfire, projectile came out gun Deep gr's on side of pellet
Aug 8	7500 6950	9	2	2a	1	15% NC, 48% RDX, 24% Sand, 12% Al	114	117	.0158			IPL - 10
Nov 3		9	4.25	1g	2	21.8% NC, 65% RDX, 10.8% Al, 2.8% glass	.535	2435	.3778	36		Adaptor moved back 2 inches. Gun powder ignited on projectile Gun powder on tab.
Nov 3		8	4.25	1g	2	21.8% NC, 65% RDX, 10.8% Al, 2.8% glass	250	.243	.160			Projectile hit blast deflector Extension tube was used
Nov 4		12	4.25	1g	2	21.8% NC, 65% RDX, 10.8% Al, 2.8% glass	517	.243	3145	36		Black powder on tab. Tube slid forward 2 inches
Nov 9	5430	9	4.5	1g	1 1	21.8% Nitro, 65% RDX, 10.8% Al, 2.8% glass 7.8% NC, 55% RDX 13.8% Al, 2.7% glass	483	243	3855	53		Adapter slid back 2 inches Projectile penetrated entire depth of honey comb. Black powder on tab
Dec 1	1951		6.0	1g	2	21.8% NC, 65% RDX, 10.8% Al, 2.8% glass	.254	238	.1775	26		Tube did not fire.
July 25	4780	9	1	1a	1	33% NC, 33% gun powder, 33% NH_4ClO_4	118	118	0176	16		
July 25	5194	11	1	1a	1	33% NC, 33% gun powder, 33% NH_4ClO_4	.122	.1175	.0215	12		
July 27	6000	9	2.5	2a	2	33% NC, 33% gun powder, 33% NH_4ClO_4	.136	.117	.0188	20		
July 31	6200	9	1.5	2a	1	25% NC, 75% NH_4ClO_4	140	.1195	.0228	14		

SUMMARY OF RESULTS CONTINUED

DATE	VEL fps	TANK PRESS psi	COATING THICKNESS mils	BASE COAT	PROPELLANT %		PROJECTILE SPECIFICATIONS			PENETRATION		COMMENTS
					COATS		LENGTH in	DIA in	MASS gr	LAYERS	DIA in	
July 31	6200	10	2 5	2a	1	25% NC, 75% NH_4ClO_4	.123	1175	.0186	15		
July 31	6200	17	1 5	2a	1	25% NC, 75 % NH_4ClO_4	.120	.1195	0208	17		
Oct 6		13	4	1b	2	25% NC, 54% NH_4ClO_4,13.5% Al, 5 4% glass	2 '	.242	3274			
Oct 12	5800	18	2 3	1b	1	27% NC, 54% NH_4ClO_4, 13 5% Al 5 4% glass	.2545	.2525	.1535			
Oct 16	.650	11	2	1b	1	27% NC, 54% NH_4ClO_4, 13.5% Al, 5.4% glass	.232	2419	1472			Tube did not fire
Oct 16		'	2 5	1b	1	27% NC, 54% NH_4ClO_4,13.5% Al, 5 4% glass	.198	.243	.140			
Oct 24		9	2	1a	1 2	50% NC,33% NH_4ClO_4, 16 5% Al 27.8% NC, 55.5% NH_4ClO_4, 8.35% Al, 8.35% glass	.230	.244	.1318	33		
Oct 23	9840 counter	8	3	1a	1 2	50% NC, 33% NH ClO_4, 16.5% Al 27.8% NC, 55.5% NH_4ClO_4, 8 35% Al, 8.35% glass	225	.244	1454	45		
July 27	70/	10	1 5	2a	2	50% NC, 50% NH_4ClO_3	.125	.113	02			
Oct 16	2700 2650 counter	11	2 5	1f	1	27% NC, 54% NH_4ClO_4, 13.5% Al, 5 4% glass	232	.2415	.1472			Tube set over weekend Looked rusty
Oct 16		9	2.3	1f	1	27% NC, 54% NH_4ClO_4, 13.5% Al, 5 4% glass	.198	243	.14			Tube set over weekend
Oct 24		9	1.9	1g	1 2	60% RC, 20% NH_4ClO_4, 20% Al 26.3% NC, 52 6% NH_4ClO_4, 13.15% Al, 7 9% glass	.238	.244	.1318	33		
Oct 23	9840 counter	8	1 8	1g	1 2	3% NC, 1% NH_4ClO_4, 1% Al, 26.3% NC, 52.6% NH_4ClO_4, 13 15% Al, 7 9% glass	.225	.244	.1454	45		Adapter blown off 1st station sheared off. Projectile not damaged
Oct 23		9	3 5	1g	3	27.9% NC, 55 5% NH_4ClO_4, 13 9% A., 2 79% glass	4625	.2425	.3609	36		NC & black powder attached to projectile on tab
Oct 27		16	4	1g	2	27.9% NC, 55.5% NH_4ClO_4, 13.9% Al, 2.79% glass	.197	.243	.1**,	29		
Oct 31	7760 6259 counter	7	2	1g	2	27.9% NC, 55.5% NH_4ClO_4, 13.9% Al, 2.79% glass	.307	.243	.362	41	.75	NC & black powder on tab of projectile. Projectile went thru 3rd station damaged in NC, much smoke.
Oct 31		12	1 5	1g	2	27.9% NC, 55.5% NH_4ClO_4, 13.9% Al, 2.79% glass	447	.241	297	18	375	Projectile went thru 3rd station Adapter & gun slid 2" on tube Pi jectile broken off otherwise no damage
Nov 2		8	4	1g	2	27.8% NC, 55% NH_4ClO_4, 13 9% Al, 2.7% glass	.497	.243	.3471	19	.50	Tube slid forward 2". Plasma interfered with trace Projectile split in half Traveling charge
Nov 2	7800	8	5	1g	2	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2 7% glass	438	243	.3265	43	75	Plasma interfered with trace Traveling charge
Nov 10		8	3 5	1g	1	27 8% NC, 55% NH_4ClO_4, 13 9% Al, 2.7% glass	.502	242	.3389	28		Adapter slid back 2 inches No reading on scope Traveling charge
Nov 10	500	8	4	1g	1	27 8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.479	242	.3465	28	.375	Adapter slid back 1 inch Vel 500 fps Traveling charge
Nov 16		8	3.5	1g	2	8% NC, 15 8% NH_4ClO_4, 4% Al, 8% glass 71.0% BA	.505	242	305	34		No reading on scope Black powder on tab. Strain gauge test.
Nov 17		10	3 25	1g	2	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.254	.244	.1736	47		Strain gauge test
Nov 20	1400	10	3 ,	1g	2	27 8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.473	.2415	3589	27		Traveling charge No scope reading Only straight lines Vel 1400
Nov 20		12	3 0	1g	2	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2 7% glass	432	.2405	3328	13		Tab broken off projectile Plasma interfered with trace
Nov 20		11	3.5	1g	2	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	48	.242	.3388	36		Plasma int, ered with trace Traveling charge
Nov 21		10	3 25	1g	2 1	8% NC, 15 8% NH_4ClO_4, 4% Al, 8% glass, 71% BA 57 NC, 8% BA, 2% Al	.577	.241	.3320	40		Adapter slid back 1 5 inches Strain gauge test. Traveling charge.
Nov 29		9	3.25	1g	2	27 8% NC, -55% NH_4ClO_4, 13.9% Al, 2.7% glass	460	.240	.3420	19		Tab broken off Very slow shot Only straight lines on scope
Nov 29	5000	13	4	1g	2	27 8% NC, 55% NH_4ClO_4, 13 9% Al, 2 7% glass	.254	.241	.179	34	1.0	Tube slid forward 4 inches
Dec 1		9	4.75	1g	2	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	255	.2425	1776	24		Adapter slid backward 2 inches Very slow vel. Only straight lines on trace.
Dec 1			3 25	1g	2	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass		.477				Steel projectile Plasma interfered w .h trace
Dec 6		10	6.25	N/A	4	27 8% NC, 55% NH_4ClO_4, 13.9% Al, 2 7% glass	.534	243	.333	42		Adapter slid back 1.5". Traveling charge. Scope did not trigger No base coat.
Dec 6	4000	9	7 5	N/A	4	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2 7% glass	.451	.242	291	38	80	Adapter knocked off No base coat. Traveling charge.
Dec 4			5	N/A	4	27 8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	460	.242	.300	52	.50	Black powder on tab. Adapter slid back 1.5 inches. Plasma interfered with trace.

