BRL-TR-3407

AD-A257 456

TECHNICAL REPORT BRL-TR-3407

BRL

A METHOD FOR THE REAL-TIME MEASUREMENT OF PROJECTILE IN-BORE VELOCITY

TODD E. ROSENBERGER
ROBERT L. MARTZ

SEPTEMBER 1992

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1992	Final, Aug 90 - Aug 92

4. TITLE AND SUBTITLE

A Method for the Real-Time Measurement of Projectile In-Bore Velocity

5. FUNDING NUMBERS

PR: 1L162618AH80

6. AUTHOR(S)

Todd E. Rosenberger and Robert L. Martz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

USA Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

BRL-TR-3407

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release - Distribution is Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Accurate projectile velocity and displacement measurements are imperative to many ballistic studies. The Interior Ballistics Division (IBD) of the Ballistic Research Laboratory (BRL) routinely uses microwave interferometry to obtain projectile displacement versus time records during the interior ballistic cycle. This report describes the setup of a microwave interferometer to obtain projectile displacement and velocity data. A discussion of some possible sources of error and the factors which limit the resolution of the measurements is also included. Finally, a novel technique is presented for processing the analog interferometer signal in real time to obtain projectile velocity.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Microwave Interferometry, displacement, velocity, interior ballistics	21
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Kevin White and Mr. Joseph Colburn of BRL for their efforts in reviewing this report and Mr. Melvin Ridgley and Ms. Karen E. Minor of BRL for their assistance in publishing this report.

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

Accurate projectile velocity and displacement measurements are imperative to many ballistic studies. The Interior Ballistic Division (IBD) of the Ballistic Research Laboratory (BRL) routinely uses microwave interferometry to obtain projectile displacement versus time records during the interior ballistic cycle. A microwave interferometer signal is reflected into the gun tube, off the front of the projectile, and back to the receiving antenna (see Figure 1). As the projectile moves, the path of the signal is reduced in length by one wavelength for each one-half wavelength of projectile travel. The phase of the reflected signal is then compared with the incident signal using a mixer and detector diode. The output of the detector is a periodic signal proportional to the displacement of the projectile; each cycle being equal to a projectile displacement of one-half wavelength of the incident signal. The signal can then be processed in real time to obtain the velocity versus time record of the projectile. It is not the author's objective to present a detailed discussion on the operation and physics of microwave interferomentry techniques. The above description outlines the basic process. A more fundamental discussion can be found in the BRL Technical Report 968 (Vest et al. 1955).

"A Method for the Real-Time Measurement of Projectile In-bore Velocity" describes the setup of a microwave interferometer to obtain projectile displacement and velocity data. Next, is a discussion of some possible sources of error and the factors which limit the resolution of the measurements. Finally, a novel technique is presented for processing the analog interferometer signals in real time to obtain projectile velocity.

2. MICROWAVE INTERFEROMETER SETUP

Figure 1 shows a typical range setup for using a microwave interferometer to obtain in-bore displacement versus time data for a projectile. Electromagnetic energy in the form of a radio frequency (RF) signal is propagated down the bore of the gun, usually off an expendable reflector such as a square of aluminum faced foam core insulation board, or an aluminum pie plate. These reflectors are needed to be able to offset the interferometer from the line of fire. A hand-held feed horn and a detector diode with a current meter are used when aligning the reflector so that the maximum amount of energy is reflected down the bore of the gun. Adjustments are made to the reflector screen so that the maximum current reading is attained, first at the muzzle of the gun, and then at the breech, if possible.

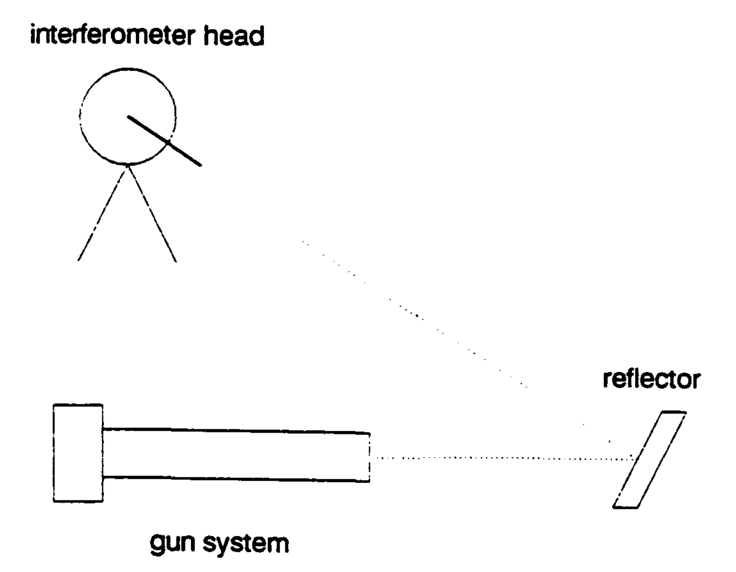

Figure 1. A Typical Range Setup For Using a Microwave Interferometer to Obtain In-bore Projectile Displacement.

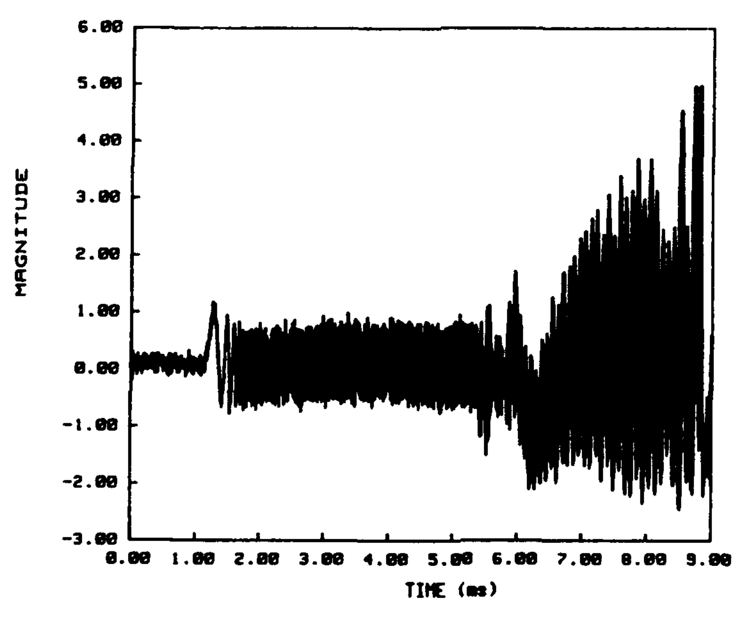

Figure 2. A Typical Interferometer Record.