SUMMARY OF RESULTS CONTINUED

DATE	VEL	TANK PRESS	COATING THICKNESS	BASE COAT	PROPELLANT		PROJECTILE SPECIFICATIONS			PENETRATION		COMMENTS
					COATS	%	LENGTH in	DIA in	MASS gr	LAYERS	DIA in	
Dec 8	5940	10	2.375	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al 2.7% glass	.510	.242	326	47	.75	Adapter blown off. Tab broken off (Black powder)
Dec 8	3100	8	3.0	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.487	.242	3104	41	1 0	Adapter slid back 2 inches. Traveling charge.
Dec 8	2100		4.0	N/A	3	27.8% NC, 55% NH_4ClO_4, Al, 2.7% glass	.485	242	281	70	40	Tube did not fire Tab broken off (Black powder)
Dec 12		9	4 0	N/A	3	27.8% NC, 55% NH_4ClO_4, 13 9% Al, 2.7% glass	.481	.2425	.304	15	.40	Adapter slid back 2 inches Tube was warm. Tab broken off, (Black powder), Plasma interfered with trace.
Dec 12		7	3.25	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.480	.242	314	36	.50	Adapter blown off Tail broken off, (Black powder), Plasma interfered with trace.
Dec 12		9	3.25	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.500	.243	.314			Adapter slid back 1 5 inches. Traveling charge.
Dec 14		9	4.0	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	550	.2425	370	42	.80	Adapter blown off. Plasma interfered with trace. Black powder on tab
Dec 14	3600	9	4.25	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.448	.2425	.294	46	.50	Adapter slid back 1 inch Black powder on tab.
Dec 18		9	4.75	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.487	.243	.326	47	.80	Adapter slid back 2". Plasma interfered with trace. Tab not broken off.
Dec 18			3.75	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.469	243	.353	49	.60	Plasma interfered with trace. Adapter slid off. Traveling charge.
Dec 18		9	4.5	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.472	.242	.357			Projectile hit third station. Tube did not fire. Traveling charge.
Dec 19		9	4.5	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.468	.242	.365	47	.75	Plasma interfered with trace Traveling charge
Dec 19		10	4.25	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.340	.241	.205	30	.90	Adapter slid back 3 inches. Very slow shot. Straight lines on scope.
Dec 19	3200	9	4.75	N/A	3	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.481	.243	.342	22	4C	10 foot tube Tube was warm. Tab found in shell case.
Jan 8	6200	7	8.25	N/A	4	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	498	.243	.353	28	.60	Tube slid forward 3½ inches. Traveling charge.
Jan 8		7	7.0	N/A	4	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.498	.242	.379			No reading Projectile hit blast deflector. Traveling charge
Jan 8	6570 tab vel		8.25	N/A	4	27.8% NC, 55% NH_4ClO_4, 13.9% Al, 2.7% glass	.464	.442	.338	15		Tab penetrated 15 layers Projectile hit blast deflector Adapter blown off
Sept 27 1966		33					1/d=1					Holes in paper but projectile apparently pulled down tube by vacuum
Sept 27		8					1/d=1					Projectile pulled down tubes by vacuum.
Sept 28		5.5					1/d=1			13		Papers broken but no velocity
Sept 28	4615	10					1/d=1			19		
Sept 28	4523	5.5					1/d=1			18		
Sept 28		6					1/C=1			18		Scope failed to trigger
Sept 28		5					1/d=1			18		Scope failed to trigger.
Nov 28 1966		6					.1215	.121				Papers broken by blast. Projectile apparently pulled down by vacuum.
Jan 25 1967							.120	.115		4		No vacuum. No velocity recorded. To clear previous lined shot.
Jan 25	1293						.1205	.114		5		No vacuum To clear previous shot
Jan 25	4615	4					.119	.120				To clear previous shot.
Jan 25	390											No vacuum
April 27		11										Oscilloscope did trigger but no velocity All stations broken. 1st shot in New Lab.
April 28		10										Solenoid found to be triggering scope before shot
April 28	5000	10 5										
April 28	4600	11										Dashed scope pattern
Nov 28 1966	4000						.126	.120				

SUMMARY OF RESULTS CONTINUED

DATE	VEL fps	TANK PRESS	COATING THICKNESS mils	BASE COAT	PROPELLANT		PROJECTILE SPECIFICATIONS			PENETRATION		COMMENTS
					COATS		LENGTH in	[illegible]	MASS gr	LAYERS	DIA in	
Sept 29	4644	5.5					.112	.121		16		Second station did not indicate velocity based on 1st & 3rd stations.
Sept 30	4350	4					.128	.121		18		
Dec 1 1966	4350	4					.113	.1205				
Dec 1	4400	4					.1135	.1205				
Dec 5	4050	4					.120	.120				IPL-10
Dec 5	4918						.136	.120				IPL-14
Jan 25 1967		4					.1205	.114				To clear lined shot. Only 1st paper broken
May 3	5000	10					.113	.117	.02			
May 4		10					.117	.113	.022			Did not trigger.
May 4		10					.1125	.1145	02			Triggered but did not record.
May 5							.117	.113	.021			Triggered but did not record. Slow leak in gun discovered.
May 8		10					.119	.117	.023			Triggered but no velocity
May 8							.116	.116	.022			Triggered but no velocity.
May 9							.115	.113				Trace triggered, 3rd station paper broken and trace resembles a discharging capicator
May 9	4700	10					.122	.117	023			No clear break on third station. Velocity calculated on 5" section.
May 9		10					.116	.1165	.021			Scope triggered but no velocity.
May 10		10					.114	116	.02			Scope triggered but no velocity.
May 10							.116	.117	.022			Scope triggered but no velocity.
May 11		10					.116	.117	.021			Scope triggered but no velocity.
May 11		10					.115	.115	.022			Scope triggered but no velocity
May 12		10					.117	.115	.023			Scope triggered but no velocity
May 16		9					115	.114	.020			Scope triggered but no velocity. Paper taped in front of tube to catch more blast.
May 16	3980	9.5					117	.1135	.020			Paper taped in front of tube to catch blast. Need to increase sweep speed.
May 16	4050	9 5					.115	.113	.02			Paper hung ahead of tube to catch blast
May 16							.118	.117	.021			No paper ahead of tube Appears to hav triggered on 2nd station
May 16	6099	10					.116	.117	.02			Sweep speed too slow for accuracy.
May 17		10					.110	.1175	.0205			Paper ahead of tube No velocity recorded.
May 17	3750	10					.116	.114	.018			Heavy paper ahead of tube
May 30	5000	9 5					.116	.116	1.5			Tapered tail plug used. New scope, old camera used.
May 30	4800	9.5					.121	.117	.023			New scope old camera
May 31	4600	10					.121	.117	0188			
June 1	4200	10					.1185	.118	.023			Clear out lined shot.
June 1	4800	10					1165	.114	.023			
June 8		9					150	116				Triggered but no velocity

SUMMARY OF RESULTS CONTINUED

DATE	VEL	TANK PRESS	COATING THICKNESS	BASE COAT	PROPELLANT		PROJECTILE SPECIFICATIONS			PENETRATION		COMMENTS
	fps	psi	mils		COATS	g	LENGTH in	DIA in	MASS gr	LAYERS	DIA in	
June 8		15					.117	113	021			Triggered but no velocity
June 8	3600	12					.115	.117	.016			
June 19							.136	118	0206	15		Test for velocity out of adapter Triggered but no velocity
June 19	3600	10					.125	.119	.020	2		Plug damaged very much Ballistic paper out - Al strip used Adapter test
June 19	3310	10					.125	.118	.020	17		Adapter test Aluminum strip used
June 19	8200	15					127	.118	.021	15		Adapter test. Al strip used
June 19	3200						.129	.118	.021			Adapter Test 3rd station hit
June 30		40					.109	.112	.0146	14		Strain gauges used. Velocity can not be recorded
July 6		7 5					.114	.115	0157	15		Scope triggered but no velocity.
July 6							116	.115	.019			Scope triggered but no velocity
July 6		22					.106	.113	0163			Scope triggered but no velocity.
July 6							120	.114	.016			Scope triggered but no velocity
July 6							.126	118	.020			3rd station hit, paper not broken
July 7		7.5					.109	.113	.0158			Hit tank door, no block backstop. Triggered but no velocity
July 7	1097	ATM					.098	.113	0122	3		
July 7		5					121	.119	020	15		Triggered but no velocity.
July 7							.104	.112	.0136			Triggered but no velocity
July 7		23					.098	.112	.0126			Triggered but no velocity
July 10		ATM					.127	.1185	0195	Dented Only		
July 11												Counter Test
July 27	3897	10					140	.118	.0246	20		Strain gauges used to trigger scope
July 27	4300	10					.145	.118	.0235			Strain gauge trigger
July 27		10										No projectile Strain gauge test
July 27		10										No projectile Strain gauge test.
July 27	2000	10					.122	.109	0174			Clearing shot
July 29	2833	12					.116	114	020	9		Strain gauge failed to trigger 1st station did
Sept 11	2684	8					273	.241	.1948	All		
Sept 11	3674	8					.2675	2375	.01835	All		Projectile from last shot used
Sept 11	4213	8					269	.2405	.1911			Projectile from last shot used
Sept 12	4150	10					2135	241	.1175			
Sept 12	4150	8					.188	.241	.1163			Penetration of all compressed H C. + 15 expanded layers
Sept 12	4150	8					.195	241	1212			Cracks on back of projectile. All compressed HC + 14 layer expanded
Sept 12	3674	8					269	.2405	1387			
Sept 12	4120	9					216	.241	1183			

SUMMARY OF RESULTS CONTINUED

DATE	VEL fps	TANK PRESS psi	COATING THICKNESS mils	BASE COAT	PROPELLANT		PROJECTILE SPECIFICATIONS			PENETRATION		COMMENTS
					COATS	%	LENGTH in	DIA in	MASS gr	LAYERS	DIA in	
Sept 16	3469	10					.184	.238	.1143			
Sept 20	3039	9					.209	.243	.1236			½" adapter test
Sept 20		8					.2425	242	.1500			½" adapter test Triggered, no velocity
Sept 20	3684	8					.244	240	.1500			Adapter test
Sept 21	3376	49					.247	.239	1486			Instrument test
Oct 4	3500	13					.232	.243	.1522			Unlined, to clear out tube.
Oct 11	3441 counter	15					.252	.2435	15			
Oct 12	3400	13					.232	.243	.15			
Oct 12	3560	20					187	.243	.1148			Blast deflector plate used It had evidence of blast on it.
Aug 15	3350 3350	8					.150	.118	.0259	10		Two 5' tubes
Aug 15	3773 3663 counter	10					.124	.1185	.0195	16		Two 5' tubes
Aug 15	3235 3367	5					.123	.119	.0403	33		Aluminum projectile
Oct 27		8					.268	241	.2132	26		
Oct 30	3500 3122	7					.492	.243	322	41		NC on tab Tab on projectile missing NC particles found in NC, no burning, indicated.
Nov 4	3569 3500	9					.262	.242	1746	40	.70	Check scope
Nov 13		9					.263	.263	.1778	38	.375	No reading, loud noise, unusual for unlined tube.
Nov 13		13					.453	.2415	.3030	51		Strain gauge test
Nov 7		8					.525	.242	.360	30		Strain gauge test.
Nov 26	227.						.262	.242	187	33		Check scope
Dec 13	3200	9					248	.242	.145	24		10 feet tube
June 8	1150		.5		1	47.6% NC, 47.6% BK powder, 4.76% Al	.147	.116	.022			
June 12	4500	10	1 5		5	23% Al, 77% NC	118	.118	.022			
June 12		10	4		5	47.6% NC, 47 6% Bk powder, 4.76% Al	.110	.1115	0185			Flat base
June 21	6700	9			5	70% Nitro-Mek, 30% Al	134	118	.021	14		
July 16	6100	24	3		5	80% NC, 20% Al	.150	.119	.0228	18		
July 11			1		5	77% NC, 23% Al	.136	.119	.02			
July 18	3599	23	1.75		1	Nitro, Blk powder	.115	.115	0173	14		
June 21	6800	10			4	30% Al, 70% Nitro-Mek	.103	118	.020			
July 27	5500	15	5		1	77% NC, 23% Al	.140	1185	.0238			
July 27		15	1 5		5	77% NC, 23% Al	.137	.1185	0228	12		
July 27	6590	15	1.3		4	77% NC, 23% Al	.136	.1185	.0238	16		
July 27	4400	18	1.5		2	77% NC, 23% Al	.142	.1185	.0233	19		
Aug 2	4700	10	2		4	77% NC, 23% Al	.124	.119	.0183	13		
Sept 16	3599	16	1		3	77% NC, 23% Al	.184	.238	.1143			