As the projectile moves down the tube, it will introduce phase changes in the RF signal, which, when mixed with the residual signal at the receiver detector, will produce an interference pattern. Figure 2 shows an interference pattern, more commonly known as an interferometer record.

For each cycle of the interferometer signal, one-half of the wavelength of the transmitted RF signal in the gun tube has been traversed by the projectile. Because the gun tube acts as a circular waveguide when propagating the transmission frequency, the wavelength in the gun tube, λ_g, is slightly different than the freespace wavelength of the transmitted frequency, λ. The formulas used to calculate both λ and λ_g are given below (Evans 1985; Ware and Reed 1958).

$$\lambda = \frac{c}{f} \quad \text{and} \quad \lambda_g = \left[\left(\frac{f}{c}\right)^2 - \left(\frac{p}{\pi d}\right)^2\right]^{-1/2}$$

where:

f = source frequency

c = speed of light

d = gun tube diameter

p = Bessel Function root depending on mode of wave propagation (p = 1.84 for the TE_{11} mode which is considered the dominant mode and will be used for all calculations in this paper).

A count of the total number of cycles from the onset of projectile motion determines the distance that the projectile has traveled at any point in time. In addition, the frequency of the signal at any instant is directly proportional to the velocity of the projectile.

There are several practical details that the user must be aware of to insure good interferometer data. As noted previously, the gun tube acts as a circular wave guide when propagating a transmitted signal. Therefore one must make sure that the transmitted frequency of the microwave interferometer being used is above the cutoff frequency of the tube. This cutoff frequency is given by (Vest 1955):

$$f_c = \frac{cp}{\pi d} \quad .$$

Figure 3 shows a plot of λ_g versus gun tube diameter for various source frequencies, f. The concept of cutoff frequency can be seen by inspection of this graph. For example, a 10 GHz interferometer will not propagate in a gun tube with a diameter less than 18 mm. One can also see that the higher the transmitted frequency, the higher the resolution of

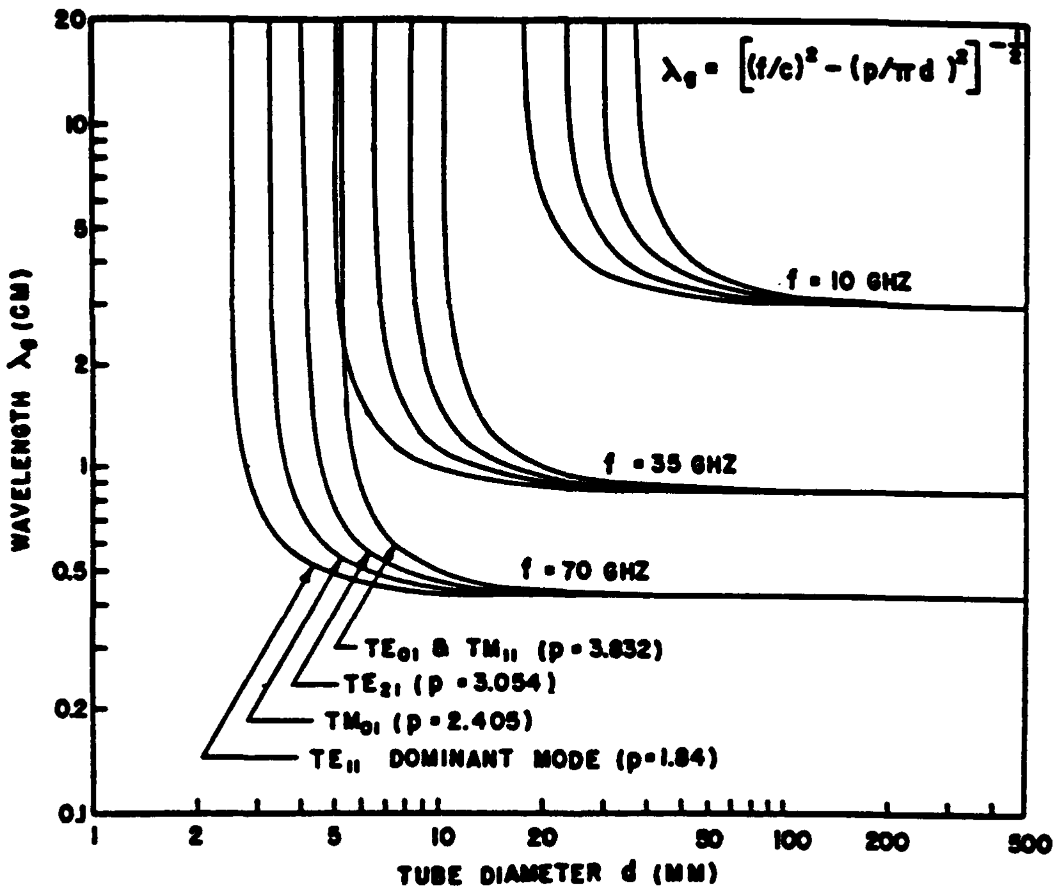

Figure 3. A Graph of Wavelength in the Gun Tube Versus Gun Tube Diameter For Given Source Frequencies.

the measurement. This is because the wavelength will be shorter, resulting in more cycles per unit of travel.

The recoil of the gun tube and the mount can cause problems with the measurement. The motion of the gun tube and mount also reflect the incident signal back to the antenna. This results in a larger low-frequency signal being superimposed on the projectile displacement signal. To alleviate this problem, an RF wave absorbing material is placed on the face of the gun tube, and mount if possible, to absorb the incident energy instead of reflecting it.

This system is easy to set up and use. However, it does have two major limitations. First, projectiles with pointed noses, or ogives, reflect the incident RF signal at various angles inside and outside the gun tube. This causes dispersion of the interferometer signal. At the present time, investigations continue in an effort to quantify the minimum flat reflective surface requirements that projectiles must have in order to produce usable interferometer data. At this time we can only say that it is very important to have a flat, metallic surface on the front of the projectile to reflect the RF signal. Second, good obturation is necessary to prevent ionized gases from leaking around the projectile. These ionized gases disperse the RF signal causing attenuation of the reflected signal. In turn, this may cause the signal to be lost in the noise of the system. This effect can be seen in a good interferometer record just as the projectile exits the muzzle. At this instant, the ionized gases overrun the projectile and thus the interferometer signal is lost. As the projectile outruns the gases, the signal returns. It is important that these two limitations be considered when attempting to acquire useful microwave inteferomenter data.