SUMMARY OF RESULTS CONTINUED

DATE	VEL fps	TANK PRESS mm	COATING THICKNESS mils	BASE COAT	PROPELLANT % COATS	PROPELLANT %	PROJECTILE SPECIFICATIONS LENGTH in	PROJECTILE SPECIFICATIONS DIA in	PROJECTILE SPECIFICATIONS MASS gr	PENETRATION LAYERS	PENETRATION DIA in	COMMENTS
Sept 20	4898	8	2 5		6	77% NC, 23% Al	.229	2425	.1427	25		
Nov 28 1966	5172	4.5			1	90% M.E K., 10% NC	.116	.116		19		
Nov 30 1966	6000	4 0	1 05		3	^0% M.E.K , 10% NC	.129	.116		14		
Dec 1 1966	6000	4 0	1		2	90% M E.K., 10% NC	.130	117				
Dec 5 1966		4 0			3	90% M.E.K., 10% NC	.1165	.129				
Dec 13 1966	6090 6120		1		4	90% M.E.K., 10% NC	128	.1174				
Dec 15 1966	5190		1		3	90% M E K , 10% NC	.125	.1171				
May 31		8 5	1		6	90% M.E.K., 10% NC	.124	.117				
June 2	6500		1 5		3	91% NC, 9% Al	.103	.116	02			
June 5		10			3	91% NC, 9% Al	.116	.118	.022			
June 6	6700	9	.5		1	91% NC, 9% Al	146	118	.024			Tapered nose
June 6	6670	9	1		1	91% NC, 9% Al	.130	.118	.025			Tapered nose
June 6	6600	9			1	91% NC, 9% Al	.133	.1175	.0242			Tapered nose
June 7		10			1	47 6% NC, 47.6% Blk powder, 4.76% Al	.143	.118	.025			
June 7		10	1 5		3	47 6% NC, 47.6% Blk powder, 4.76% Al	.139	.117	.023			
June 7		10	1		1	47.6% NC, 47.6% Blk powder, 4.76% Al	.119	.1195	.022			Flat base
June 8	2600	10	1		1	47.6% NC, 47.6% Blk powder, 4.76% Al	.140	.116	.023			
Aug 2	4260 4396	10	6	1b	1	77% NC, 23% Al	.145	.1185	026	16		
Aug 15	6000 6250	10	6	3a	1	77% NC, 23% Al	120	.117	.0186	16		Two 5' tubes
Aug 15	4645 counter	8	3	1a	1	77% NC, 23% Al	.137	.1185	0236	20		Two 5' tubes
Aug 3?			1	1a	1	54 5% NC, 46 4% Petn.	151	.118	.0267			
Aug 30		7	1.2	1a	1	46 6% NC, 26 7% Petn 26.7% glass	.128	.118	.0219	2		Pellet broke up
Aug 17	638	8	2	1a	1	16 7% NC, 16 7% Al, 50% $KCLO_3$, 16 7% glass	142	.118	.0587	2		Nylon,steel wires Pellet recovered without wires Wires found in tank.
Aug 17	830	9	2	1a	1 1	16 7% NC, 16.7% Al, 50% $KCLO_3$,16 7% glass 15.8% NC, 84 2% MEK	.118	.118	0409			Al projectile recovered Dented NC
Aug 18	3300	9	1	1a	1 1	16 7% NC, 16.7% Al, 50% $KCLO_3$,16 7% glass 15.8% NC, 84 2% MEK	.119	118	0168	2		Plexiglass projectile. Many holes in 3rd station. Projectile not found Loud Report
Aug 18		8	1 6	1a	1	16 7% NC, 16.7% Al, 50% $KCLO_3$,16.7% glass	.123	.116	0171			Plexiglass Only trash hit 1st station Tube did not burn fully
Aug 18	4976 4786 counter	9	1 7	1a	1	25% NC, 25% $KCLO_3$, 25% glass, 12 5% Al 12 5% C	123	.118	0393	33		Al projectile Mass after= 0305
Aug 9			8 5	1a	1	20% NC, 30% $KCLO_3$, 20% glass, 30% Al	.124	.118	.0385			Al projectile not found
Aug 9	5990 6000		1 4	1a	1	20% NC, 30% $KCLO_3$, 20% glass, 30% Al	.147	119	.0252	17		Loud report, burned clear
Aug 9		12	1 6	1a	1	20% NC, 30% $KCLO_3$, 20% glass, 30% Al	.129	.117	.0363			Aluminum. Melted Al blob found could be projectile
Aug 9	5000 5250	10	2	1a	1	20% NC, 30% $KCLO_3$, 20% glass, 30% Al	.136	118	021			Nylon, aluminum too, Elmer's glue held together both recovered, nylon undamaged, Al melted Al part-l=1 38 D=118 m=.061
Aug 9	1356 counter		2	2a	1	20% NC, 30% $KCLO_3$, 20% glass, 30% Al	.118	.115	.0148	6		IPL-10 Plug coated with NC and glass
Aug 16	492	10	3	1a	1	16.7% NC, 16.7% Al, 50% $KCLO_3$,16 7% glass	.115	.118	.0168			Two 5' tubes 2nd tube did not fire Dented NC only
Aug 16	6300		2..	1a	1 1	16.7% NC, 16 7% Al, 50% $KCLO_3$, 16.7% glass 15.8% NC, 84 2% MEK	116	116	.1075			Nylon & wires L= 392 without wires L= 172 Two 5' tubes. 1st tube partially fired 2nd tube did not fire