3. ERRORS

There are several possible sources of error when using a microwave interferometer to measure in-bore projectile displacement and velocity. As noted earlier, the frequency of the interferometer signal over a finite period of time is directly proportional to the velocity of the projectile over that period of time. More specifically;

$v = .5\ \lambda_g * f$

where:

v = velocity of the projectile

λ_g = wavelength of the incident RF signal in the gun tube

f = frequency of the interferometer signal over a finite time.

Note that the equation is multiplied by .5. This is because a full cycle of the resultant interferometer signal is equivalent to .5 λ_g of projectile travel. Obviously, any error in measuring the wavelength in the gun tube or the period of the interferometer signal will result in an error in the velocity measurement. It can be seen from the equation for λ_g on page three that λ_g is proportional to the source frequency and the gun tube diameter. A finite error can be associated with each of these parameters. One should actually measure the frequency of the microwave interferometer. This measurement can be performed very accurately using a precision high frequency counter. Another source of possible error is in measuring the diameter of the gun tube. Tubes can become worn and should be measured periodically. This measurement can be performed to within 1% for smooth gun tubes; however, measuring rifled tubes can be more difficult. The typical convention used in the IBD of the BRL is to measure the diameter between the lands. The error in calculating the wavelength in the gun tube caused by an error of 1% in measuring the tube will vary with tube diameter (decreases with increasing diameter) and source frequency (decreases with increasing frequency). The following examples, in the author's opinion, are considered typical applications. For a 30-mm gun tube and a 35 GHz microwave interferometer, the resultant error in calculating λ_g is .01%. For a 120-mm gun tube and a 15 GHz microwave interferometer, the resultant error is also .01%. However, for a 30-mm gun tube and 10 GHz microwave interferometer, the resultant error is .5 %. Obviously, the error can be significant if the microwave interferometer frequency is not suitable for the tube diameter. It is important to note that as the wavelength in the gun tube approaches freespace the error in measuring the diameter of the gun tube becomes negligible. However, near the cutoff frequency of the gun tube other modes of propagation can be excited futher complicating the measurement. In general, the smaller the tube diameter, the higher the microwave interferometer frequency one should use. As pointed out earlier, this can be seen by inspecting the graph in Figure 3.

The largest error in calculating the velocity from an interferometer signal is in measuring the period of the cycles over a finite time. The measurement most often desired is the velocity of the projectile at the muzzle of the gun. When the projectile is located at the muzzle of the gun, the frequency of the corresponding interferometer signal is generally quite high; therefore, it can be difficult to resolve the cycles of the interferometer signal accurately. This high frequency signal is resolved through the use of a high speed digitizer. The error involved in using a high speed digitizer to determine muzzle velocity is considered; if a 15 GHz microwave interferometer is used for a 120-mm gun firing, the projectile will travel 1.00409 cm per cycle of the interferometer signal (these values were obtained from the equation for λ_g). As the projectile begins to move, the resultant output from the interferometer becomes periodic, increasing in frequency as the projectile accelerates. At or near the muzzle, the projectile is traveling at nearly a constant speed, therefore, the frequency of the microwave interferomenter output signal will be relatively constant. For a given time window, one can count the number of cycles, and since we know the displacement per cycle, λ_g, it is a trivial exercise to calculate the velocity. If there are 10 cycles of interferometer data in 66.9 micro-seconds, then we know that the projectile has traveled 10.0409 cm, and the velocity is 1500 m/s, assuming the frequency over those 10 cycles remained constant. The faster the digitizer, the more accurate the muzzle velocity determination will be because we can resolve the signal more accurately. If a 1 MHz sampling rate is used, a very conservative error would be 1%. It is actually possible to interpolate between points so that an accuracy of .5 % is possible. If a 10 MHz sampling rate is used, then the error would be less than .5%. If instead of using a higher sampling rate, one chooses to use more cycles of interferometer data in the calculation, the error would also be less than .5%.

If one chooses the correct microwave interferometer frequency for the gun tube diameter being used, and correctly measures that frequency and the tube diameter, then the error will be limited by the speed of the digitizer being used.

4. DISPLACEMENT TO VELOCITY CONVERSION

In many ballistic studies, the velocity of the projectile, rather than the displacement history of the projectile, is the parameter of interest. Several methods have been developed to extract detailed projectile in-bore motion information from the recorded interferometer signal. However, these methods involve complex and lengthy digital signal processing and are not amenable to real-time application (an example of this type of system is the TERMA BS310 Interferometer Reduction Package). Usually there is a considerable delay involved in having the interferometer records processed. Hence, there is a real need for a method capable of processing the analog interferometer signals in real time to obtain the in-bore projectile velocity history. A method has been developed for the real-time measurement of projectile in-bore velocity and will be described in the following paragraphs.

Since each cycle of the interferometer record corresponds to a known displacement, the frequency of the sinusoidal interferometer record is directly proportional to the velocity of the projectile. A technique for the conversion of the interferometer signal to velocity involves a calibrated frequency-to-voltage conversion. The block diagram for the calibrated conversion of the analog interferometer record to in-bore projectile velocity is shown in Figure 4.

The interferometer signal is fed through a band-pass filter. The band-pass filter is not necessary for the conversion, but it is useful in removing extraneous noise such as 60 Hz and signals from leaves and other objects moving in the background. The output signal from the band-pass filter is then fed into a frequency-to-voltage converter (discriminator),

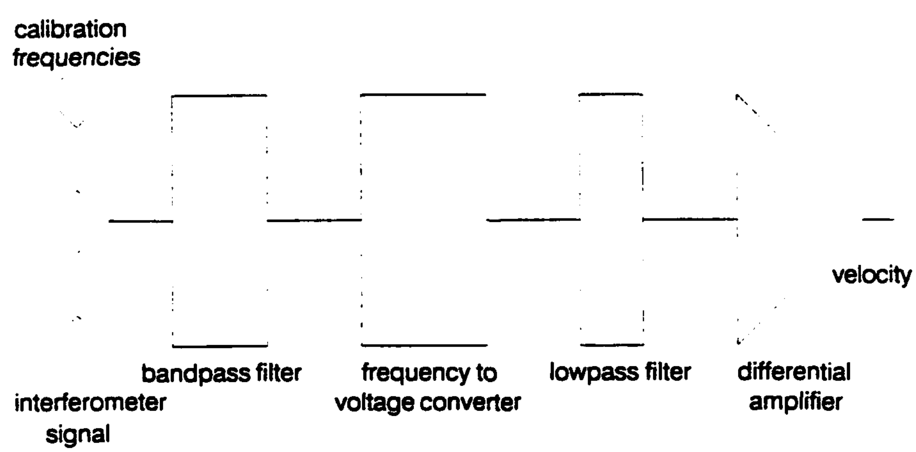

Figure 4. Block Diagram: Frequency to DC Conversion.

which produces a precision pulse of constant amplitude and duration for each positive going zero crossing of the input signal. One can also achieve good results by replacing the discriminator with a precision pulse generator. As with the discriminator, for each positive going zero crossing of the input waveform, a precision pulse of constant amplitude and duration is produced. With a constant frequency input signal, the output pulses will be uniformly spaced and have a constant amplitude as shown in Figure 5. It is important that the user verify that a given input frequency produces a constant amplitude and duration pulse for each zero crossing over the range of intended use. These frequencies should simulate the interferometer signal that results as the projectile increases in velocity (resulting in an increase in frequency). The intent here is to demonstrate that the precision pulse generator is generating uniform pulses over the frequency range in which the system will be used. This can be accomplished by inputting constant frequencies from typically

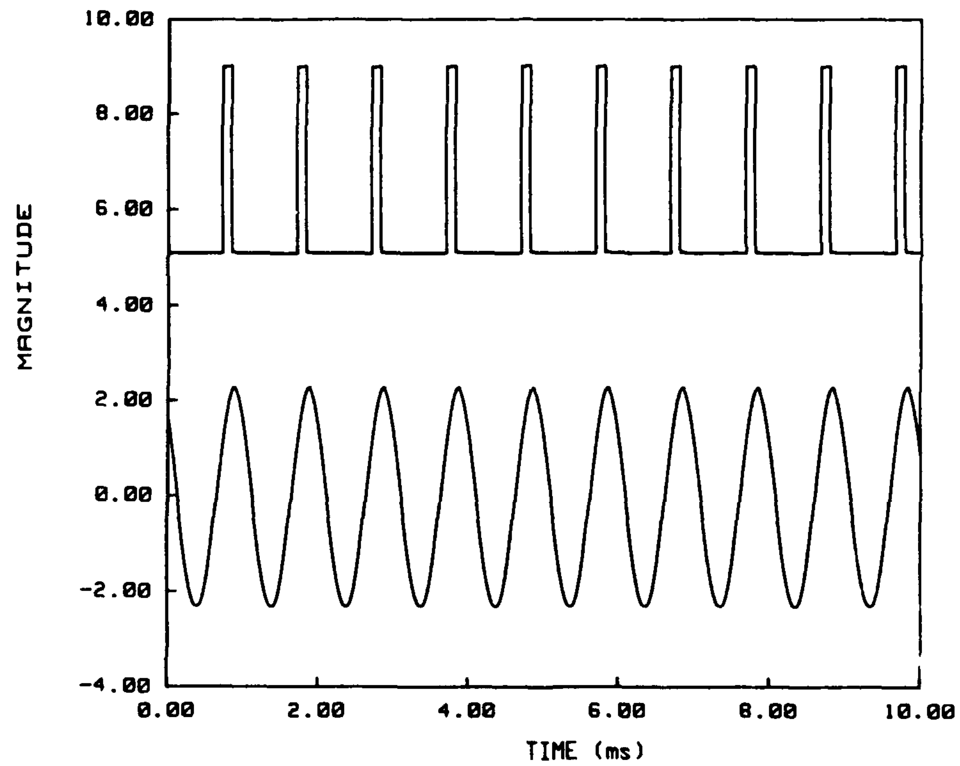

Figure 5. Constant Frequency Input and Corresponding Uniform Output Pulses From Precision Pulse Generator.

10 KHz to 300 KHz and observing the output of the pulse generator. The output voltage should maintain a constant amplitude and duration while maintaining the same frequency as the input frequency.

The pulse train in Figure 5 can be expanded into a Fourier series. The Fourier series expansion is a trigonometric series consisting of sine and cosine terms of the form (Lathi 1983):

$$f(t) = \frac{a_o}{2} + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)$$

$$a_n = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} f(t) \cos n\omega t$$

$$b_n = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} f(t) \sin n\omega t$$

$$\frac{a_o}{2} = \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} f(t)\, dt \, .$$

The $a_o/2$ term is the average value of f(t) over one period. If the pulse train is fed into a low-pass filter, the average value can be shown to be proportional to the input frequency, i.e., the higher the input frequency, the closer the pulses, and the larger the average DC term. Figure 6 shows the input pulse train and the corresponding output from the low-pass filter.

From the preceding equation it can be seen that a problem exists at the start of motion. The "ω" in the sin (nωt) and cos (nωt) terms will be 2π times the frequency of the interferometer signal at any time, and of course, the interferometer signal frequency starts at zero. It is therefore impossible for the low-pass filter to separate the DC term from the terms containing "ω" at the start of projectile motion. This is not a serious problem except where a detailed description or evaluation of the start of projectile motion is required. Because of the rapid projectile acceleration, the frequency of the interferometer signal is, in general, greater than 5000 Hz after the first several cycles. By using a six pole, active,

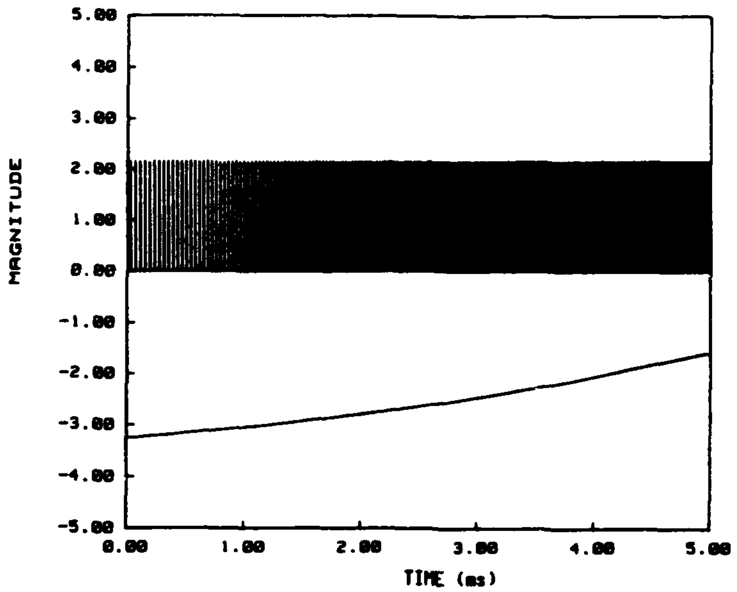

Figure 6. Constant Increasing Frequency Input Pulses and Corresponding Output From Low-pass Filter.