SUMMARY OF RESULTS CONTINUED

DATE	VEL fps	TANK PRESS	COATING THICKNESS mils	BASE COAT	PROPELLANT COATS	PROPELLANT %	PROJECTILE SPECIFICATIONS LENGTH in	DIA in	MASS gr	PENETRATION LAYERS	PENETRATION DIA in	COMMENTS
Aug 17		.0	3	3a			130	.1143	.0445			Al projectile not found. Did not hit 3rd station 2nd tube did not fire, 1st tube fired only adaptor end
Aug 2	1447 counter	10	6	2a	2	25% NC, 75% $KClO_3$	..16	114	0173	5		Blast probably triggered scope
Aug 2	4500 4460	.0	3	2a	2	25% NC, 75% $KClO_3$	142	.117	02	12		
Aug 3	645 counter	10 5	1.2	1a	1	20% NC, 70% $KClO_3$, 10% C	.118	1175	.0181	Dented		Loud, dented HC only
Aug 3	508	9	5	1a	1	20% NC, 70% $KClO_3$, 10% C	.155	119	0253	Dented		Loud, dented HC only.
Aug 7			2 5	1a	1	14.3% NC, 60.9% $KClO_3$, 5 71% ZnO, 19 05% Sand	131	118	0192			IPL-10
Aug 7			2	1a	1	14 3% NC, 60.9% $KClO_3$, 5.71% ZnO, 19 05% Sand	.131	.1185	0454			Aluminum
Aug 8	3347 2750	8	3 6	2a	1	14 3% NC, 60 9% $KClO_3$, 5 71% ZnO, 19 05% Sand	129	.118	0249	15		Backfire, tube didn't burn completely
Aug 8			2 6	2a	1	14 3% NC, 60.9% $KClO_3$, 5.71% ZnO, 19.05% Sand	.123	.116	.0163			IPL-10. Projectile did not hit 3rd station Found in bottom of tank Nose & back coated with soot
July 18	4170	9	1 87		1	83 5% KNO_3, 16.5% C, 4.35 Elmer's Glue, 14.59 H_2O, 4 Methyl Cellulose	108	.114	0144	19		
July 18	3500	24	3 5		1	5 65 Elmer's Glue, 81.5% KNO_3, 18.15 H_2O, 18.5% C, 13 Dextrin	.127	.112	0178	15		
July 18	3363	12	3		1	4.35 Elmer's Glue, 83.5% KNO_3,14 59 H_2O, 16.5% C, 4 Methyl Cellulose	.120	.112	.C169	17		
July 18	3558	9	2 5		1	5.65 Elmer's Glue, 81.5% KNO_3, 18.15 H_2O, 18 5% C, 13 Dextrin	.118	.113	.0175	15		
July 19	2870	20	2		1 1	33% Nitro, 67% Al, 18 79% KNO_3, 3.75C, 2.5 S	.126	114	.018			
July 20	263	14	2	1b	2	74 9% KNO_3, 14 95% C, 9 97% S	136	.119	0246	11		
July 21	6000	8	2	1b	1	74.9% KNO_3, 14.95% C, 9 97% S	.136	.119	.0246	15		
July 14	4620	8			1	95.3% NH_4NO_3, 4.7% Al, 1 Elmer's Glue, 1 H_2O	.124	.118	0213	19		
Aug 1	4976	9	1	1a	1	50% NC, 50% Lead Azide, 8 MEK	.145	.119	.0203	19		
Sept 21	3329	12	2	1a	2	50% NC, 1 Silica Gel, 50% Lead Azide	2445	.241	.1679	25		
July 19	3278	10	2		1	Black powder and Glue	.117	.114	.0178			Tube did not ignite.
July ..	4469		.8		1 1	47.6% NC, 4.76% Al, 47.6% Blk powder, 1 NC, 1 Al	.14	12	.0237			
July 26	4.71		2		1 1	31 2% Nitro, 62 5% Gun Powder, 6.3% Al 1 b	.146	.116	0253			Hit 3rd station
July 26	4499	9	2	1a	2	50% Nitro, 50% Gun Powder, 8 MEK	145	.117	.0222	15		
July 25	4.43	9	3..	1a	3	50% Nitro, 50% Gun Powder	.119	119	0174	15		
June 9		10			1	27 8% $KClO_3$, 55 6% NC, 16.7% Al	126	.117	.02			
June 1		9	5		1	27 8% $KClO_3$, 55.6% NC, 16.7% Al	126	.117	02			
July 25	4786	10		1a	1	53% NC, 33% Gun Powder, 37% $KClO_3$	.122	.1185	02			
July 28	4980	35	1.5	2a	2	33% NC, 33% $KClO_3$, 33% Gun Powder	.119	.113	0157	13		
July 28	5920	35	1.5	2a	2	50% Nitro, 50% $KClO_3$	.123	.1165	.0184	14		
Sept 13	2400	9	3	1a	1 1	22 1% NC, 44 5% $KClO_3$, 22 1% C, 11% glass 82 5% NC, 42% Al, 17% Glass	.1845	.242	.1229			
Sept 14	3400	8	3	1a	1 1 1	25.6% NC, 50.7% $KClO_3$, 17 7% Al,6 43% gl 25% NC, 25% $KClO_3$, 12.5% Al, 25% glass 77% N_2, 23% Al 12.5% C	185	.2425	.1242	All HC 20		
Sept 19	3470	10	5	1a	2 2	25% NC, 25% $KClO_3$, 25% glass, 12.5% Al, 77% NC, 23% Al 12 5% C	.249	.241	.1584	8		
Sept 21		9		1a	½* 1 1	75% NC, 7% $KClO_3$ 25% NC, 75% $KClO_3$ 97% NC, 3% Al	.304	24	.1234			*Last ½ of tube was coated to build up That half to have pure propellant available when projectile is moving faster.
Sept 22			4	1a	1 1	47.9% NC, 42.9% $KClO_3$, 14 3% Al 1NC, (75% KNO_3, 15% C, 10% S)	248	.2605	1580			contacts blown off 1st station

SUMMARY OF RESULTS CONTINUED

DATE	VEL fps	TANK PRESS psig	COATING THICKNESS mils	BASE COAT	PROPELLANT % COATS	PROPELLANT %	PROJECTILE SPECIFICATIONS LENGTH in	PROJECTILE SPECIFICATIONS DIA in	PROJECTILE SPECIFICATIONS MASS gr	PENETRATION LAYERS	PENETRATION DIA in	COMMENTS
Sept 26			10	1a	3 3	42 9% NC, 42 9% $KClO_3$, 14 3% Al 14 3% NC, 71 4% KNO_3, 14 3% Al	2525	241	1445			Adapter blown off 1st station blown off Very loud
Aug 18	700 1450 counter	8	1 3	1a	1	33% NC, 33% $KClO_3$, 16 7% Al, 16 7% C	120	118	040			Aluminum projectile
Aug 22	2700 3600	7	1 6	1a	1	25% NC, 25% $KClO_3$, 25% Al, 25% glass	120	119	0393	10		Aluminum base on nylon head Nylon only recovered
Aug 22		10	1	1a	1	16 7% NC, 16 7% Al, 50% $KClO_3$, 16 7% glass	124	119	0386			Al projectile Only 1st station broken Projectile not recovered.
Aug 22		9	2 4	1a	1	16 7% NC, 16 7% Al, 50% $KClO_3$, 16 7% glass	198	118	0541			Al base on nylon head Only 1st station broken
Aug 25	6000	10	2 5	1a	1	16 7% NC, 16 7% Al, 50% $KClO_3$, 16 7% glass	148	119	0251	17		
Aug 28			1 5	1a	1	16 7% NC, 16 7% Al, 50% $KClO_3$, 16 7% glass	165	1185	0244	4		Very slow
Aug 28			2	3a	1	16 7% NC,16.7% Al, 50% $KClO_3$, 16.7% glass	.143	1185	0239			
Aug 28		7	2	1a	1	16 7% NC, 16.7% Al, 50% $KClO_3$, 16 7% glass	.135	.118	0348			Projectile found in tube, 1½' down tube Nylon ok, Aluminum gone Aluminum base with Nylon head.
Aug 29		8	1 3	1a	1	16 7% NC, 50% $KClO_3$, 16.7% glass, 16.7% Al	.135	1195	.0349			Nylon head, steel tail Projectile not found
Aug 30			2	1a	1 2	16 7% NC, 50% $KClO_3$,16 7% glass,16 7% Al NC, BA	127	1175	023			Plexiglass projectile
Feb 6 366	2570 2956 counter	17	6 75	N/A	4	28% NC, 55% NH_4ClO_4, 14% Al 3% glass	.489	.242	.348	*		Mass of projectile before = 209 *Made 3/8 in. hole in 1/8 in. Al
Feb 7		13	6	N/A	4	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	507	241	208/ .389			Back fired Strain gage
Feb 7		13	8 5	N/A	4	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	.505	242	.202/ 381			Projectile hit blast deflector Strain gage
Feb 12		13	4 5	N/A	4	1NC, 2 NH_4ClO_4, .5 Al, 1 glass	508	243	.204/ 325			Back fired Strain gage
Feb 13			5	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	.506	243	.203/ .366			Back fired Strain gage
Feb 13		15	5	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	.520	242	.209/ .382			Back fired Strain gage
Feb 16	2290 433 counter	8 5	3	N/A	2	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	294	240	205			Strain gage
Feb 16		14	6	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	512	.242	204/ 331			Strain gage Projectile hit blast deflector
Feb 19	5750 3490 counter	9	2 75	N/A	2	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	.527	242	.203/ 366			Projectile hit third station Strain gage
Feb 19	2.20 2300 counter	9		N/A	2	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	530	241	.213/ 365			Dent in Al plate Strain gage
Feb 20	2090 counter	9	3 0	N/A	2	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	.505	242	376			Tube did not fire Strain gage.
Feb 21	2800 counter	25	4	N/A	4	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	.522	242	368			Strain gage
Feb 23		13	3	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	.424	.241	.215/ 351			Projectile hit blast deflector Strain gage
Feb 23		16	4	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al,.1 glass	.425	242	193/ .329			Projectile hit blast deflector Strain gage.
Feb 23	2800 counter	9	4	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al, 1 glass	417	.241	188/ 337	25	.37"	Strain gage.
Feb 26	3050	8				Unlined	.453	243	191/ 338			Strain gage.
Feb 26	3600	8				Unlined	.272	.242	187			Strain gage.
Feb 26	2700					Unlined	268	.243	200			Strain gage
Feb 28	6000	8	4.5	N/A	3	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	370	.241	.162/ 198	30	5	Strain gage
Mar 1		9	4.5	N/A	4	1 NC, 2 NH_4ClO_4, .5 Al, .1 glass	.513	.242	.193/ 315	4		Slow

DATE	VEL fps	TANK PRESS psi	COATING 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 P.S.I/SEC	ULT. PRESS PSI	AVE VEL. BTWN GAUGES fps	COMMENTS
March 22	2870	9	5.5	3	1NC,2NH_4ClO_4,.5Al, .1G	.485	.243	.183/.343	28L	----						Flapper caught blast.
March 23	----	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 10	----	25	2.5	3	1NC,2NH_4ClO_4, .5Al, .1G	.509	.241	.197/.402	26L	.375						Tube slid forward three inches.
April 10	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/.563	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	3300	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	4786	17	1.5	4	1NC, 3Al, .5G	.541	.243	.182/.428	28L	.50						

DATE	VEL fps	TANK PRESS psi	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTILE SPECIFICATIONS LENG IN.	DIA IN.	MASS GR	PENETRATION DEPTH	DIA IN.	GAGE NO IN.	BASE PRESS PSI	STOPPING PSI/SEC	ULT. PRESS PSI	AVE. VEL. BTWN GAUGES fps	COMMENTS
May 7	4150	12	2.5	3	INC, 3Al, .5F	.551	.293	.177 .399	31L	.375						
May 9	3500	17	1.0	4	INC, 3Al	.572	.243	.191 .613	26L	.80						
May 13	2400	8	1.0	4	INC, 3Al	.529	.240	.176 .462	26L	.75						
May 13	5250	9	1.5	4	INC, 3Al	.537	.242	.200 .494	33L	.80						
May 14	6300	8	4.0	4	INC, $2NH_4ClO_3$, .5Al, .5G	.582	.242	.197 .506	33L	1.0						
May 14	----	8	5.0	4	INC, $2NH_4ClO_3$, .5Al, .5G	.522	.242	----	---	---						Tube w/o worm; fired in front of projectile.
May 17	5900	11	4.0	3	INC, $2NH_4ClO_3$, .5Al, .5F	.520	.243	.189 .461	30L	.75						
May 17	5920	--	3.5	3	INC, $2NH_4ClO_3$, .5Al, .5G	.550	.243	.196 .477	33L	.88						
May 20	4200	14	3.0	1 3	INC, 3Al INC, 1 RDX, .1G	.615	.243	.192 .390	38L	.375						
May 20	4900	11	3.0	4	INC, 3Al	.632	.243	.196 .609	28L	.50						
May 21	5200	11	4.0	1 3 1	INC, 3Al, .1G INC, 1 RDX, .1G INC, $2NH_4ClO_3$, .1G	.612	.243	.193 .598	---	---						Tank blown back one inch.
May 24	5652	12	4.5	1 2 2	INC, 3Al, .5G INC, 1RDX, .5G INC, $2NH_4ClO_3$, .5Al, .1G	----	----	.196 .609	19L	.35						
May 29	1700	13	4.0	1 3	INC, 3Al INC, $2NH_4ClO_3$, .5Al, .2G	.650	.244	.196 .663	---	---						
June 4	2011	10	----	1 2	INC, 3Al INC, $2NH_4ClO_3$, .5Al, .2G	.483	.243	.194 .424	23L	.43						
June 4	3540	16	2.5	1 2	INC, 3Al INC, $2NH_4ClO_3$, .5Al, .2G	.467	.243	.197 .393	13L	.375						
June 5	3500	14	3.5	3	INC, $2NH_4ClO_3$, .5Al, .2G	.467	.243	.188 .404	31L	.05						
June 5	2400	18	2.2	3	INC, $2NH_4ClO_4$, .5Al, .1G	.483	.243	.194 .424	23L	.43						
June 6	----	24	3	3	INC, $2NH_4ClO_4$, .5Al, .1G	.467	.244	.207 .425	---	---						Hit flapper valve Apperently fired ahead of projectile
June 12	2308	25	3.5	3	INC, $2NH_4ClO_4$, .5Al, .1G	.548	.243	.197 .466	23L	---						
June 19	1861	26	3.0	3	INC, $2NH_4ClO_4$, .5Al, .1G	.462	.242	.186 .424	18L	.25						
June 19	3700	10	2.0	3	INC, $2NH_4ClO_4$, .5Al, .1G	.568	.442	.193 .531	27L	.50						
June 20	2300	27	3.0	3	INC, $2NH_4ClO_4$, .5Al, .1G	.495	.243	.199 .487	20L	.375						
June 20	2450	14	3.0	3	INC, $2NH_4ClO_4$, .5Al, .1G	.469	.244	.200 .400	21L	.375						

DATE	VEL fps	TANK PRESS psi	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROPELLING SPECIFICATIONS LENG IN.	DIA IN.	MASS GR	PENETRATION DEPTH	DIA IN.	CAPS NO IN.	BASE PRESS PSI	SLOPE PSI/SEC	ULT. PRESS PSI	AVE.VEL. BTWN GAUGES fps	COMMENTS
June 21	4460	9	3.0	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.445	.241	.189/.340	29L	.625						
June 25	5340	10	3.75	3	1NC, $2NH_4ClO_4$, .5Al, .1G	.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	1206	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, .1G	.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, .1G	.504	.242	.204/.462	---	---						
July 12	2250	--	--	-		.465	.243	---	---	.75						
July 17	4789	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, .1G	.502	.242	.190/.460	37L	.375	12	--	1.67 2.50	7,500 11,200	5450	Approximate 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	13	4.5	4	1NC, $2NH_4ClO_4$, .5Al, .1G	.450	.241	.177/.401	13L	.375	12 48	---	0.26 0.66	2,500 4,200	4680	Part of projetile 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	--	----	----	-----	----	

DATE	VEL f/s	TANK PRESS PSI	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 f/s	COMMENTS
July 29	5361	15	3.0	1 2	INC, Bs INC, $2NH_4ClO_4$, .5Al, .1G	.479	.243	.197 .436	3L	.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	2097	90	5.0	3	INC, $2NH_4ClO_4$, .5Al, .1G	.440	.246	.213 .347	22L	.50	12 48		0.75 0.38	7,000	4840	Plasma recloced Station # 2
August 1		17	4.0	1	NC INC, $2NH_4ClO_4$, .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	INC, $2KClO_3$, .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	INC INC, $2KClO_3$, .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	INC, $2NH_4ClO_4$, .5Al, .1G	.485	.249	.215 .353	26L	1.0						
August 15	6214	11	4.0	4	INC, $2KClO_3$, .5Al, .1G	.445	.249	.214 .322	40L	0.9						
August 16	5892	12	4.0	4	INC, $2KClO_3$, .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	5460				Unlined		.242	.190								
August 20	5892	14	4.0	4	INC, $2KClO_3$, .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	INC, $2NH_4ClO_4$, .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	INC, $2NH_4ClO_4$, .5Al, .1G	.489	.248	.212 .416	.1	.375	12 12v		0.45 0.83	5,000		
August 22	4842	20	4.5	3	INC, $2NH_4ClO_4$, .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	INC, $2KClO_3$, .5Al, .1G INC, 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	INC, 1 $KClO_3$, .5Al, .1G INC, 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	INC, 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	INC, 2NH ClO , .5Al, .1G	.502	.248	.211 .373			12 48 12v		0.60 0.68 0.75	5,500 9,000	6,350	
August 29	5756	17	4.0	1	NC INC, $2KClO_3$, .5Al, .1G	.471	.249	.212 .370	.375	.626	12 48		0.51 0.75	3,500 5,000	4,680	

DATE	VEL fps	TANK PRESS psi	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
August 29		14	4.0	1	1NC 1NC, 1.8NH_4ClO_4, .2K-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, .2K-104 .5Al	.427	.249	.197 .363			12 48		0.23 0.88	2,500 6,000	5,360	
August 30		17	4.0	1 3	1NC 1NC, 1.8NH_4ClO_4, .2K-104 .5Al	.431	.249	.203 .372	.25	.625						
September 2		15	4.0	2	1NC, $2KClO_3$, .5Al, .1G 1NC, 1.8NH_4ClO_4, .2K-104, .5Al	.438	.249	.206 .373	.25	.625	12 48	1,000 1,000	0.23 0.78	3,500 3,000	4,400	
September 2	3948	13	4.0	2 1	1NC, $2KClO_3$, .5Al, .1G 1NC, 1.8 NH_4ClO_4, .2K-104 .5Al	.437	.24d	.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, .5K-104, .1G	.426	.249	.201 .369	.25	.625	12 48	750	0.50 1.67		3,770	
September 5	4109	14	4.0	2 1 1	1NC, $2KClO_3$, .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, $2KClO_3$, .5Al, .1G 1NC, 3 Lead Azide 1NC, 1G	.435	.125	.206 .359	.375							
September 6	4916	14	3.5	2 1 1	1NC, $2KClO_3$, .5Al, .1G 1NC, 1.5 NH_4ClO_4, .5 K-104 .5Al,.1G 1NC, $2KClO_3$, 1K-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, $2KClO_3$, .5Al 1NC, $2KClO_3$, 1K-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, $2KClO_3$, .5Al 1NC, $2KClO_3$1K-104 .5Al, .1G	.435	.248	.200 .421			12 48	750	0.25 0.40	3,000 4,000	536	
Sept. 10	5783	14	3.5	2 2	1NC, $2KClO_3$, .5Al 1NC, $2KClO_3$, 1K-104, .5Al, .1G	.505	.249	.191 .397	.25	.375						
Sept. 10	2005	14	3.5	2 2	1NC, $2KClO_3$, .5Al, .1G 1NC, $2KClO_3$, 1K-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, $2KClO_3$, .5Al 1NC, 1.8NH_4ClO_4, .2K-104, .5Al, .1G	.446	.248	.196 .430								
Sept. 11	6472	14	3.25	1 3 2	BA 1NC, $2KClO_3$, .5Al 1NC, 1.8NH_4ClO_4, .2K-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, .2K-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	5976		4.5	2 2	1NC, $2NH_4ClO_4$, .5Al, .1G 1NC, 1.8NH_4ClO_4, .2K-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, $2KClO_3$, .5Al 1NC, 1.8NH_4ClO_3, .2K-164 .5Al, .1G	.438	.249	.207 .394	.25	.625	12 48		0.58 1.25	5,700 6,500	4,500	

DATE	VEL fps	TANK PRESS psi	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTING SPECIFICATIONS LENG IN.	PROJECTING SPECIFICATIONS DIA IN.	PROJECTING SPECIFICATIONS MASS GR	PENETRATION DEPTH	PENETRATION 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 .471	.25	.625						
Sept. 17	6506	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	4,690 5,000	4,670	
Sept. 20	4322	8	3.5	3	1NC, $2NH_4ClO_4$, .5Al 1NC, $2NH_4ClO_4$, .3Al, .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, 2KC1O , .5Al 1NC, $1.8NH_4ClO_4$, .2X-164, .5Al	.495	.249	.202 .77			12 48	1,600	1.60 2.80	8,000 10,000	6,230	
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, $1.8NH_4ClO_4$, .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	.518	.249	.210 .392			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

DATE	VEL fps	TANK PRESS psi	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTILE SPECIFICATIONS LENG in.	DIA in.	MASS gr	PENETRATION DEPTH	PENETRATION DIA in.	GAUGE NO IN.	BASE PRESS PSI	STOPP PSI/SEC	ULT. PRESS PSI	AVE. VEL. BTWN GAUGES fps	COMMENTS
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	.490	.248	.207 .420	.375	.625	14 32 56 105		3,500 4,800 9,000	3,500 4,800 9,000		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	.597	.241	.208 .424			14AA 32 56AA 105		1.00 0.50 1.00 0.20	10,000 8,000 20,000 4,000	9,000 6,000	
Dec. 10	6752	9	3.5	1 1 6	1NC 1NC, 2NH_4ClO_4 1NC, 1NH_4ClO_4, 1X-164	.542	.241	.194 .452	.375	.625	14AA 56AA		1.00 2.50	16,000 16,000	4,600	#35 & #103 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	#103 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, 1.9MB164	.460	.248	.177 .378	.25	.375						Pressure gauges not used.
March 5	1542	7	1.0	5	4NC, 9.7X-164, 91.3 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, 3MB164, 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, 3MB164, 1 PVC	.486	.248	.210 .408	.25	.25	12 48					Did not trigger
April 24	4879	25	4.5	1 2	NC 3KNO_3, 3MB164, 1PVC	.557	.242	.207 .370	.25	.25	12 48					Did not trigger
April 29	5001	25	4.5	1 2	NC 3KNO_3, 3MB164, 1PVC	.487	.449	.207 .408	.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, 3MB164, 1PV		.243	.564 .243			12 48	1,500	5.00 3.00	10,000 13,000	5,400	
April 29	3800	25	3.5	1	3KNO_3, 3MB164, 1PVC		.243	.606			14AA 32		2.00 2.00	6,000 6,000	3,000	
April 30	4976	25	7.0	2	3KNO_3, 3MB164, 1PVC	.435	.242	.198 .305	.25	.25	12 48		1.20 5.00	8,000 11,000	4,200	
May 9		7	6.5	1 2	NC 3KNO_3, 3MB164, 1PVC		.243	.644			12 48		2.00 3.00	10,000 14,000	4,800	
May 13			7.0	1 2	NC 3KNO_3, 3MB164, 1PVC	.643	.242	.556			12 48		3.00 2.00	5,000 8,000	4,300	

DATE	VEL fps	TANK PRESS psi	COATING DEPTH	NO OF COATS	PROPELLANT COMPOSITION	PROJECTING SPECIFICATIONS LENG IN.	DIA IN.	MASS GM	PENETRATION DEPTH	DIA IN.	GAUGE NO IN.	BASE PRESS PSI	SLOPE PSI/INC	ULT. PRESS PSI	AVE.VEL. BTWN GAUGES fps	COMMENTS
21 May	3539	7	3	1	15% PVC 42.5% MS164 42.5% KNO_3	.70	.243	.359	.25	.25						Nylon-spring proj. Afterbody broke off proj. No press. developed
25 July	3349	11	5	2	15% PVC 42.5% MS164 42.5% KNO_3	.670	.242	1.11	.75	.25						Steel-spring proj. Gages did not trigger
29 July	3130	6	5	2	15% PVC 42.5% MS164 42.5% KNO_3	.659	.240	.745	.375	.375	12 48	1000 1000	5.0 5.0	8000 4000	3000	Spring-Rivet proj.
30 July	4559	6	5	2	15% PVC 42.5% MS164 42.5% KNO_3	.451	.242	.360	.125	.25	12 48		1.0 1.2	5000 5000	4000	Traveling charge proj.
15 Aug.		6	4.5	2	10% PVC 45% MS 164 45% KNO_3	.650	.242	.343			12 48		5.0 2.5	4000 4000	5000	Nylon-spring proj. Afterbody broke off proj. Press. due to shock front
21 Aug.		7	5.5	2	10% PVC 45% MS164 45% KNO_3	.629	.243	.539			12 48	500 500	1.5 5.0	8000 10,000	1400	Nylon-stud proj. Afterbody broke off proj. Press. due to shock front
27 Aug.		9	4	1	10% PVC 45% MS164 45% KNO_3	.548	.240	.413			12 48		1.25 2.5	5000 5000	2000	Traveling charge proj. Tube fire ahead of proj.
29 Aug.		8	5.5	2	10% PVC 30% MS164 60% KNO_3	.452	.242	.550			12 48	1000	1.0	8000		Nylon-stud proj. Afterbody broke off proj.
5 Sept.	3739	9	4	2	10% PVC 30% MS164 60% KNO_3	.65	.242	.70	.25	1.0						Spring-Rivet proj. Gages didnot trigger
23 Sept.		6	4.5	2	10% PVC 45% MS164 45% KNO_3	.622	.242	.55			12 48		.33 .20	2000 2000	4400	Spring-Rivet proj. Proj. hit flapper valve
26 Sept.	3084	8	3	2	10% PVC 45% MS164 45% KNO_3	.677	.242	.59	.375	.375	12 48		0 .22	0 1000		Spring-Rivet proj.
1 Oct.		8	9	4	10% PVC 45% MS164 45% KNO_3	.743	.232	.60								Spring-Rivet proj. Proj. hit flapper valve Gages did not trigger
3 Oct.		8	8	4	10% PVC 45% MS164 45% KNO_3	.672	.232	.55			12 48		5.0 2.0	10,000 10,000	5550	Spring-Rivet proj. Proj. broke up. Press. due to shock front
14 Oct.		8	8	5	10% PVC 45% MS164 45% KNO_3	.616	.232	.497			12 48		5.0 2.5	12,000 10,000	5550	Spring-Rivet proj. Proj. blown back Press. due to shock front
16 Oct.		8	5.5	3	10% PVC 45% MS164 45% KNO_3	.520	.237	.454			12 48		3.3	1.,000		Spring-Rivet proj. Proj. blown back Press. due to shock front
17 Oct.		8	7	4	10% PVC 45% MS164 45% KNO_3	.60	.232	.40			12 48		3.3 1.6	8000 8000	5500	Nylon-spring proj. Proj. head broke off Press. due to shock front
27 Oct.		8	7.5	5	10% PVC 45% MS164 45% KNO_3	.375	.232	.25			12 48	500	10.0 2.5	12,000 10,000	5000	Nylon-conical base proj. Proj. torn up, hit flapper valve. Tube fired ahead after half way

DATE	VEL fps	TANK PRESS psi	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
29 Oct.	5384	9	9	5	10% PVC 45% MS164 45% KNO_3	.338	.231	.218	.25	.375	12 48	1000 500	5.0 5.0	10,000 10,000	4700	Nylon conical base proj.
10 Nov.		6	9	8	10% PVC 45% MS164 45% KNO_3											No. proj. used. Purpose was to measure shock effect. Gages did not trigger shock vel. =3122 fps obtained from vel. station
11 Dec.		6	8.5	6	10% PVC 45% MS164 45% KNO_3	.468	.232	.290			12 48		1.0 1.0	12,000 10,000	5500	Nylon-staple proj. Tubed fired ahead
17 Dec.		6	10	9	10% PVC 45% MS164 45% KNO_3	.613	.231	.415			12 48	1000 1000	5.0 5.0	15,000 10,000	5550	Nylon-staple proj. Head broke off proj. Press. due to shock front
19 Dec.		6	10	6	10% PVC 45% MS164 45% KNO_3	.80	.231	.685			12 48	1000	5.0 10.0	12,000 8,000	5500	Nylon-staple proj. Tube fired ahead Press. due to shock front
7 Jan.		6	9	5	10% PVC 45% MS164 45% KNO_3	.690	.231	.425			12 48	1000	4.25 1.25	15,000 10,000	6000	Nylon-staple proj. Tube fired ahead Press. due to shock front
22 Jan.		6	9	5	10% PVC 45% MS164 45% KNO_3	.498	.231	.348			12 48	1000	2.5 1.6	10,000 8,000	5500	Nylon-staple proj. Tube fired ahead Press. due to shock front
2 Feb.		6	10.5	8	10% PVC 45% MS164 45% KNO_3	.463	.227	.322			12 48	1000 1000	2.0 0.5	11,000 7,000	5550	Nylon conical base proj. Proj. blown back Press. due to shock front
10 Feb.		7	9	7	15% PVC 42.5% MS164 42.5% KNO_3	.430	.227	.227								Nylon conical base proj. Proj. blown back
24 Feb.		8	8	5	15% PVC 42.5% MS164 42.5% KNO_3	.354	.227	.200								Nylon-conical base proj. Proj. broke up Found in Exp. Chamber
5 May		8	5	5	15% PVC 42.5% MS164 42.5% KNO_3	.480	.239	.15								Nylon-conical base proj. Proj. hit flapper valve
11 May	5057	8	9.5	9	15% PVC 42.5% MS164 42.5% KNO_3 Geon 427, AL	.339	.228	.22	.125	.375						Nylon-conical base proj. Adapter blown off
18 May	4977	9	10	10	15% PVC 42.5% MS164 42.5% KNO_3 Geon 427, AL	.595	.228	.430	.375	.50						Nylon-staple proj. Adapter blown off
22 May		8	10	9	15% PVC 42.5% MS164 42.5% KNO_3 Geon 427, AL	.567	.227	.332								Nylon-staple proj. Staple dia = .237 Adapter blown off
27 May		8	10	9	15% PVC 42.5% MS164 42.5% KNO_3	.50	.227	.305								Nylon-staple proj. Staple dia = .238 Adapter blown off Proj. hit flapper valve

DATE	VEL fps	TANK PRESS mm	COAT-ING 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.						
5 June		13	11	11	15% PVC 42.5% MS164 42.5% KNO_3 Geon 427, AL	.585	.227	.373								Nylon-staple proj. Staple dia = .238 Adapter blown off Proj. hit flapper valve
13 Aug.	5037	10	10	12	15% PVC 42.5% MS164 42.5% KNO_3 60% Geon 427 40% AL	.544	.227	.322	.25	.50						Nylon-staple proj. Staple dia = .239 Adapter blown off