low-pass, electronic filter with a selectable cut-off frequency, the start of motion problem can be reduced to a few cycles of ripple on the first part of the velocity versus time record (A Precision Filter model number 616-01-LP1-G05 is a good example of this type of filter). It should be noted that the acceleration of the projectile is the controlling factor in setting the cut-off frequency of the low-pass filter. The cut-off frequency should be set as low as possible to separate the DC term from the "ω" terms and reduce the amount of ripple at the start of projectile motion. However, if it is set too low, the filter will remove the velocity changes, i.e. the acceleration of the projectile. This cutoff frequency can be experimentally set to optimize the operation. By inputting a frequency sweep into the system which approximates the acceleration of the projectile in the gun system being evaluated, one can adjust the low-pass filter cutoff frequency to minimize the ripple while maintaining the integrity of the signal during the time of maximum acceleration.

A differential DC amplifier is used for convenience to adjust the level and the polarity of the velocity signal for recording on magnetic tape and for on-line analog-to-digital conversion. Calibration is done by switching precise frequency levels into the input of the system. Five precision frequencies are switched into the system at 50 ms intervals to create a staircase output of the low-pass filter (recall that a constant frequency will give a constant DC voltage out of the low-pass filter). The interferometer signal is then switched into the system using a relay. Both the calibration signal and the processed interferometer signal are fed to an analog-to-digital converter after which they are processed by a computer. By comparing the known calibration frequencies output from the above system with the output from the interferometer signal, the magnitude of the velocity at any point in time can be determined, except of course at the start of motion.

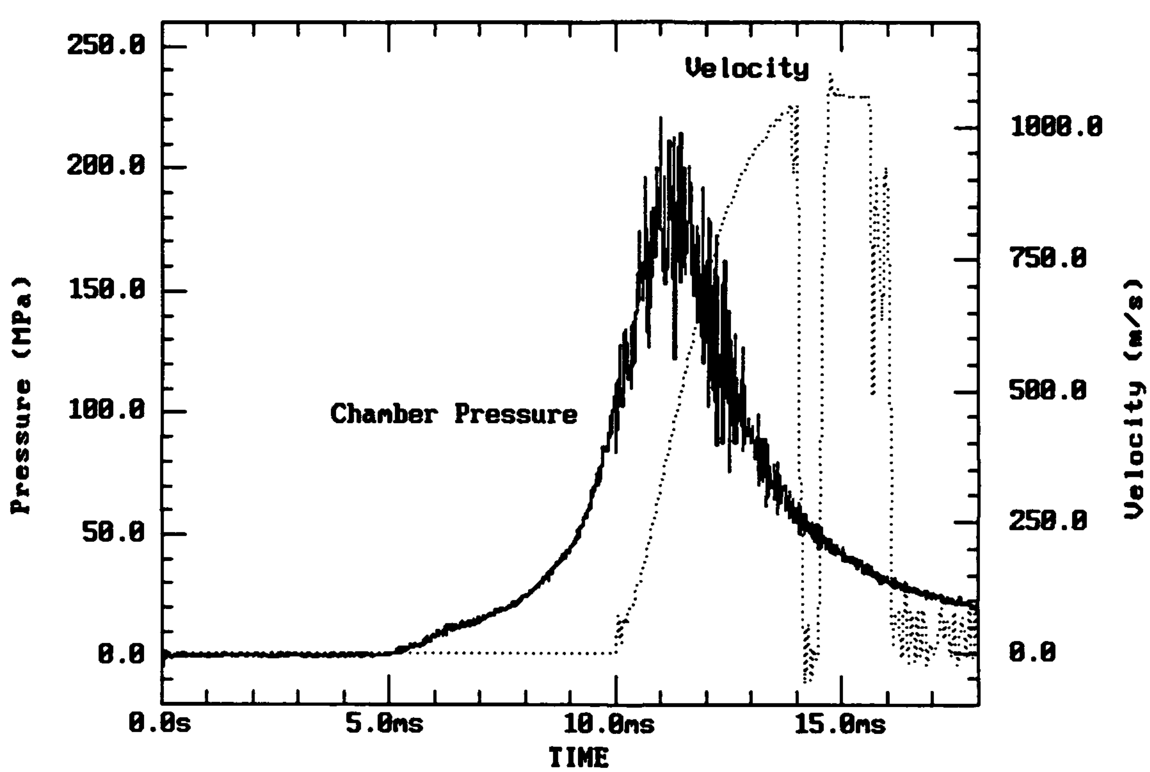

Figure 7. Real Time Velocity and Pressure Histories For a 30-mm Liquid Propellant Gun.

Figure 7 shows a plot of projectile velocity and chamber pressure for a 30-mm liquid propellant gun firing. The pressure is included to illustrate how the electronic conversion simplifies data processing by allowing the use of the same method for processing velocity-time records as for processing pressure-time records. At the start of motion a few cycles of ripple can be seen as previously described. The velocity then tracks well until the projectile exits the gun tube, at which time the combustion gases over run the projectile. This can be seen in Figure 7 where the signal drops out and then returns as the projectile out runs the combustion gases. We define the level at which the velocity curve returns and then flattens out to be the muzzle velocity. Finally, as the projectile impacts the reflective medium, the signal is lost.

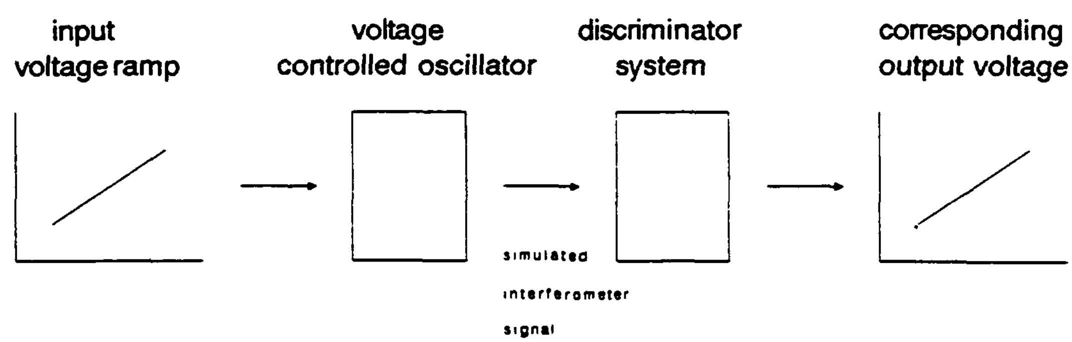

Figure 8. Block diagram: Correction Process For Using Method to Determine Discrete In-bore Projectile Velocity.

In practice, the velocity versus time curve serves as a very accurate method of determining muzzle velocity. However, there is an inherent time shift associated with the low-pass filter that will cause any correlation to time to be slightly incorrect unless the entire system is compensated. This time shift is proportional to the low-pass filter setting and is usually on the order of 100 micro-seconds, which in most cases can be ignored. However, for purposes of completeness, the authors recommend the compensation process shown in the block diagram in Figure 8.

The process of compensating the system is simple in theory. Using a voltage ramp and a voltage controlled oscillator, one can generate a frequency sweep from 10 KHz to 300 KHz that is proportional to the input voltage ramp. This frequency sweep will serve to simulate an interferometer signal, which in turn is fed into the displacement-to-velocity conversion system outlined previously. The output of the low-pass filter will be a corresponding voltage ramp with the same slope as that used to generate the simulated interferometer signal. However, this voltage ramp will be shifted by a finite time, determined by the low-pass filter cut-off frequency. This time can be measured by using a dual channel storage oscilloscope. By varying the low-pass filter cut-off frequency, a corresponding shift in time between the input and output voltage ramps will be observed. This shift will be unique to the low-pass filter settings used in a particular system and therefore the calibration results will be different from system to system. By noting the time shift inherent at a particular cut-off frequency, one can adjust the time-base of the velocity versus time curve produced as the projectile traverses the gun tube. This will allow the displacement-to-velocity conversion system outlined previously to be used to more accurately determine a given projectile velocity at any point in time, except at the start of motion.

The error analysis presented earlier is directly applicable to the real-time displacement-to-velocity system described in this paper. In addition, the accuracy of the system is limited by the accuracy of the calibration steps used in the system. The calibration steps used in the system are accurate to less than 1%. Therefore the error in making the displacement-to-velocity conversion to measure muzzle velocity is less than 1 %.

5. CONCLUSIONS

The setup and theory of using a microwave interferometer to measure in-bore projectile displacement was presented. The major limitations of the measurement were discussed including the effects of pointed projectiles, ineffective obturation of the combustion gases, and gun system recoil. A method of processing a difference, or interferometer, signal in real time to obtain in-bore projectile velocity was outlined.

The resultant velocity profile serves as an accurate method of determining projectile muzzle velocity. However, it was noted that there is an inherent time shift associated with the low-pass filter in the displacement-to-velocity conversion. To account for this time shift, a compensation procedure was suggested which would allow the method to be used to determine projectile velocity at any point in time, except at projectile start of motion. In addition, an error analysis suggested that the error in determining muzzle velocity from a microwave interferometer record is less than .5 %. It was also suggested that the error of the real-time projectile displacement to projectile in-bore velocity was less than 1 %.

6. REFERENCES

Evans, J.W. "Measurement Of Interior Ballistic Performance Using FM/FM Radio Telemetry Techniques." BRL-TR-2699, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1985.

Lathi, B.P. Modern Digital And Analog Communication Systems. Holt, Rinehart and Winston Publishing Co., New York, NY, 1983.

Vest, D.C., J.E. Anders, B.B. Grollman, B.L. DeMare. "Ballistic Studies With A Microwave Interferometer - Part I." BRL-TR-968, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1955.

INTENTIONALLY LEFT BLANK.

No. of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Commander U.S. Army Materiel Command ATTN: AMCAM 5001 Eisenhower Ave. Alexandria, VA 22333-0001
1	Commander U.S. Army Laboratory Command ATTN: AMSLC-DL 2800 Powder Mill Rd. Adelphi, MD 20783-1145
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
(Unclass. only)1	Commander U.S. Army Rock Island Arsenal ATTN: SMCRI-TL/Technical Library Rock Island, IL 61299-5000
1	Director U.S. Army Aviation Research and Technology Activity ATTN: SAVRT-R (Library) M/S 219-3 Ames Research Center Moffett Field, CA 94035-1000
1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010

No. of Copies	Organization
1	Commander U.S. Army Tank-Automotive Command ATTN: ASQNC-TAC-DIT (Technical Information Center) Warren, MI 48397-5000
1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
1	Commandant U.S. Army Field Artillery School ATTN: ATSF-CSI Ft. Sill, OK 73503-5000
(Class. only)1	Commandant U.S. Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only)1	Commandant U.S. Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	WL/MNOI Eglin AFB, FL 32542-5000
	Aberdeen Proving Ground
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TC
3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
1	Dir, VLAMO ATTN: AMSLC-VL-D
10	Dir, USABRL ATTN: SLCBR-DD-T

No. of Copies	Organization
1	C.I.A. 01R/DB/Standard Washington, DC 20505
1	Director U.S. Army Ballistic Missile Defense Systems Command Advanced Technology Center P. O. Box 1500 Huntsville, AL 35807-3801
1	Chairman DOD Explosives Safety Board Room 856-C Hoffman Bldg. 1 2461 Eisenhower Ave. Alexandria, VA 22331-0600
1	Department of the Army Office of the Product Manager 155mm Howitzer, M109A6, Paladin ATTN: SFAE-AR-HIP-IP, Mr. R. De Kleine Picatinny Arsenal, NJ 07806-5000
2	Commander Production Base Modernization Agency U.S. Army Armament Research, Development, and Engineering Center ATTN: AMSMC-PBM, A. Siklosi AMSMC-PBM-E, L. Laibson Picatinny Arsenal, NJ 07806-5000
3	PEO-Armaments Project Manager Tank Main Armament Systems ATTN: AMCPM-TMA/K. Russell AMCPM-TMA-105 AMCPM-TMA-120, C. Roller Picatinny Arsenal, NJ 07806-5000
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCD, D. Spring SMCAR-CCH-V, C. Mandala Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
14	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-AEE SMCAR-AEE-B, A. Beardell D. Downs S. Einstein S. Westley S. Bernstein J. Rutkowski B. Brodman R. Cirincione A. Grabowsky P. Hui J. O'Reilly P. O'Reilly SMCAR-AES, S. Kaplowitz, Bldg. 321 Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-HFM, E. Barrieres Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSA-T, M. Salsbury Picatinny Arsenal, NJ 07806-5000
1	Commander, USACECOM R&D Technical Library ATTN: ASQNC-ELC-IS-L-R, Myer Center Fort Monmouth, NJ 07703-5301
1	Commander U.S. Army Harry Diamond Laboratories ATTN: SLCHD-TA-L 2800 Powder Mill Rd. Adelphi, MD 20783-1145
1	Commandant U.S. Army Aviation School ATTN: Aviation Agency Fort Rucker, AL 36360

No. of Copies	Organization
2	Program Manager U.S. Army Tank-Automotive Command ATTN: AMCPM-ABMS, T. Dean (2 cps) Warren, MI 48092-2498
1	Program Manager U.S. Army Tank-Automotive Command Fighting Vehicles Systems ATTN: SFAE-ASM-BV Warren, MI 48092-2498
1	Project Manager Abrams Tank System ATTN: SFAE-ASM-AB Warren, MI 48397-5000
1	Director HQ, TRAC RPD ATTN: ATCD-MA Fort Monroe, VA 23651-5143
2	Director U.S. Army Materials Technology Laboratory ATTN: SLCMT-ATL (2 cps) Watertown, MA 02172-0001
1	Commander U.S. Army Research Office ATTN: Technical Library P.O. Box 12211 Research Triangle Park, NC 27709-2211
1	Commander U.S. Army Belvoir Research and Development Center ATTN: STRBE-WC Fort Belvoir, VA 22060-5006
1	Director U.S. Army TRAC-Ft. Lee ATTN: ATRC-L, Mr. Cameron Fort Lee, VA 23801-6140
1	Commandant U.S. Army Command and General Staff College Fort Leavenworth, KS 66027

No. of Copies	Organization
1	Commandant U.S. Army Special Warfare School ATTN: Rev and Trng Lit Div Fort Bragg, NC 28307
3	Commander Radford Army Ammunition Plant ATTN: SMCAR-QA/HI LIB (3 cps) Radford, VA 24141-0298
1	Commander U.S. Army Foreign Science and Technology Center ATTN: AMXST-MC-3 220 Seventh Street, NE Charlottesville, VA 22901-5396
2	Commander Naval Sea Systems Command ATTN: SEA 62R SEA 64 Washington, DC 20362-5101
1	Commander Naval Air Systems Command ATTN: AIR-954-Technical Library Washington, DC 20360
1	Naval Research Laboratory Technical Library Washington, DC 20375
2	Commandant U.S. Army Field Artillery Center and School ATTN: ATSF-CO-MW, E. Dublisky (2 cps) Fort Sill, OK 73503-5600
1	Office of Naval Research ATTN: Code 473, R. S. Miller 800 N. Quincy Street Arlington, VA 22217-9999
3	Commandant U.S. Army Armor School ATTN: ATZK-CD-MS, M. Falkovitch (3 cps) Armor Agency Fort Knox, KY 40121-5215

No. of Copies	Organization
2	Commander U.S. Naval Surface Warfare Center ATTN: J. P. Consaga C. Gotzmer Indian Head, MD 20640-5000
4	Commander Naval Surface Warfare Center ATTN: Code 730 Code R-13, K. Kim R. Bernecker H. Sandusky Silver Spring, MD 20903-5000
2	Commanding Officer Naval Underwater Systems Center ATTN: Code 5B331, R. S. Lazar Technical Library Newport, RI 02840
1	Director Benet Weapons Laboratories ATTN: SMCAR-CCB-RA, G. P. O'Hara Watervliet, NY 12189-4050
4	Commander Dahlgren Division Naval Surface Warfare Center ATTN: Code G30, Guns and Munitions Division Code G301, D. Wilson Code G32, Gun Systems Branch Code E23, Technical Library Dahlgren, VA 22448-5000
3	Commander Naval Weapons Center ATTN: Code 388, C. F. Price Code 3895, T. Parr Information Science Division China Lake, CA 93555-6001
1	OSD/SDIO/IST ATTN: Dr. Len Caveny Pentagon Washington, DC 20301-7100

No. of Copies	Organization
3	Commander Indian Head Division Naval Surface Warfare Center ATTN: Code 610, T. C. Smith K. Rice Technical Library Indian Head, MD 20640-5035
1	OLAC PL/TSTL ATTN: D. Shiplett Edwards AFB, CA 93523-5000
1	AFATL/DLYV Eglin AFB, FL 32542-5000
1	AFATL/DLXP Eglin AFB, FL 32542-5000
1	AFATL/DLJE Eglin AFB, FL 32542-5000
1	AFELM, The Rand Corporation ATTN: Library D 1700 Main Street Santa Monica, CA 90401-3297
3	AAI Corporation ATTN: J. Hebert J. Frankle D. Cleveland P.O. Box 126 Hunt Valley, MD 21030-0126
3	AL/LSCF ATTN: J. Levine L. Quinn T. Edwards Edwards AFB, CA 93523-5000
3	ARMTEC Defense Products Company ATTN: S. J. Dyer N. S. Cielik Tech Library 85-901 Avenue 53 Coachella, CA 92236
1	AVCO Everett Research Laboratory ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149-5936

No. of Copies	Organization
1	CPIA - JHU ATTN: Harry J. Hoffman 10630 Little Patuxent Parkway, Suite 202 Columbia, MD 21044
1	General Electric Company Tactical Systems Department ATTN: J. Mandzy 100 Plastics Ave. Pittsfield, MA 01201-3698
1	IITRI ATTN: M. J. Klein 10 W. 35th Street Chicago, IL 60616-3799
1	Hercules, Inc. Allegheny Ballistics Laboratory ATTN: William B. Walkup P.O. Box 210 Rocket Center, WV 26726
1	Hercules, Inc. Radford Army Ammunition Plant ATTN: E. Hibshman Radford, VA 24141-0299
1	Hercules, Inc. Hercules Plaza ATTN: B. M. Riggleman Wilmington, DE 19894
3	Director Lawrence Livermore National Laboratory ATTN: L-355, A. Buckingham M. Finger L-324, M. Constantino P.O. Box 808 Livermore, CA 94550-0622
1	Olin Corporation Badger Army Ammunition Plant ATTN: F. E. Wolf Baraboo, WI 53913

No. of Copies	Organization
3	Olin Ordnance ATTN: E. J. Kirschke A. F. Gonzalez D. W. Worthington P.O. Box 222 St. Marks, FL 32355-0222
1	Olin Ordnance ATTN: H. A. McElroy 10101 9th Street, North St. Petersburg, FL 33716
1	Paul Gough Associates, Inc. ATTN: Dr. Paul S. Gough 1048 South Street Portsmouth, NH 03801-5423
1	Physics International Library ATTN: H. Wayne Wampler P.O. Box 5010 San Leandro, CA 94577-0599
1	Princeton Combustion Research Laboratories, Inc. ATTN: Dr. Martin Summerfield Princeton Corporate Plaza 11 Deerpark Dr., Bldg. IV, Suite 119 Monmouth Junction, NJ 08852
2	Rockwell International Rocketdyne Division ATTN: BA08, J.E. Flanagan J. Gray 6633 Canoga Ave. Canoga Park, CA 91303-2703
1	Sverdrup Technology, Inc. ATTN: Dr. John Deur 2001 Aerospace Parkway Brook Park, OH 44142
2	Thiokol Corporation Elkton Division ATTN: R. Biddle Technical Library P.O. Box 241 Elkton, MD 21921-0241

No. of Copies	Organization
1	Veritay Technology, Inc. ATTN: E. Fisher 4845 Millersport Highway East Amherst, NY 14501-0305
1	Universal Propulsion Company ATTN: H. J. McSpadden 25401 North Central Ave. Phoenix, AZ 85027-7837
1	Battelle ATTN: TACTEC Library, J.N. Huggins 505 King Ave. Columbus, OH 43201-2693
1	Brigham Young University Department of Chemical Engineering ATTN: M. Beckstead Provo, UT 84601
1	California Institute of Technology 204 Karman Laboratory Main Stop 301-46 ATTN: F.E.C. Culick 1201 E. California Street Pasadena, CA 91109
1	California Institute of Technology Jet Propulsion Laboratory ATTN: L. D. Strand, MS 125-224 4800 Oak Grove Drive Pasadena, CA 91109-8099
1	University of Illinois Department of Mechanical/Industrial Engineering ATTN: H. Krier 144 MEB; 1206 N. Green Street Urbana, IL 61801-2978
1	University of Massachusetts Department of Mechanical Engineering ATTN: K. Jakus Amherst, MA 01002-0014
1	University of Minnesota Department of Mechanical Engineering ATTN: E. Fletcher Minneapolis, MN 55414-3368

No. of Copies	Organization
3	Georgia Institute of Technology School of Aerospace Engineering ATTN: B.T. Zim E. Price W.C. Strahle Atlanta, GA 30332
1	Institute of Gas Technology ATTN: D. Gidaspow 3424 S. State Street Chicago, IL 60616-3896
1	The Johns Hopkins University/CPIA ATTN: T. Christian 10630 Little Patuxent Parkway, Suite 202 Columbia, MD 21044-3200
1	Massachusetts Institute of Technology Department of Mechanical Engineering ATTN: T. Toong 77 Massachusetts Ave. Cambridge, MA 02139-4307
1	Pennsylvania State University Department of Mechanical Engineering ATTN: V. Yang University Park, PA 16802-7501
1	Pennsylvania State University Department of Mechanical Engineering ATTN: K. Kuo University Park, PA 16802-7501
1	Pennsylvania State University Assistant Professor Department of Mechanical Engineering ATTN: Dr. Stefan T. Thynell 219 Hallowell Building University Park, PA 16802-7501
1	Pennsylvania State University Director, Gas Dynamics Laboratory Department of Mechanical Engineering ATTN: Dr. Gary S. Settles 303 Mechanical Engineering Building University Park, PA 16802-7501

No. of Copies	Organization
1	SRI International Propulsion Sciences Division ATTN: Technical Library 333 Ravenwood Ave. Menlo Park, CA 94025-3493
1	Rensselaer Ploytechnic Institute Department of Mathematics Troy, NY 12181
2	Director Los Alamos Scientific Laboratory ATTN: T3, D. Butler M. Division, B. Craig P.O. Box 1663 Los Alamos, NM 87544
1	General Applied Sciences Laboratory ATTN: J. Erdos 77 Raynor Ave. Ronkonkama, NY 11779-6649
1	Battelle PNL ATTN: Mr. Mark Garnich P.O. Box 999 Richland, WA 99352
1	Stevens Institute of Technology Davidson Laboratory ATTN: R. McAlevy III Castle Point Station Hoboken, NJ 07030-5907
1	Rutgers University Department of Mechanical and Aerospace Engineering ATTN: S. Temkin University Heights Campus New Brunswick, NJ 08903
1	University of Southern California Mechanical Engineering Department ATTN: 0HE200, M. Gerstein Los Angeles, CA 90089-5199
1	University of Utah Department of Chemical Engineering ATTN: A. Baer Salt Lake City, UT 84112-1194

No. of Copies	Organization
1	Washington State University Department of Mechanical Engineering ATTN: C. T. Crowe Pullman, WA 99163-5201
1	Alliant Techsystems, Inc. ATTN: Robert E. Tompkins 7225 Northland Dr. Brooklyn Park, MN 55428
1	Alliant Techsystems, Inc. ATTN: J. Kennedy 7225 Northland Drive Brooklyn Park, MN 55428
1	Science Applications, Inc. ATTN: R. B. Edelman 23146 Cumorah Crest Drive Woodland Hills, CA 91364-3710
1	Battelle ATTN: Mr. Victor Levin 505 King Ave. Columbus, OH 43201-2693
1	Allegheny Ballistics Laboratory Propulsion Technology Department Hercules Aerospace Company ATTN: Mr. Thomas F. Farabaugh P.O. Box 210 Rocket Center, WV 26726
1	MBR Research Inc. ATTN: Dr. Moshe Ben-Reuven 601 Ewing St., Suite C-22 Princeton, NJ 08540

Aberdeen Proving Ground

No. of Copies	Organization
1	Cdr, USACSTA ATTN: STECS-PO, R. Hendricksen

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number BRL-TR-3407 ____________ Date of Report September 1992

2. Date Report Received ____________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ____________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ____________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ____________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ____________________

CURRENT ADDRESS

Name

Organization

Address

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name

Organization

Address

City, State, Zip Code

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

Postage will be paid by addressee.

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES