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NSWC TR 81-128

REDUCTION OF 5"/54 GUN BLAST OVERPRESSURE BY MEANS OF AN AQUEOUS FOAM-FILLED MUZZLE DEVICE

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AUGUST 1981

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NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448
Silver Spring, Maryland 20910

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER NSWC TR 81-128	2. GOVT ACCESSION NO. AD-A112 280	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REDUCTION OF 5"/54 GUN BLAST OVERPRESSURE BY MEANS OF AN AQUEOUS FOAM-FILLED MUZZLE DEVICE		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) G. Stevens Miller Richard E. Miller, Jr. Larry L. Pater John W. Shea		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center Code N43 Dahlgren, Virginia 22448		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 63721N, 63657N
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command 62Y1 Washington, DC 20362		12. REPORT DATE August 1981 13. NUMBER OF PAGES 93
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

5"/54, Muzzle Dive, Aqueous Foam, Barrel Pressure, Muzzle Device Pressure, Foam in Barrel, Muzzle Clamp, Muzzle Weight, Aqueous Foam Generator

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It has been conclusively demonstrated that aqueous foam can effect significant (greater than 10 dB) reductions in major-caliber (5"/54) gun muzzle blast peak sound pressure level; reduction of more than 15 dB was attained. Containment of the foam in a muzzle-mounted canister was investigated. This report addresses related areas of gun ballistics, interior barrel ballistics, effects on projectile velocity, and general gun operational effects.

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S/N 0102-014-6601

FOREWORD

This report was prepared as part of a research and development program to determine a method of reducing the noise levels of naval weapons, particularly the noise created by the blast wave of large naval guns. The report has specific application to operations conducted at naval training ranges. The island training ranges of Kahoolawe in the Hawaiian Islands and Vieques in the Puerto Rican Islands were of particular concern. Early work was funded by the Naval Science Assistance Program (NSAP) at the request of COMTHIRDFLT and by the Navy Independent Research Program. The majority of work was carried out under the Gun Blast Effects Program, NAVSEATASK 653/497/004-1-S0956.

This report has been reviewed and approved by F.H. Maillie and J.F. Horton of the System Safety Division (N40) of the Combat Systems Department(N).

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ABBREVIATIONS AND ACRONYMS

BL&P	Blind loaded and plugged
caliber	1.0 barrel bore diameter
dB	Decibel
°F	Degree Fahrenheit
dc	Direct current
I.D.	Inside diameter
in.	Inch
kHz	Kilohertz
ksig	Unit of gauge pressure. One ksig is a thousand pounds per square inch above atmospheric pressure of 14.7 psi.
mV	Millivolt
mm	Millimeter
No.	Number
NSWC	Naval Surface Weapons Center
psig	Pounds per square inch, gauge
Rd	Round
SPL	Sound pressure peak level in flat response far-field

INTRODUCTION

Noise from the operation of major-caliber naval guns has long been a source of environmental concern. Closing training and testing facilities or even placing an operational restriction at the training ranges can limit the effectiveness of the Fleet in combat situations. Consequently, the Navy is keenly interested in finding a way to reduce blast noise in the far field without restricting training and testing operations.

Investigation of conventional "silencer" technology yielded devices with enormous size and weight requirements.[1] The requirements were so large, in fact, that any adaptation of conventional "silencer" technology to a major-caliber 5"/54 gun was totally impractical. As an outgrowth of that investigation, a unique approach of producing a potentially feasible mechanism to reduce muzzle blast associated noise was discovered. The previous search for literature dealing with existing "silencer" related subjects revealed a paper on the reduction of explosive blast overpressure[2] and related noise from the detonation of large explosive charges. It was reported that if an explosive charge was covered with an unconfined aqueous foam in the order of 20 charge diameters, significant noise reductions, in the order of 20 dB, were obtained. To reduce gun muzzle blast and associated noise, the approach of shooting the projectile through a cylindrical muzzle-attached device filled with aqueous foam was investigated[3] at a reduced scale. The scale model gun was a 7.62-mm rifle. The results of the reduced scale experiments yielded significant reductions in muzzle blast overpressure and its associated noise level, and muzzle devices that were significantly smaller than a conventional silencer yielded the same results. As a result of this work, it was decided to design, fabricate, and test a full-scale 5"/54 muzzle device to verify the results obtained from the scale model.

The effectiveness of the method is greatly influenced by the density of the foam. Thus, the parameter of foam density was investigated experimentally.

Part of the full-scale test dealt with answering questions of important design considerations: Would particulate collect in the device? Would foam leaking into the barrel create a problem in the interior ballistics? What would the pressures in the device be? In general, questions about the environment had to be answered so that an efficient design could follow.

EXPERIMENTAL APPARATUS AND PROCEDURES

GUNS

Two 5"/54 guns were used to test muzzle device effectiveness. One gun was the Mk 28 Mod 0 with the muzzle device attached to it. The muzzle of the other gun, the Mk 28 Mod 3, remained bare to provide reference information about sound pressure levels (SPL) in the far field. Both barrels were set in Mk 39 gun mounts.

The two guns were located 26 feet apart and were aligned with firing lines parallel to within 1.0 degree. Obstructions on the test range required that each gun be slightly elevated. The gun with the device was elevated 2.0 degrees, while the reference gun required an elevation of 4.0 degrees.

The arrangement of the guns is pictured in Figure 1. The effect of these differences on far-field SPL is not significant. For example, a 1.0-degree change in directivity represents less than 0.2 dB change in far-field SPL.[4] Indeed, the error introduced is smaller than the measurement accuracy of conventional sound measurement equipment.

Peak level sound pressure measurements were made in the far field for each gun firing. First, the gun with the muzzle device was fired and the SPL was recorded. Approximately 15 seconds later, the bare muzzle gun was fired and again the SPL was measured in the far field. The later measurement serves as the baseline value from which the difference in sound pressure between the two gun firings is found. The effectiveness of the muzzle device is evaluated according to this change in pressure level, expressed in decibels of sound. The guns were fired as close together in time as possible so that atmospheric conditions might be treated as constant for each data set. Over the entire far field, however, it is impossible to ignore the possibility for atmospheric disturbances such as shifts in the wind. These disturbances, when they occur, affect the measured results.

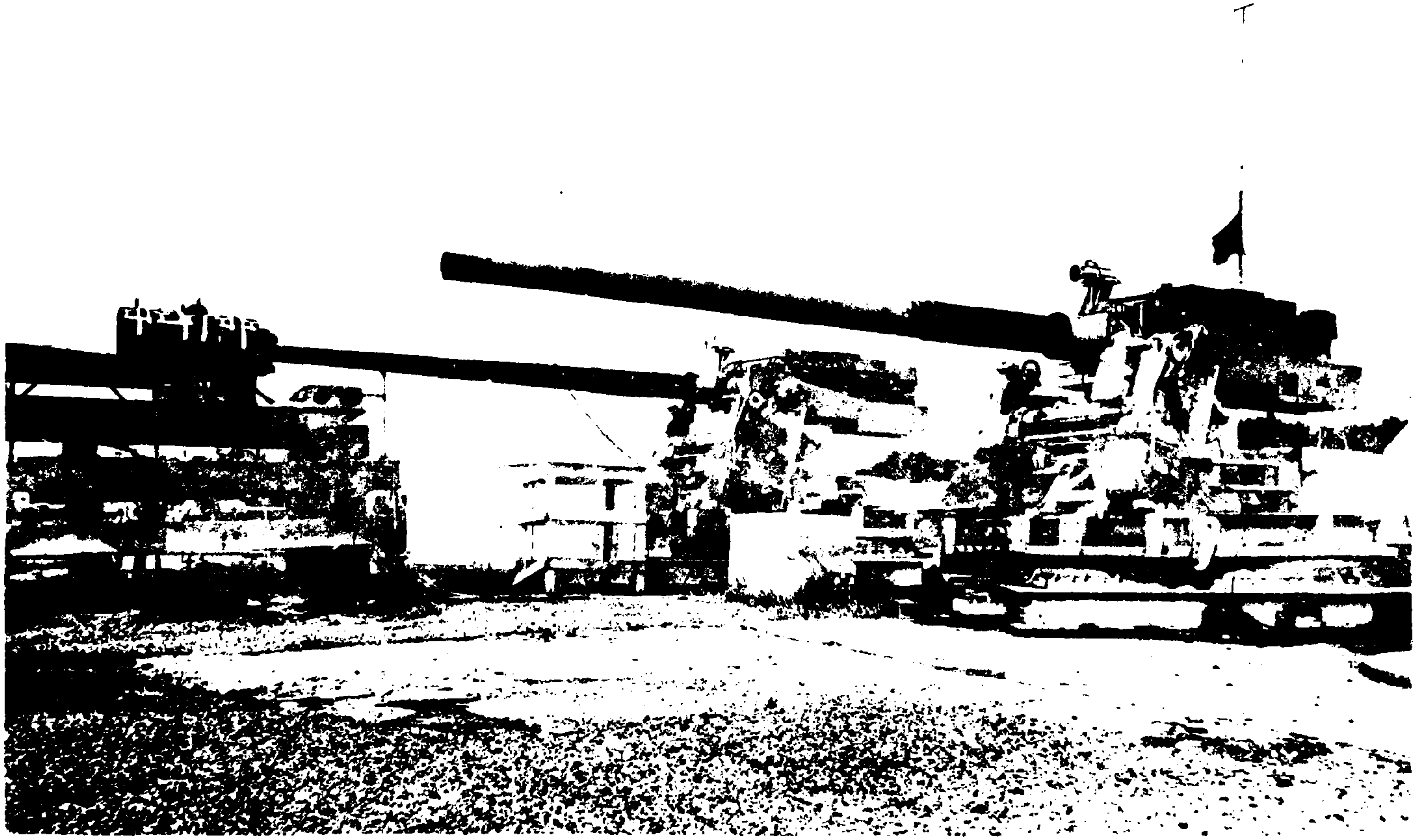

Figure 1. 5"/54 Gun Arrangement

The muzzle device was tested for several conditions, i.e., several different foam densities. For each condition, an average of three data sets was obtained.

AMMUNITION

Projectiles of the blind loaded and plugged (BL&P) type and full-service depot-loaded propelling charges were used. This minimized the round-to-round variation in projectile velocity and in far-field overpressure. The projectiles were Mk 92 Mod 1 with a nominal weight of 70.0 pounds. The charges were of SPCF-11185 propellant, each with a weight of 20.48 pounds. The propelling charge cases were Mk 9 Mod 0; the primers were Mk 42 Mod 1; the plugs were Mk 9 Mod 0 (cork); and the wads were polyethylene. All projectiles and charges were from a single lot and all were conditioned to 90°F for firing.

MUZZLE DEVICE

A foam-containing device, measuring more than 9 calibers in length and 5 calibers in diameter, was mounted on the muzzle of a 5"/54 naval gun. Such a device is normally attached to a gun muzzle to reduce blast, but a second purpose in this testing was to obtain information about the blast environment. Accordingly, the design of the device was very conservative. Not only did the device have to withstand a very dynamic set of loads, but provisions had to be made for instrumentation. The shape of the device is cylindrical along the axis of the gun; perpendicular to this axis are flat front and rear endcaps, as well as a baffle located at the center of the device. The implemented design is best described by Figure 2. The internal geometry and overall dimensions are specified in more detail in Figure 3. The design is essentially scaled from a device previously tested on a 7.62-mm gun and discussed in Reference 3.

The primary design criterion was that the device withstand a static 5 ksig internal pressure and have a safety factor near 2. The use of conventional low or medium carbon steel for fabrication would have resulted in a device weight of more than 7,000 pounds. Therefore, the high-strength alloy ASTM 4340 steel was

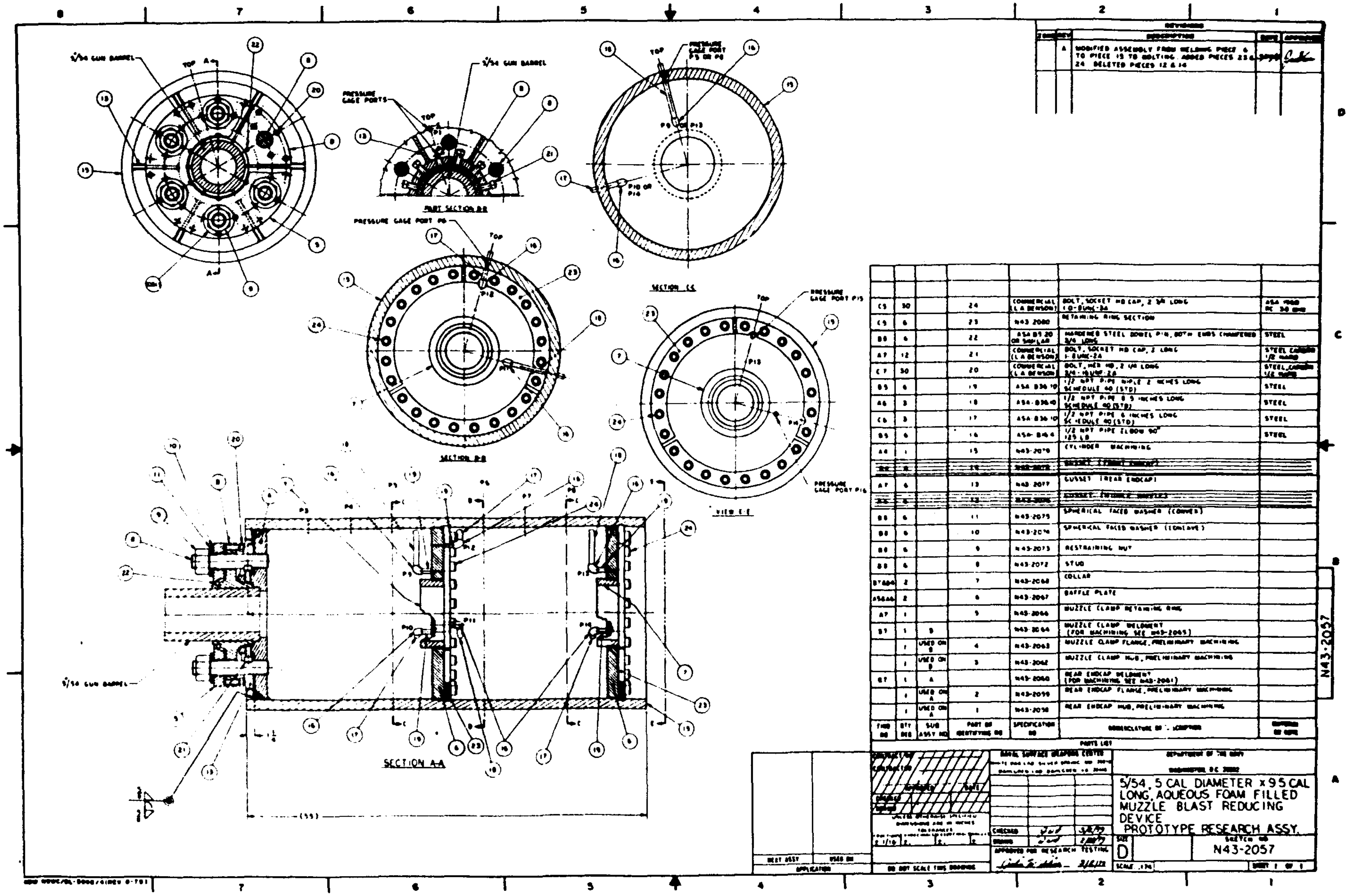

Figure 2. Assembly Drawing of the 5"/54 Muzzle Device

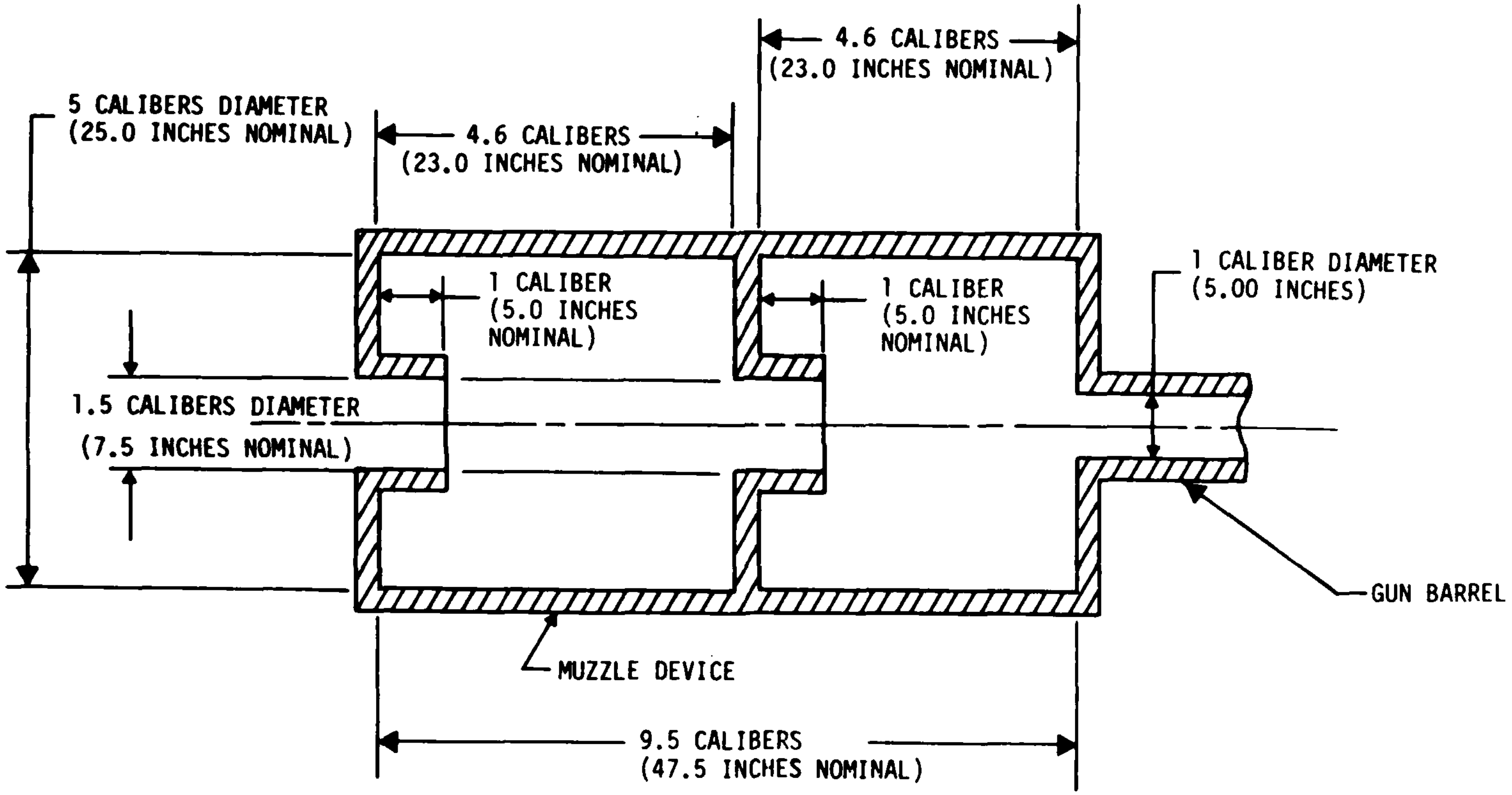

Figure 3. Schematic of the Internal Configuration of the 5"/54 Muzzle Device

used. The muzzle device assembly weight was then reduced to about 3,600 pounds,* and many of the handling and assembly problems were alleviated.

Fabrication of the completed device was made more difficult, however, by this choice of metal. The high-strength steel required preheat temperatures of 500°F to 600°F and a slow, controlled post cooling to ensure a reliable weld. To accomplish this, a heating furnace had to be constructed that allowed for welding while still maintaining heat input to the surrounding material.

MUZZLE DEVICE SUPPORT

A clamp mechanism was devised to attach the foam-containing device to the muzzle of an unmodified gun barrel. The forces that work to separate the muzzle device from the gun are largely axial. As a projectile exits the muzzle, the escaping high-pressure gases exert a force on the walls and baffles of the device and this axial baffle force is transmitted to the clamp. The clamp design turns a component of this axial force into an increased clamping force. Also, as a result of the weight of this device, there is a large inertial force that is encountered when the gun begins to recoil. To react against these axial forces, the design of the clamp relied on the shear strength of the lifting ring at the end of the barrel to supplement friction generated from its clamping action against the barrel.

The lifting ring on 5"/54 naval guns has a nominal height of only 0.050 inch. After six rounds were fired, it was apparent that the lifting ring could not survive further testing. The device was welded directly to the barrel for the remaining test shots. Note, however, that the clamp design maintained alignment of the device with the centerline of the gun barrel throughout the testing.

A cradle was fabricated to provide support for the muzzle device while at the same time allowing the device to recoil with the gun barrel. The cradle, which contained four support rollers, was mounted on a wooden platform which was constructed to the height of the gun barrel (see Figure 1). Each roller was

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* Different steels will probably be required, along with accurate internal pressure information, to reduce muzzle device weight to acceptable values.

positioned with a separate hydraulic jack. When secured, the four jacks served to support the muzzle device uniformly so that the excessive weight of the prototype device did not cause the barrel to be unduly stressed. The cradle, muzzle device, and barrel clamp are shown in more detail in Figure 4.

FOAM GENERATION EQUIPMENT

The decision to evaluate the effectiveness of a full-scale 5"/54 muzzle device carried with it some problems of equipment development. Prior to each round fired, foam generation equipment was needed that could fill the prototype device rapidly and uniformly and with foam of a known density. The development of a foam-making apparatus to fill the full-scale device is described in Appendix A. Also discussed is the procedure used for filling the device and for monitoring the foam expansion ratio during the testing. The foam generator was capable of producing a stable foam in a range of from 100:1 to 350:1 expansion ratios. To attain a foam at lower expansion ratios, a nozzle was designed for use with the liquid solution supply system. A larger diameter was used to allow for greater foam volume production per minute. A less dense agitation aggregate was also used. With this system, aqueous foam could be produced in a nominal range of 20:1 to 70:1 expansion.

As part of the general procedure used to fill the muzzle device with foam, a blanking disk was used to restrict the foam and keep it from entering the gun barrel. During the filling operation, the disk was inserted at the breech end of the gun and positioned at the muzzle of the barrel. The blanking disk was designed so that it could be withdrawn from the foam-containing device without suction so that the foam was not drawn into the gun barrel upon removal of the obstructing disk.

The prototype device was filled with foam from the muzzle opening. The rate of foam generation chosen allowed for reasonable control in filling the device. The rate selected was about 4 to 8 feet^3/minute depending on the expansion ratio being produced. For the most uniform and complete foam distribution, the device was filled from the rear toward the front or open end of the device.

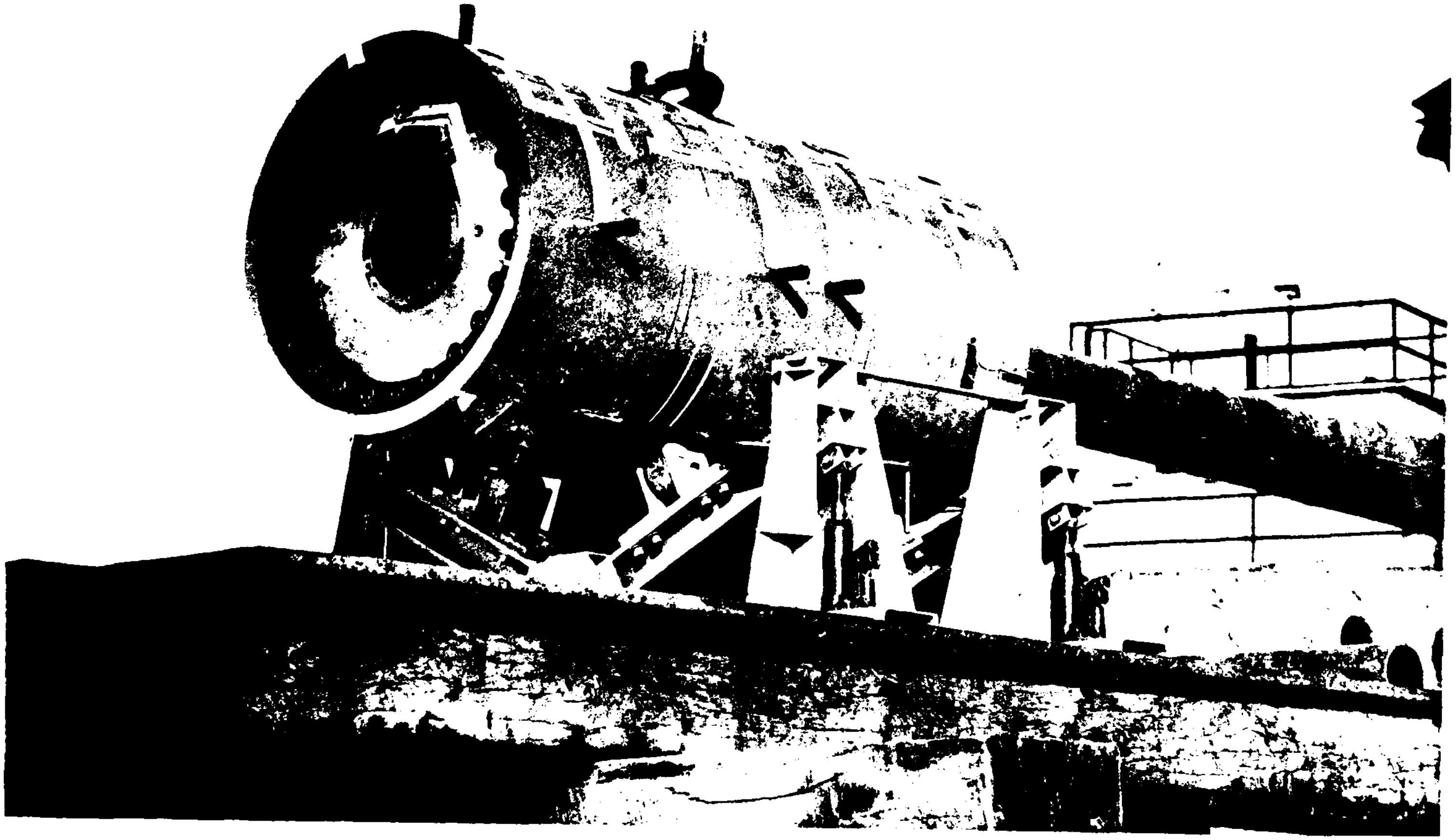

Figure 4. Muzzle Device and Cradle Support

INSTRUMENTATION

GENERAL

Several types of measurements were taken for the test program. These included far-field SPLs, together with the near-field blast level established from each gun firing. Pressure and strain gauges were carefully located on the muzzle device so that the internal pressure distribution could be established and information could be provided about the strength requirement of the device. Pressure inside the gun barrel was also monitored. In addition, the speed of the projectile as it exited the muzzle device was recorded. A common time signal was used for the pressure and the strain data and for the near-field blast records.

The far-field SPLs are of primary importance. They were needed so that the effectiveness of the muzzle device with its various expansion foams could be established.

The internal barrel pressures and the projectile velocity measurements provide pertinent information about the practicality of using such a device with existing weapons. The effect of the muzzle device, particularly when the device is filled with a foam, upon the internal pressure of the barrel is important since that can influence the ballistics of the projectile. The life of the gun barrel can even be jeopardized. The projectile velocity records were used to make a preliminary assessment of ballistic influence.

The near-field data and the gauge response obtained on the muzzle device were taken primarily to expedite advanced development. A weight optimization of the device is needed before a final feasibility determination can be made. The internal pressures and strain data for the muzzle device were obtained so that loading conditions could be established for use in a structural model.

MEASUREMENT OF SOUND PRESSURE IN THE FAR FIELD

The sound produced from the test firing of the 5"/54 guns was measured using an arrangement that requires two sound level meters. A schematic of the instrumentation technique is provided in Figure 5. General Radio precision meters (model 1982) were selected to measure the sound level. These use a 0.5-inch random incidence microphone and provide a dc voltage output that is linear in decibel over a 70-dB range. The sensitivity is 60 mV/dB over the 70- to 140-dB range selected for the testing. The meters, which were set to measure flat response peak levels, had been modified to hold the peak level observed until the device was reset. The meters were also adjusted to allow a remote signal to effect a reset just prior to each event. The instruments were calibrated using General Radio calibrator model 1567. The dc voltage output was verified at the data logger, and the system error was found to be only ±0.08 dB. The reference used was 117 dB peak at 1 kHz.

The topography of the test site dictated that the instruments be located at an angle of 107 degrees from the line of fire and 900 feet from the gun muzzle. The configuration is depicted in Figure 6.

The technique used for data acquisition was a great deal simpler than would have been required if the meters had been located within the zone of bow shock influence. In the region roughly defined by the first 63 degrees from the line of fire for the gun, overpressure readings are complicated by the presence of another shock wave. This shock is created by the motion of the projectile as it travels through the atmosphere. Although limited in its range of influence, the bow shock may actually exceed the blast wave in peak overpressure. As a result, data taken in this region require that a provision be made in the measurement system to distinguish between the two phenomena.

MEASUREMENT OF PRESSURE IN THE GUN BARREL

The use of aqueous foam in the muzzle device posed a question of how the operation of a full-scale gun might be affected. Of particular concern was the possibility that the device would reflect shock waves back down the barrel. To help determine if use of the muzzle device affects the in-bore ballistics of the gun, pressure data were taken on the interior of the barrel.

Pressure in the barrel was monitored at eight locations along the length of the gun. The axial locations are tabulated in Table 1 and the gauge stations are

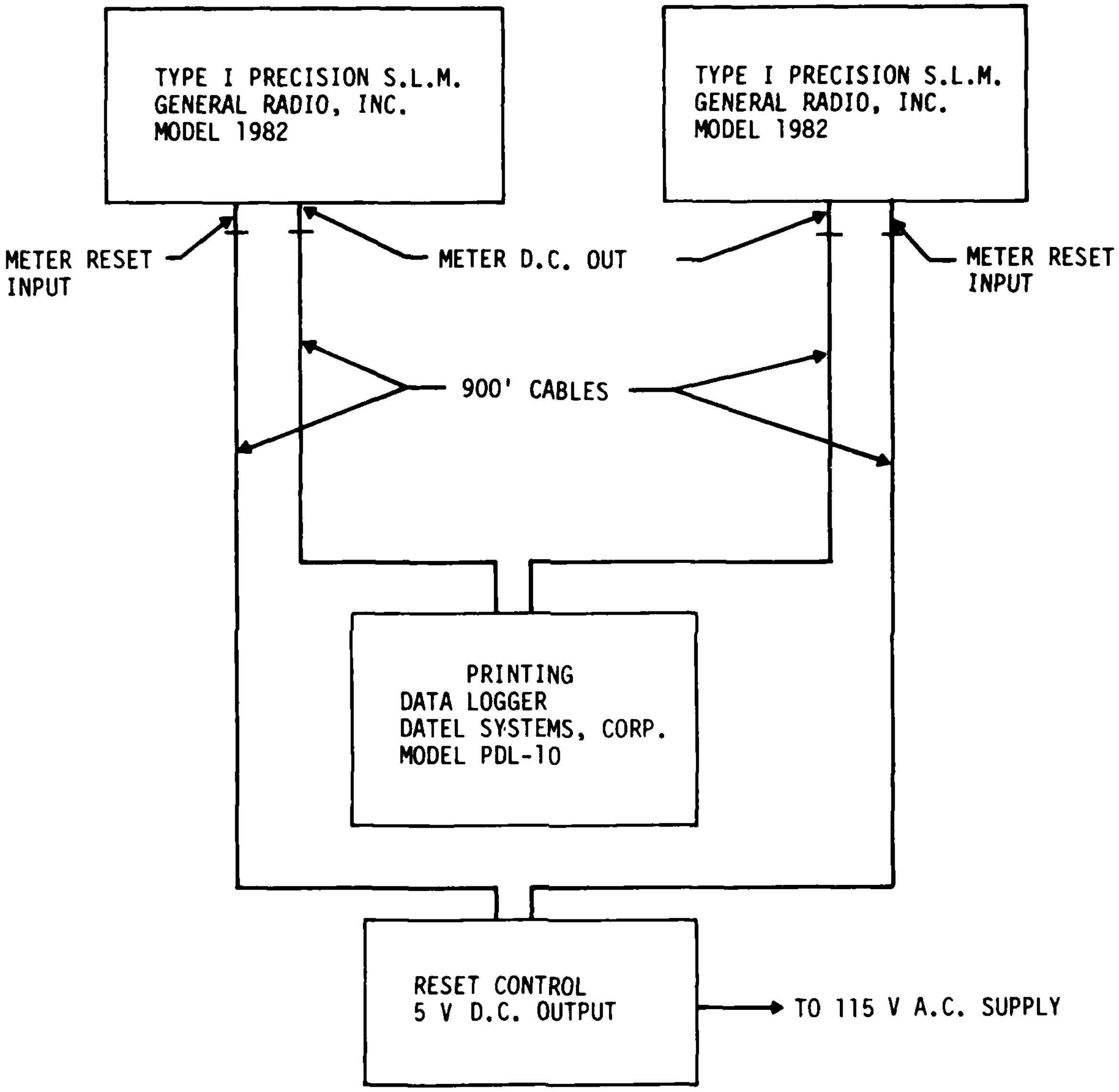

Figure 5. Instrumentation Schematic for Sound Level Measurements

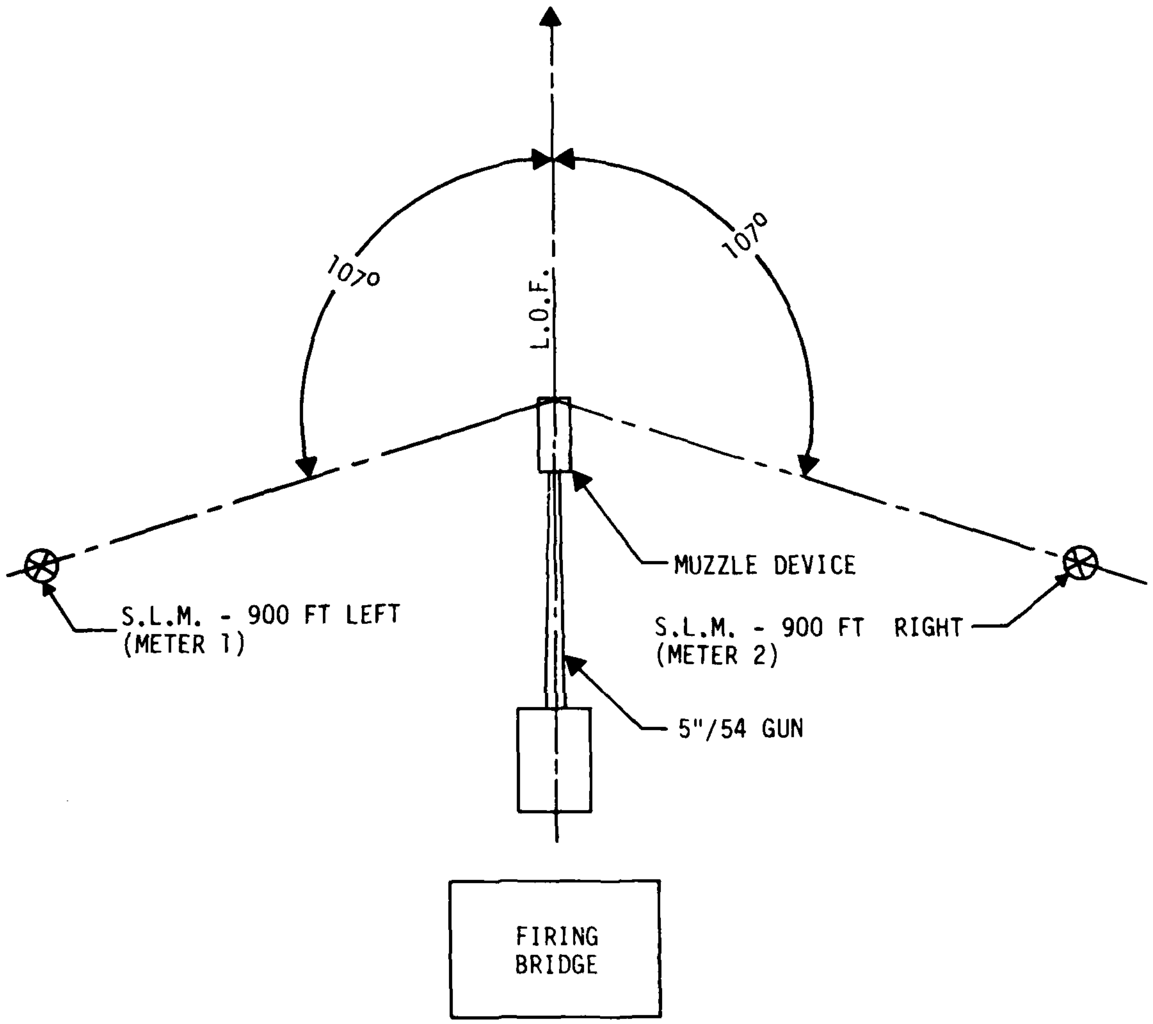

Figure 6. Positions for Sound Level Measurements Relative to the Gun Muzzle Device

identified in Figure 7 according to their angular orientation about the gun barrel. The instrumentation setup is depicted by Figure 8.

MEASUREMENT OF PROJECTILE VELOCITY AT THE MUZZLE

Projectile velocities were recorded at the muzzles of the reference gun and of the gun with the muzzle device attached. Exit velocity of the projectile is information that can be used to provide a preliminary judgment about the influence of the foam-containing device on interior ballistics. The measurement is computed via the Doppler Measurement System. A Doppler technique is used which measures the projectile velocity to within ±0.5 foot/second. The Doppler radar measurement device is shown in Figure 9. The associated data reduction schematic is not shown.

Table 1. Gun Barrel Pressure Gauge Positions

Gauge Station	Distance from Breech Face (in.)	Clock Position
B1	36.25	9:00
H1	96.00	10:00
J2	140.00	12:00
K1	180.00	10:00
K2	180.00	4:00
L1	220.00	8:00
L2	220.00	2:00
M1	258.00	8:00
M2	258.00	2:00

MEASUREMENT OF PRESSURE AND STRAIN IN THE MUZZLE DEVICE

Pressures were recorded to describe the environment within the muzzle device during a gun firing. There were 16 positions considered. Data were taken with foam in the device as well as for the foamless condition. The arrangement of the gauge locations is depicted in Figure 10. The transducers used were Piezotronics, Inc., model 11A23, and the response was recorded on Honeywell, model 101,

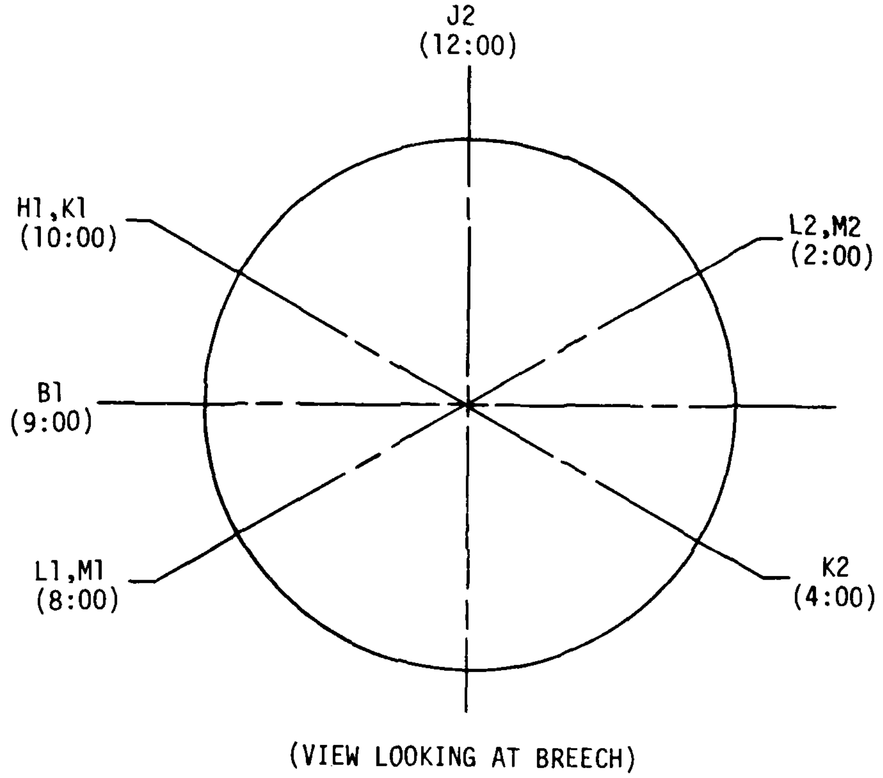

Figure 7. Gun Barrel Pressure Gauge Locations--
View Looking at Breech

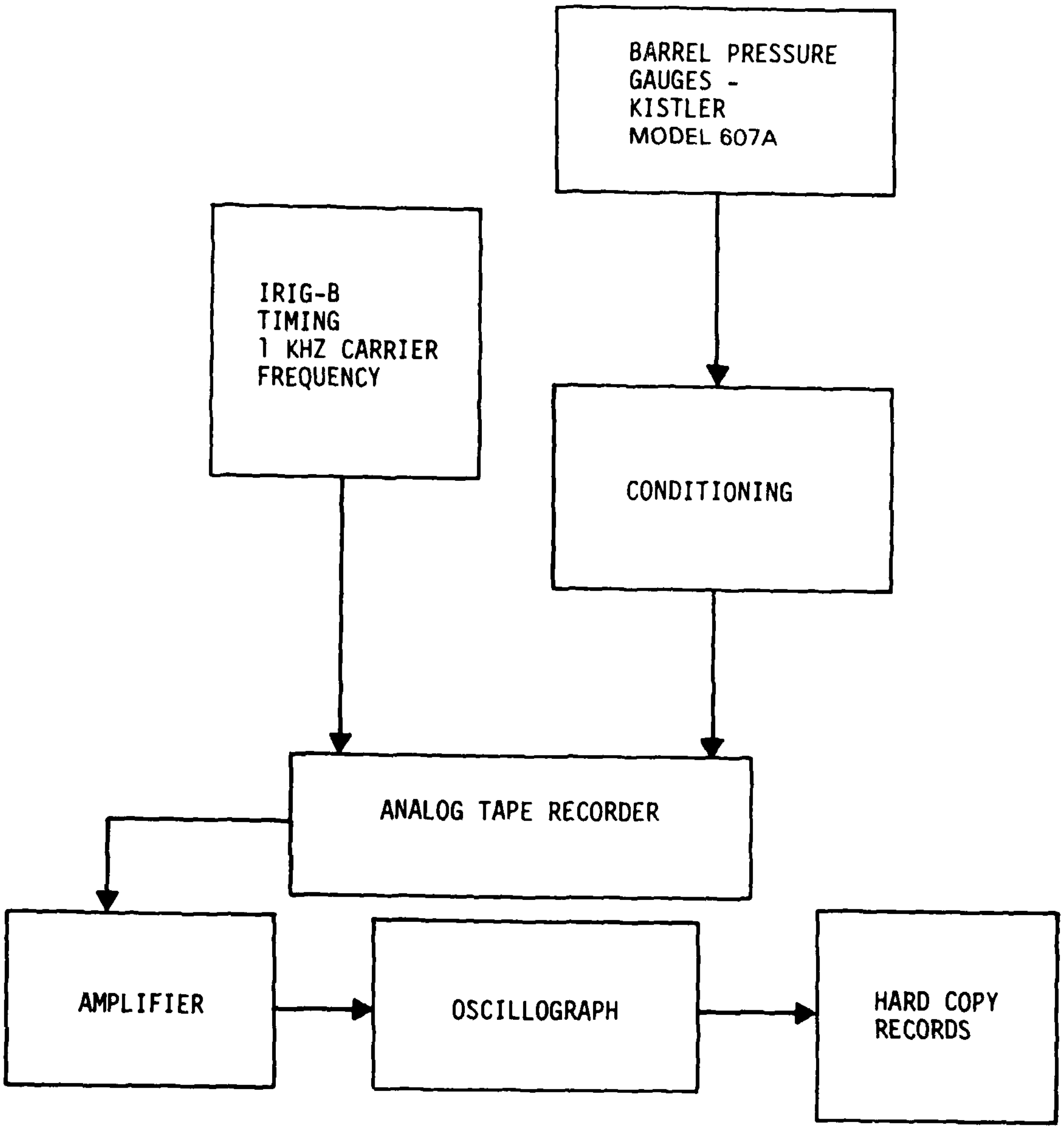

Figure 8. Schematic for Acquisition and Data Reduction of Gun Barrel Pressure

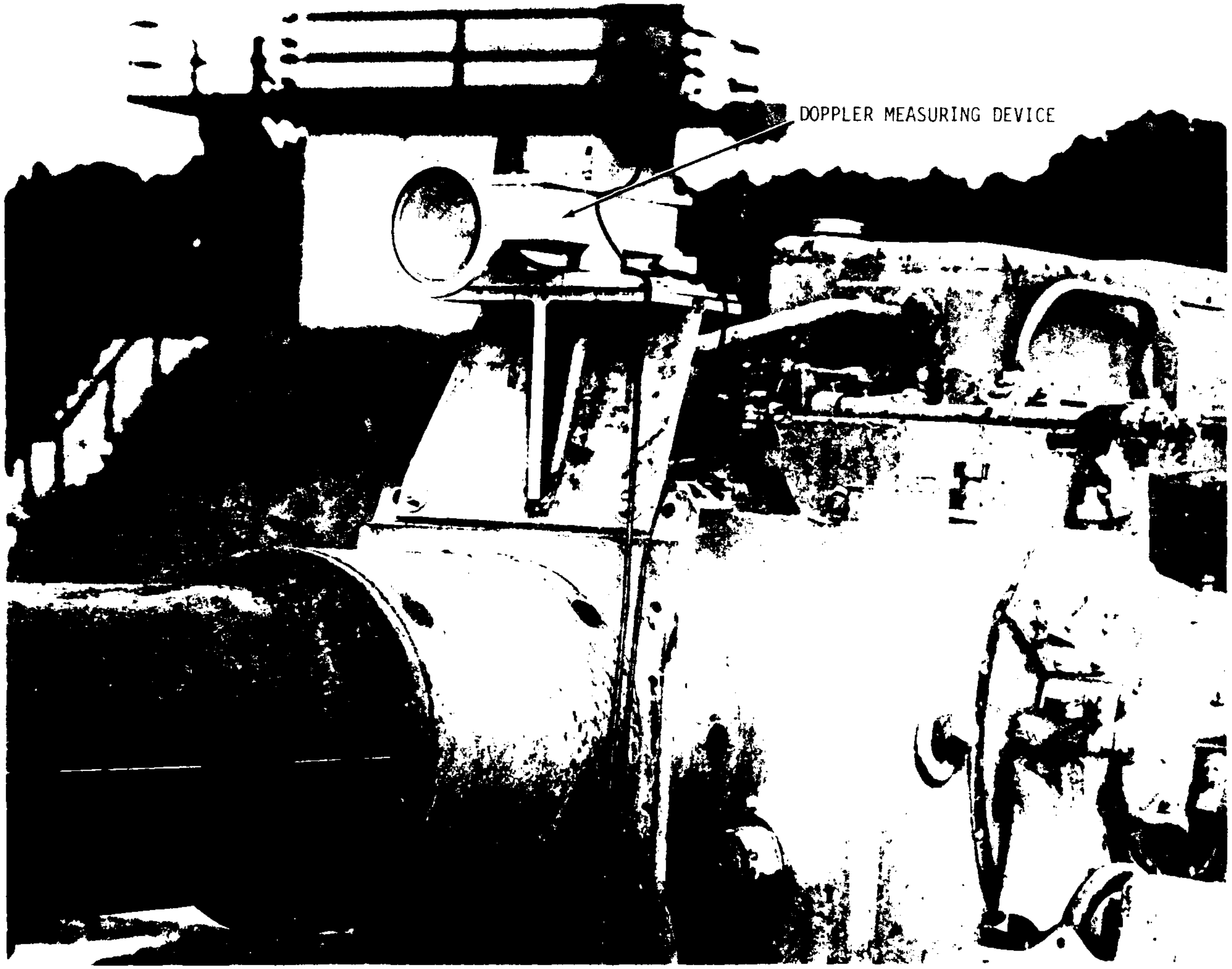

Figure 9. Doppler Radar for Measurement of Projectile Muzzle Velocity

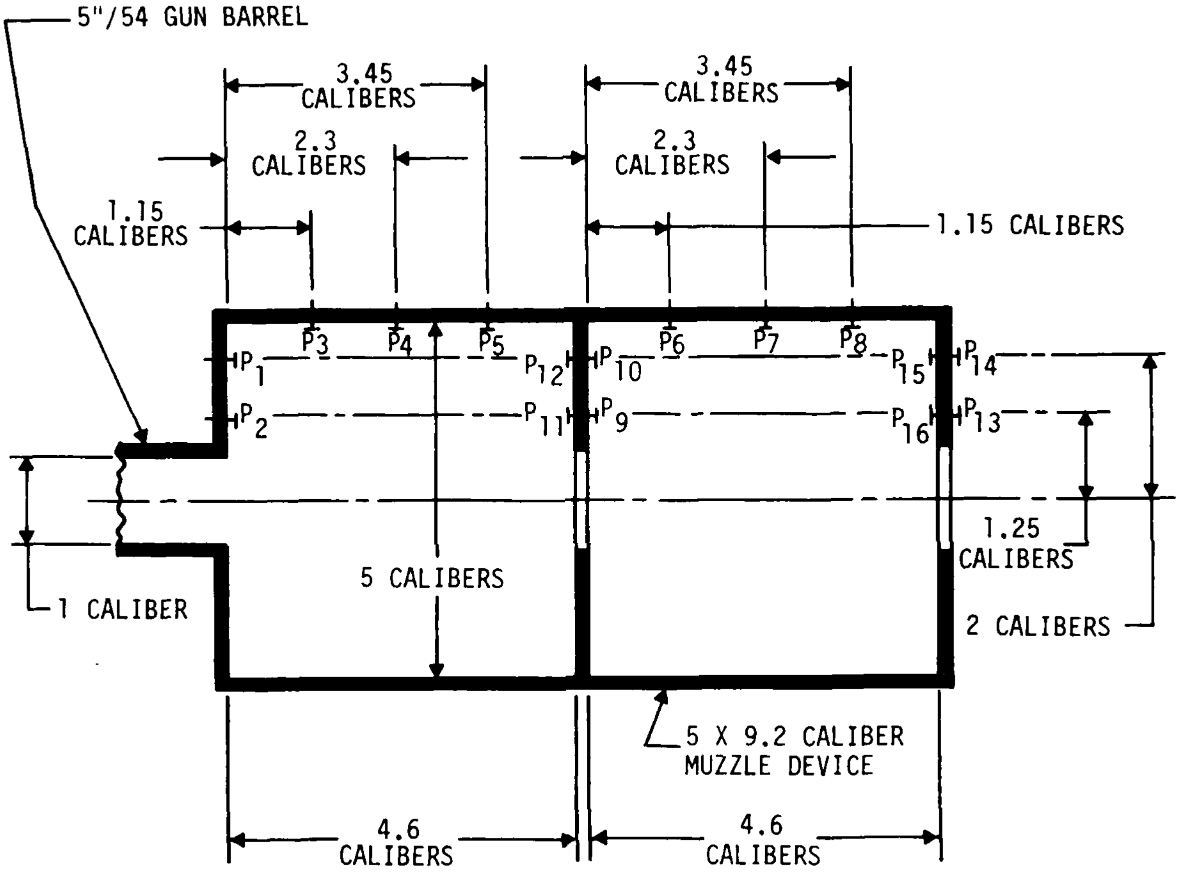

Figure 10. Pressure Gauge Locations of the Muzzle Device

wide-band magnetic tape recorders. Figure 11 is a schematic of the instrumentation setup.

The test schedule did not allow time between the rounds fired for connections to be repaired or for gauges to be replaced. It should be noted that in several cases, gauge replacement would have required a major disassembly of the device and was, therefore, quite impractical. Particularly sensitive were those gauges located within the device (specifically, gauges P16, P15, and P9 through P12). Piping was used to protect the transducer leads coming from these inner gauge locations, but the integrity of these adaptations in the blast environment was questionable.

Strain measurements were taken at 10 locations about the muzzle device. The locations are shown schematically in Figure 12 and the tabulations are shown in Table 2. Three types of gauges were used according to the individual placements. A single-element type gauge was used to measure the axial strain in the attachment bolts for the muzzle device. Along the outer surface of the device where a principal axis of strain was known, a two-element type gauge was employed. A three-element gauge was used on those parts of the device perpendicular to the flow field. With this type of gauge, the principal axis of strain could be determined.

The instrumentation setup for data taking is represented in Figure 11 together with that for the pressure measurements in the muzzle device.

The technique used to retrieve the data and provide hard copies for analysis is represented schematically in Figure 13.

TIME SYNCHRONIZATION OF DATA

Four magnetic tape recorders were used to record transducer output. As a result, it was necessary to have a record common to each tape unit so that all data could be referenced to a specific point in time. A pressure gauge, positioned at gauge location J2, was used for this data correlation. The transducer location is detailed in Table 1 and in Figure 7.

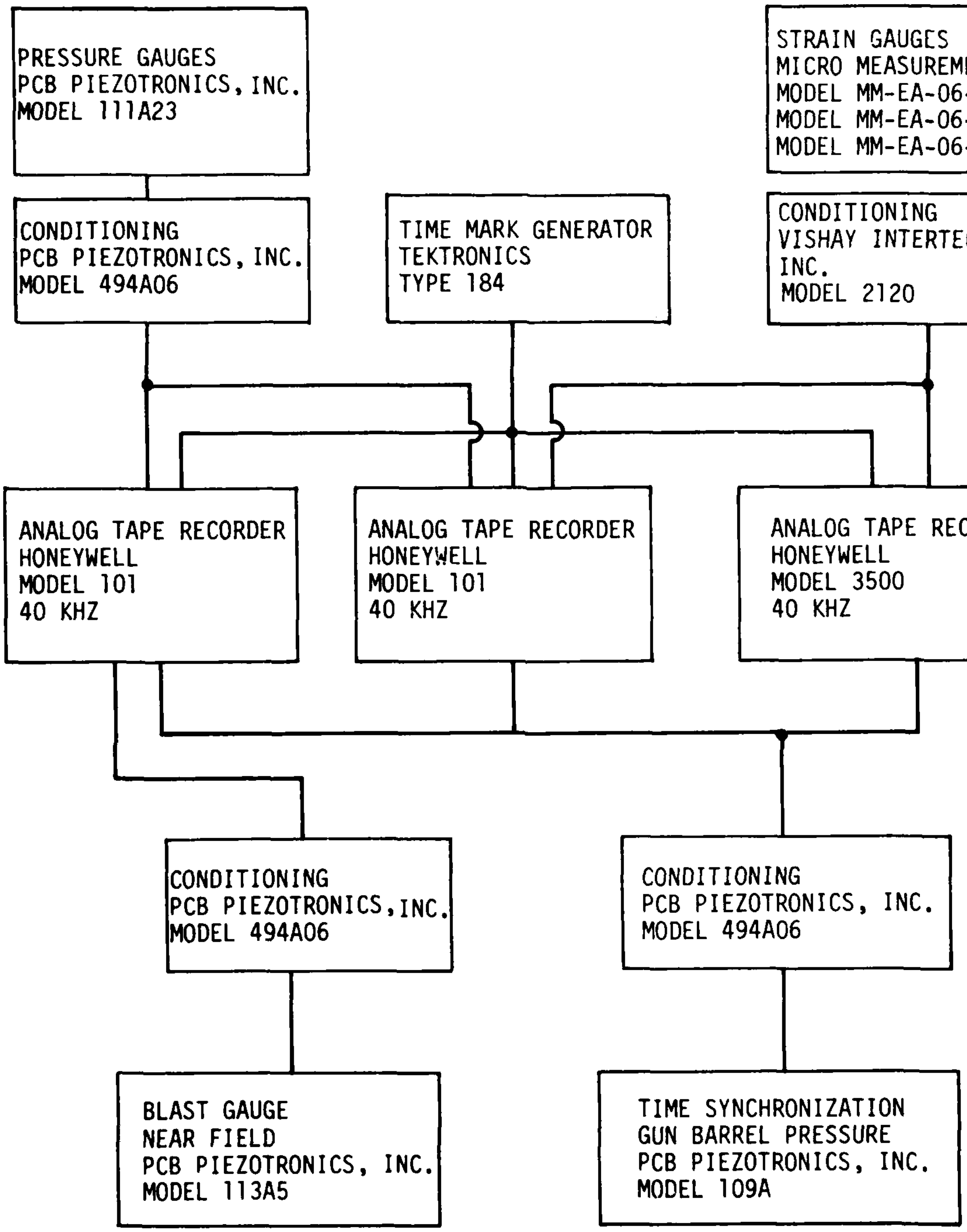

Figure 11. Schematic for Data Acquisition from the Muzzle Device and from the Near-Field Blast

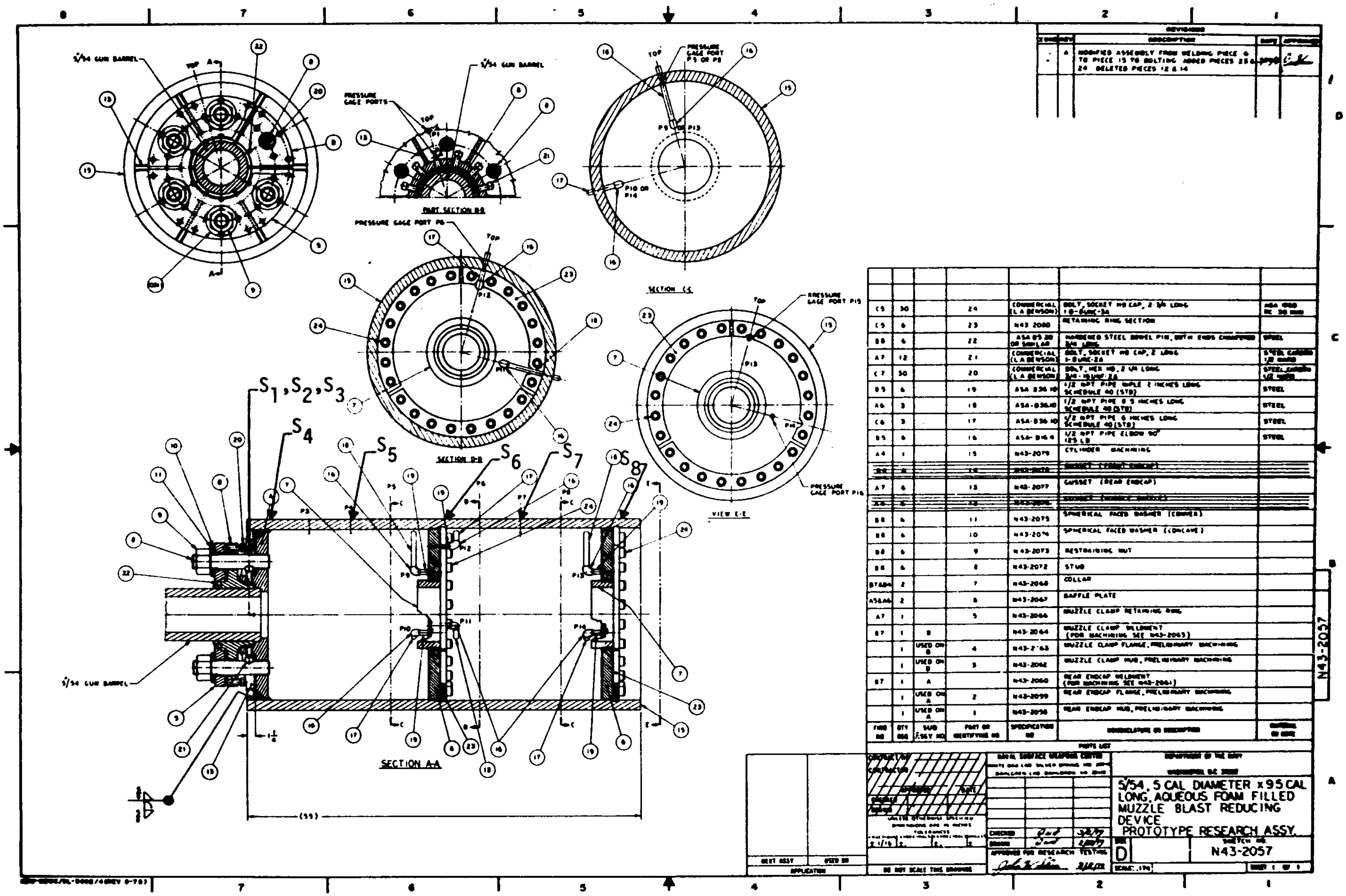

Figure 12. Muzzle Device Strain Gauge Locations Schematic

Table 2. Strain Gauge Type and Location

Strain Gauge Location No.	Type Gauge	Attached to Part No. ( ) of N43-2057	Distance Location	O'clock Position Looking at Muzzle	Measurement Axis With Relation to Gun Bore Axis
S_1, S_2, S_3	Single element	(8) every other one	2" from rear face of Assembly A	S_1 - 11:30 S_2 - 3:30 S_3 - 7:30	Bore
S_4	2 element 90°	Outside surface (15)	3-1/16" from rear end of part 15	1:00	1 element - bore 1 element - hoop
S_5	2 element 90°	Outside surface (15)	14-9/16" from rear face of part 15	1:00	1 element - bore 1 element - hoop
S_6	2 element 90°	Outside surface (15)	28-9/16" from front end of part 15	1:00	1 element - bore 1 element - hoop
S_7	2 element 90°	Outside surface (15)	39" from rear end of part 15	1:00	1 element - bore 1 element - hoop
S_8	2 element 90°	Outside surface (15)	2-3/8" from front end of part 15	1:00	1 element - hoop 1 element - hoop
S_9, S_{10}	3 element (120° between elements)	Front face (6) one on each piece	5" radially from outside diameter of part 6	12:00	1 element - perpendicular to bore on radial of part 6

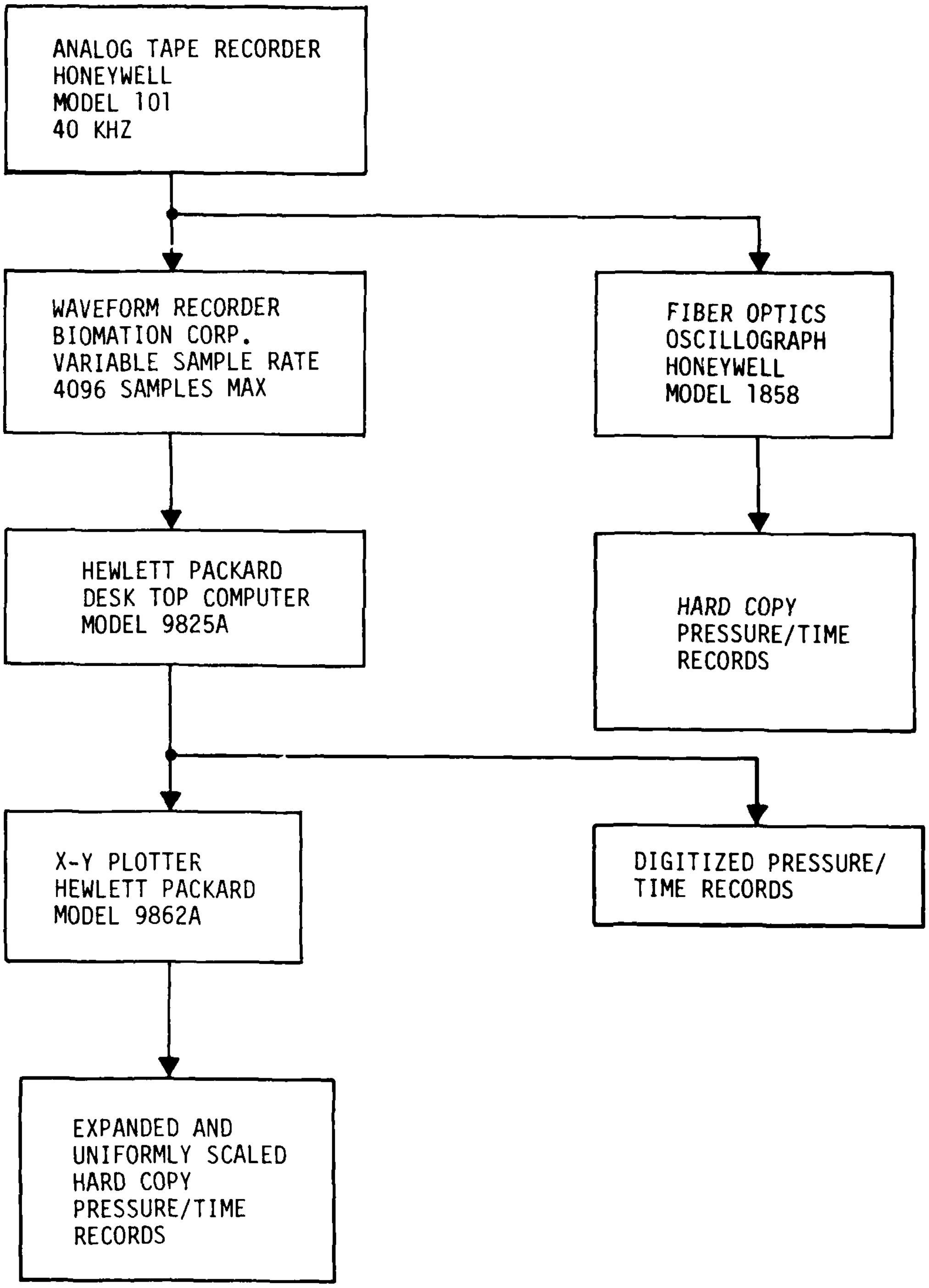

Figure 13. Schematic for Data Reduction of Pressure and Strain Gauge Data for the Muzzle Device

The barrel pressure data are all recorded on a single tape recorder. The interior ballistics of the 5"/54 gun are known, so that each pressure record can be related in time relative to the J2 record. The three other tape units were used to record the internal pressure and strain of the muzzle device. The J2 pressure record was also recorded in each unit. Thus, the pressure and strain of the device can be related in time to the barrel pressure records. Time synchronization was achieved with a resolution of 0.05 ms.

EXPERIMENTAL DATA

SOUND PRESSURE IN THE FAR FIELD

The most important aspect of the testing was to ascertain the effectiveness of a foam-containing device in reducing far-field blast intensity from 5"/54 naval guns. To accomplish this, data were taken by two sound level meters located symmetrically off the gun line of fire (Figure 6). Although more locations would have been desirable from a statistical point of view, the orientation selected is adequate for the assessment. The justification for this lies in the nature of gun blast overpressure far away from its source. Testing has shown that the effect of a muzzle device in reducing noise at a point far away from the gun is not dependent on angular position relative to the line of fire or upon the actual distance from the gun. This result was reported in Reference 2 for the case of a 7.62-mm device. It was then investigated experimentally to see if it applied for larger caliber guns.

Sound pressure data were obtained at the two far-field locations for a total of 18 gun firings. The main parameter under consideration was the foam density used in the device. Expansion ratios from 301:1 to the more dense 20:1 were evaluated. There was also a set of data obtained without any foam in the device. In general, three rounds of data were taken with each particular expansion ratio foam. The peak value readings are displayed in Table 3.

Meter readings were recorded at both locations each time the guns were fired. The data are registered according to the peak sound levels obtained after the bare muzzle gun was fired, together with those obtained after the gun with

Table 3. Sound Pressure Level in the Far Field

Rd. No.	Foam Exp. Ratio	Peak Sound Pressure Level (dB)				Effect of Device (Change of dB)		
		Bare Muzzle		Muzzle Device				
		Meter 1	Meter 2	Meter 1	Meter 2	Meter 1	Meter 2	Avg.*
1	302	145.8	133.5	140.2	128.3	5.6	5.2	5.40
2	305	148.1	132.2	142.1	130.2	6.0	2.0	4.00
3	297	146.1	134.5	139.0	127.7	6.9	6.8	6.85
Mean	301.3					6.17	4.67	5.42
4	143	145.4	132.9	140.3	129.3	5.1	3.6	4.35
5	141	146.1	133.2	138.5	126.1	7.6	7.1	7.35
6	143	146.8	133.6	139.1	130.1	7.7	3.5	5.60
Mean	142.3					6.80	4.73	5.77
7	58	135.9	134.9	122.0	122.2	13.9	12.7	13.30
8	45	138.9	134.4	123.5	123.8	15.4	10.6	13.00
9	60	138.4	134.6	124.5	124.7	13.9	9.9	11.90
Mean	54.3					14.40	11.07	12.74
10	21.0	139.7	137.6	124.9	121.6	14.8	16.0	15.40
11	19.8	138.1	133.9	123.8	118.5	14.3	15.4	14.85
12	20.3	140.5	133.7	123.5	119.3	17.0	14.4	15.70
Mean	20.4					15.37	15.27	15.32
13	No-Foam	140.5	135.1	133.1	130.3	7.4	4.8	6.10
14	No-Foam	141.4	134.8	137.7	131.1	3.7	3.7	3.70
15	No-Foam	141.2	135.0	137.5	132.2	3.7	2.8	3.25
Mean						4.93	3.77	4.35
16	123	139.1	134.0	134.4	126.1	4.7	7.9	6.30
17	133	140.2	133.7	131.5	127.1	8.7	6.6	7.65
Mean	128					6.70	7.25	6.98
18	288	139.5	134.0	135.7	126.9	3.8	7.1	5.45

* Atmospheric conditions may vary so that some difference in effect between the two meters should be expected.

the foam-containing device was fired. Sound levels are expressed in decibels. The effect of the foam-containing device is found by taking the difference between the readings of the reference gun and those obtained when the muzzle device is used. This difference is tabulated in Table 3 and the results are presented graphically in Figure 14. It should be noted that even when no foam was used in the device, some pressure reduction was obtained in the far field because of the muzzle device itself. For the prototype design, the average effect of the device alone was 4.35 dB.

In most instances, there is a disparity between the sound level reading of the two meters. A large fault in these cases is that atmospheric conditions are not the same over the entire far field. The propagation of sound intensity is affected by wind shifts and temperature gradients between the gun muzzle (where the sound is produced) and the meter that records the level. For this test and the associated short separation distance between the gun muzzle and the sound level meters, wind shifts are the major cause of the disparity observed.

Absolute values of sound level reduction should not be emphasized because of the scatter present in the data. A general trend can be established by averaging the readings of both meters and all the rounds of a given data set. Over the range of foam expansion ratios from the most dense ratio of 20:1 to about 140:1, the muzzle device achieved a sound reduction effect that was very nearly linear. The highest density foam tested effected a reduction in the far field of 15.4 dB. The sound reduction observed by the device when it contained 140:1 foam was much less, only about 5.8 dB. For greater expansion ratios, the effect approaches that of the muzzle device without any foam; the rate at which the reduction declines is much slower, however. Figure 14 illustrates this effect.

PRESSURE IN THE GUN BARREL

The peak pressure responses for the eight barrel gauge locations are presented as part of Table 4. Data are given for cases where the muzzle device was filled with foam as well as for the case of an empty device. Foam expansion ratios of 300:1, 140:1, 55:1, and 20:1 are represented. It should be emphasized that in all of these cases, the foam was restricted to the muzzle device and

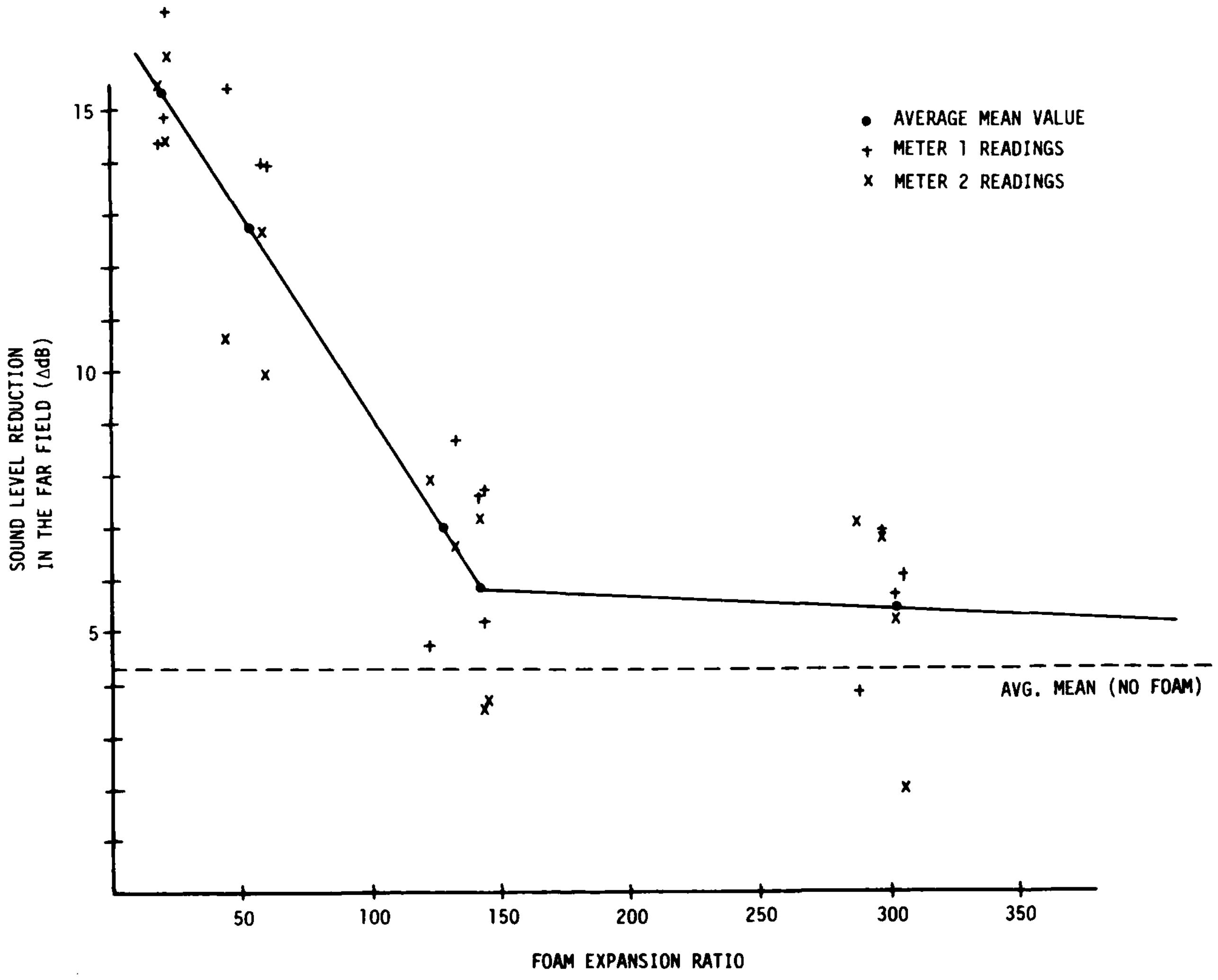

Figure 14. Sound Level Reductions vs. Foam Expansion Ratio

Table 4. Peak Pressure in the Barrel ksig (Muzzle Device Attached)

Rd. No.	Date Fired	Nominal Foam Expansion	B1	H1	Barrel Gauge Location* K1	K2	L1	L2	M1	M2
1	8-15-79	300:1	45.226	34.351	11.786	11.658	9.698	10.106	7.661	7.840
2			48.763	32.791	12.063	12.474	9.552	9.674	8.441	7.887
3			48.167	32.954	11.978	12.175	9.777	9.651	8.800	8.047
4		140:1	49.135	32.817	11.959	12.144	11.149	9.838	9.850	8.278
5			48.950	33.078	11.662	11.968	9.371	9.814	8.678	7.803
6	8-15-79		47.716	33.207	11.863	12.061	9.177	9.330	8.400	7.795
7	8-31-79	55:1	46.802	35.562	12.101	12.151	10.740	9.970	8.126	7.478
8			46.511	34.194	12.000	12.063	9.107	9.854	7.528	7.252
9			48.110	35.151	11.963	12.190	9.169	10.233	7.529	7.415
10		20:1	47.965	35.369	11.962	12.280	9.104	10.022	7.578	7.267
11			47.521	35.256	11.963	12.215	9.141	10.056	7.457	7.191
12			44.281	33.601	12.012	12.151	9.079	9.859	7.329	7.098
13		No Foam	49.854	34.230	11.975	12.302	9.113	9.775	7.570	7.415
14			47.383	33.439	11.840	12.151	9.174	9.771	7.584	6.983
15			49.125	33.653	11.938	12.151	9.107	9.828	7.175	7.114
16		125:1	49.271	34.304	11.888	11.835	8.929	9.542	7.098	7.002
17		''	45.494	33.895	11.953	12.121	8.963	10.085	7.640	7.170
18	8-31-79	288:1	48.688	34.250	11.754	12.278	8.929	9.657	7.323	7.002

* Notation for the gauge locations is defined in Table 1.

there was no problem with foam entering the gun barrel. The latter possibility was investigated separately, as reported in Appendix B.

For each set of data, the pressures were evaluated according to the mean value and the standard deviation (σ) attained. These results are tabulated in Table 5. The gauge locations designated by the letter "M" are of the greatest interest because these transducers are nearest the muzzle. Even at these locations, there is nothing to distinguish the pressure levels from those that may occur in a gun with a bare muzzle. This point is illustrated in Table 6. Data for several rounds (taken from Appendix B) are presented for the bare muzzle gun as a comparison with those records where the muzzle device was attached (Tables 4 and 5). It is apparent that the internal barrel pressure is unaffected by the presence of the device attached to the muzzle, with or without foam.

One should not conclude from this that the barrel pressures cannot be affected by foam. The experiment reported in Appendix B studied the effect of actually injecting foam into the muzzle end of a 5"/54 gun barrel. It is clear from these tests that there is a limit to the depth that the foam should be permitted to penetrate the gun barrel. Beyond this point, the internal barrel pressures are affected. For a 35:1 foam, this distance is about 30 inches.

PROJECTILE VELOCITY AT THE MUZZLE

Velocity measurements were taken on both guns to determine how fast the projectile was moving as it left the muzzle. Data were collected for each round fired in the gun containing a muzzle device, and in the bare muzzle reference gun. The measurements taken during this test series are tabulated in Table 7. The results are listed according to firing order, and an overall average value is provided. Also provided is the standard deviation of the velocity measurements for each gun. It is clear from this limited statistical information that the two guns launched projectiles at velocities of the same magnitude. The difference in average velocity between the gun with the foam-containing device and the reference bare muzzle gun was only 4.4 feet/second, while in both cases, the standard deviation was in excess of 13 feet/second.

Table 5. Mean Pressure and Standard Deviation for Barrel Pressures (Muzzle Device Attached)

Rd. No.	B1	H1	Barrel Gauge Location*			L2	M1	M2
			K1	K2	L1			
1 2 3	$\bar{P}$ = 47.385 σ = 1.893	33.365 0.857	11.942 0.142	12.102 0.412	9.675 0.114	9.810 0.256	8.300 0.582	7.924 0.108
4 5 6	$\bar{P}$ = 48.600 σ = 0.771	33.034 0.198	11.828 0.151	12.057 0.088	9.899 1.086	9.660 0.286	8.976 0.769	7.958 0.276
7 8 9	$\bar{P}$ = 47.141 σ = 0.851	34.969 0.702	12.021 0.071	12.134 0.065	9.672 0.925	10.019 0.194	7.727 0.344	7.380 0.115
10 11 12	$\bar{P}$ = 46.589 σ = 2.011	34.742 0.989	11.979 0.028	12.215 0.064	9.108 0.031	9.976 0.105	7.454 0.124	7.185 0.084
13 14 15	$\bar{P}$ = 48.787 σ = 1.269	33.774 0.409	11.917 0.069	12.201 0.087	9.131 0.037	9.791 0.031	7.443 0.232	7.170 0.221
16 17	$\bar{P}$ = 47.382 σ = 2.670	34.099 0.289	11.920 0.045	11.978 0.202	8.946 0.024	9.813 0.383	7.369 0.383	7.086 0.118
18	$\bar{P}$ = 48.688	34.250	11.754	12.278	8.929	9.657	7.323	7.002

* Refers to Table 1.
$\bar{P}$ = Mean pressure
σ = Standard deviation

Table 6. Peak Pressure in the Barrel ksig (Bare Muzzle Gun)

Rd. No.	Date Fired	B1	H1	Barrel Gauge Location*				M1	M2
				K1	K2	L1	L2		
2	3-14-79	--	--	--	12.9	9.6	10.1	10.4	7.8
3	3-14-79	--	--	--	14.4	10.2	10.2	9.9	7.8
13	3-15-79	--	--	--	13.4	10.2	10.6	11.1	8.7
15	3-16-79	--	--	--	13.9	9.7	9.4	11.1	9.2
20	3-16-79	--	--	--	13.1	9.9	9.8	9.5	7.9
Mean Pressure $\overline{P}$					13.54	9.92	10.02	10.40	8.28
Standard Deviation σ					.61	.28	.45	.71	.64

* Refers to Table 1.

NOTE: All of the above data are for warming rounds and, thus, the values are slightly higher than would be observed in a warm gun.

Table 7. Projectile Exit Velocity Measurements

Rd. No.	Bare Muzzle Gun		Foam Expansion Ratio	Muzzle Device Gun		Date Fired
	Muzzle Velocity (ft/sec)	Data Set Mean Velocity (ft/sec)		Muzzle Velocity (ft/sec)	Data Set Mean Velocity (ft/sec)	
1	2630	2639.6	300:1	2659	2666.3	8/15/79
2	2639			2674		
3	2650			2666		
4	2673	2665.0	140:1	2667	2663.6	8/15/79
5	2656			2658		
6	2666			2666		
7	2636	2651.0	55:1	2652	2653.3	8/31/79
8	2651			2630		
9	2666			2678		
10	2671	2663.3	20:1	2673	2657.0	8/31/79
11	2655			2662		
12	2664			2636		
13	2665	2666.0	No-Foam	2683	2676.7	8/31/79
14	2671			2677		
15	2662			2670		
16	2674	2672.5	125:1	2660	2661.0	8/31/79
17	2671			2662		
18	2670		188:1	2676		8/31/79
Overall Mean Velocity =	2659.4			2663.8		
Overall Standard Deviation =	±13.5			±13.9		

It is reasonable to conclude from the results obtained from the muzzle device gun that the foam had no apparent effect on projectile velocity. Statistically speaking, however, a much larger sample of test data would be required to achieve a degree of confidence for this observation. In general, no appreciable influence from the use of the muzzle device was observed through the projectile velocities.

PRESSURE AND STRAIN IN THE MUZZLE DEVICE

The muzzle device was instrumented to measure the pressure distribution on its interior and the strain in its components. These data are most useful for design development toward an optimum weight muzzle device. Although an important consideration, funding constraints made it impossible to complete this aspect of the muzzle device feasibility question. The transducer records are available for those with an interest in pursuing an answer to this problem. The retention period of the data will be at least a year from the date of release for this report.

These data have not been reduced completely, but the pressure records from the gun firings were inspected qualitatively. A preliminary analysis revealed two problems. First is the problem of data loss due to instrument failure. These occurrences are hardly surprising considering the harsh environment created at the muzzle when the gun is fired. Time limitations of the test program made it impossible to replace gauges that malfunctioned; consequently, information at several locations was lost and usually for a significant number of the gun firings. A second problem in evidence on most of the pressure records was biasing of the gauge response caused by thermal induced stress.

A record of the pressure data obtained is charted in Table 8. An investigation of the effects of thermal stress is needed before a degree of confidence can be placed in these data. It is known, for example, that muzzle blast temperatures can generate thermal stress and that such stress induces a negative component in the output of a pressure gauge. The difficulty is that the amount of bias induced is dependent upon the degree of induced stress for each gauge; the bias is not linear. Also, thermal stress influences gauge output to a larger

Table 8. Pressure Data in the Muzzle Device--A Qualitative View

Rd. No.	Foam Expansion	Pressure Gauge Identification																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	302:1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	Q		
2	305	+	+	+	+	+	+	+	+	+	+	0	+	+	+	+	Q		
3	297	+	+	+	+	+	+	+	+	+	+	0	+	+	0	+	Q		
4	143:1	+	+	+	+	+	+	+	+	+	+	0	+	+	0	+	Q		
5	141	+	+	+	+	+	+	+	+	+	+	0	+	+	0	+	I		
6	143	+	+	+	+	+	+	+	+	+	+	0	+	+	0	+	I		
7	58:1	+	I	+	I	+	+	+	Q	Q	+	Q	+	+	+	I	I		
8	45	+	I	+	I	+	0	0	0	0	0	0	0	0	0	0	0		
9	60	+	I	+	I	+	+	+	Q	Q	+	0	+	+	+	Q	I		
10	21:1		I		I				0	Q		0			+	Q	I		
11	20		I		I				0	0		0			0	Q	I		
12	20		I		I				0	0		0			0	Q	I		
13	None	+	I	+	I	+	+	+	0	0	+	0	+	+	0	Q	I		
14	None	+	I	+	I	+	+	+	0	0	+	0	+	+	0		I		
15	None	+	I	+	I	+	+	+	0	0	+	0	+	+	0		I		
16	123:1	+	I	+	I	+	+	+	0	0	+	0	Q	+	0	+	I		
17	133:1	+	I	+	I	+	+	+	0	0	+	0	0	+	0	+	I		
18	288:1	+	I	+	I	+	+	+	0	0	+	0	0	+	0	+	I		

NOTES:

1. P17 is located in the gun barrel and is used for synchronization in time.
2. P18 is near-field blast gauge.

Legend For Gauge Failures

0 - data lost altogether
I - gauge response is intermittent
Q - data are questionable
+ - record is influenced with thermal stress

extent over the pressure decay period than it does during the rapid rise to peak pressure.

The effect of thermal stress is illustrated in Figure 15. The transducer responses of two gauges and two successive firings are displayed. Gauge locations P5 and P12 were chosen because they are representative of the effect observed when the muzzle device contained no foam. The data uncertainty is associated primarily with the positive phase duration and the rate of pressure decay. An analytical prediction model has indicated agreement with the transducer records for the duration of the pressure rise (approximately the first 10 milliseconds).

The data obtained when the muzzle device was filled with 20:1 expansion ratio foam do not exhibit the effect of thermal stress. (This can be seen in Figure 16.) The gauges at locations P5 and P7 are representative, and it is evident that the negative component observed previously is not present in these records. The 20:1 ratio foam provided enough thermal protection for the gauges to perform accurately.

An interesting attribute for the use of 20:1 expansion foam is that it suppresses visible muzzle flash. This suppressed muzzle flash was first observed in the scale model tests of Reference 3. Also the internal peak wall pressures within the muzzle device are substantially reduced (~½) when using 20:1 foam versus an empty device.

CONCLUSIONS AND RECOMMENDATIONS

The results of this test show that use of a muzzle device filled with aqueous foam significantly reduces the far-field SPL produced from a full-scale naval gun. For the 5"/54 gun, the reduction was in excess of 15 dB. The principle behind the sound reduction has been validated, but work remains to fully assess the feasibility of applying the technique.

Additional work in the design of the device is necessary. The primary aim must be to establish a thoroughly weight-optimized device. At this time, the

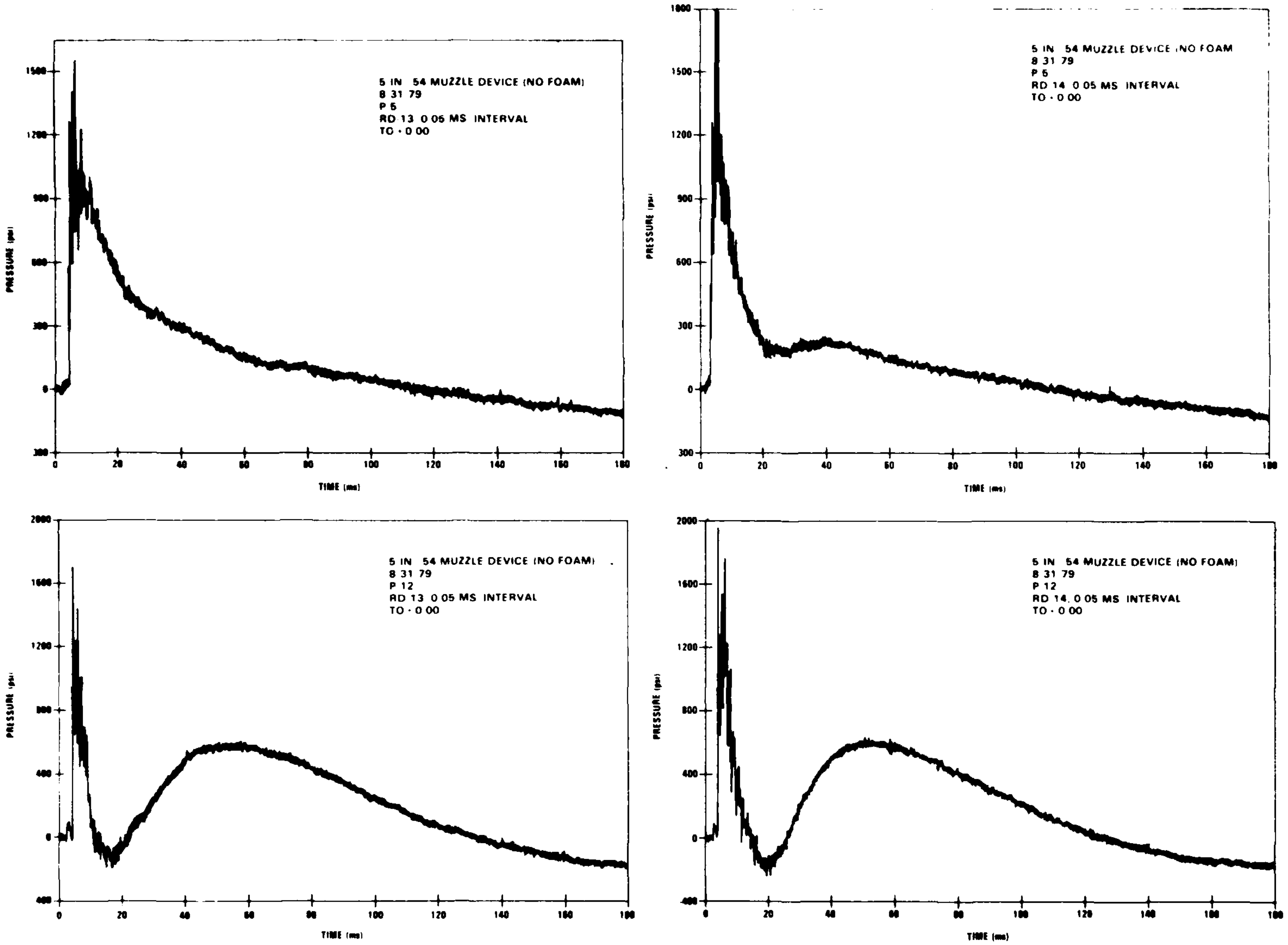

Figure 15. Muzzle Device Pressure Records Showing Effect of Thermal Stress on Pressure Gauges

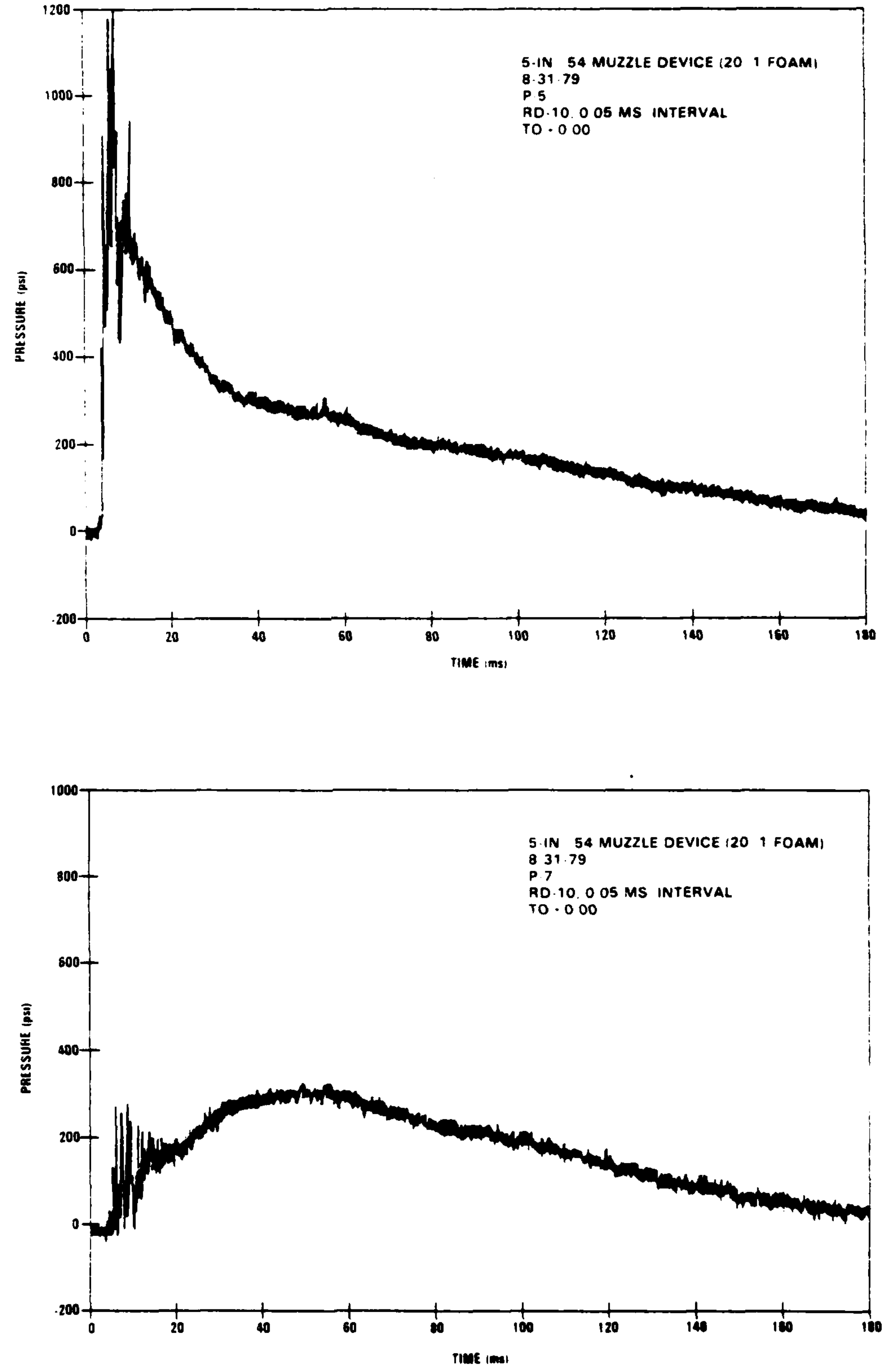

Figure 16. Muzzle Device Pressure Records Showing No Sign of Thermal Induced Stress on Pressure Gauges

total weight of a production device has not been established. The pressure loadings realized inside the device were less than half that of the design loadings. From this standpoint alone, the thicknesses of the device components can be adjusted to substantially reduce the weight. Substantial savings in weight can also be achieved with the use of exotic materials. Although expensive in prototype development usage, such materials combine strength with unusually light weight.

Work has been done to modify the clamping technique used to fasten the device to the gun muzzle. It has been concluded that a secure attachment requires modification of the barrel.

For a complete assessment of the muzzle device concept, additional considerations must be resolved. One such consideration is how the gun will react with an unsupported weight at its muzzle. It is essential that the performance of the gun not be adversely affected. Similarly, it is known that the presence of too much foam inside the gun tube is detrimental to performance. A method to prevent this occurrence is in the conceptual stage. A major question concerning the effect of the foam on the projectile and its fuse must be answered. In addition, specialized foam production techniques would have to be developed to meet the requirement of rapid fire. For the study of these questions, an experimental approach, coupled with an analytical method, is recommended.

More experimental data are also needed to determine if the muzzle device has an adverse effect upon projectile trajectory. However, there is no evidence from the work done with the prototype model to suggest that this is the case.

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3. L. L. Pater and J. W. Shea, *Use of Foam to Reduce Gun Blast Noise Levels*, NSWC TR 81-94, Naval Surface Weapons Center, Dahlgren, VA, March 1981.

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APPENDIX A

AQUEOUS FOAM GENERATION

OBJECTIVE

The objective of the work reported in this appendix was to develop a means of producing aqueous foam for filling the full-scale prototype 5"/54 muzzle device for full-scale firing experiments.

FOAM AND FOAM PRODUCTION EQUIPMENT REQUIREMENTS

The 7.62-mm scale model experiments[3] utilized foams with expansion ratios* between 10:1 and 20:1. For the full-scale 5"/54 experiments, it was required that foams of various expansion ratios be tested to determine if expansion ratio is a critical parameter regulating the degree of noise reduction obtainable. Expansion ratios in the range from 20:1 to 400:1 were of interest. It was further desired that the foam produced for the 5"/54 muzzle device tests have a uniform bubble size and structure and maintain them as long as possible, since several minute delays would be encountered from the time of the foam filling to gun firing. These delays would relate to the time required after filling to remove the foam-making equipment from the muzzle area, to load the round, and to clear personnel to shelter. Bubble size was not a specified requirement except how it might relate to foam stability.

All aqueous foams exhibit what is generally referred to as a natural quarter life. Most foams return to a liquid state in some period of time. The time it takes for 25 percent of the liquid solution to drain from the foam is known as the natural quarter life. The greater this time factor, the greater the stability of the foam. Well proportioned and generated foams have a quarter life of several minutes, i.e., an estimated 2 to 5 minutes. Thus, the foam generator must be capable of producing foam at a rate that can fill the 5"/54 muzzle device in a few minutes. The muzzle device would contain 12 feet^3 of foam; therefore, the generator(s) must produce from ~4.0 to 6.0 feet^3 of foam/minute (minimum) at the desired densities. The muzzle device must be filled through the muzzle opening in a manner that ensures that the device be at least 90 percent full.

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* Expansion ratio = Volume of produced foam/volume of liquid constituents.

The 7.62-mm tests were first conducted with commercial shaving cream and later an aqueous protein-based fire fighting foam. The resulting sound level reductions were unchanged by the use of substantially different foam compositions. Therefore, the composition of the foam produced for the 5"/54 muzzle device test was unspecified; however, an aqueous* foam, rather than a chemical one,** was desired. Of course the composition was required to be nonflammable.

EVALUATION OF COMMERCIAL AQUEOUS FOAM GENERATING EQUIPMENT

In surveying the commercial means of foam generation available and their potential for use in the full-scale tests, it was determined that two classes of foam generation equipment existed. One class can be said to encompass firefighting aqueous foam generation and the other to encompass dust suppression aqueous foam generation. The latter consists basically of denser type foams in the order of 50:1 maximum expansion ratio, for use in such areas as rock drilling or subsurface injection. The firefighting foam generation equipment, on the other hand, can range from the production of 5:1 expansion ("wet water") up to 1000:1 expansion foams. In all cases, the production of aqueous foam requires three prime ingredients: water, foam liquid, and air.

The expansion ratio of the foam produced by a particular piece of commercial equipment is generally limited to a set value or a very narrow range expansion ratio (100:1 to 300:1 as an example). Also the firefighting foam generators are generally designed for the production of very large volumes of foam per minute. The volumes can range from ≈50 feet^3/minute to as great as ≈22,000 feet^3/minute. The dust or friction suppression foam generation equipment is generally designed for the production of small volumes of 2 to 10 feet^3/minute.

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* The liquid constituents of the foam are mostly water.

** Foam bubbles result from chemical reaction, rather than mechanical agitation.

The aqueous liquid foaming agents[*] used with both classes of foam generators have a wide range of chemical compositions related to their particular designed usage. Perhaps the most common is the conventional protein-based foaming agents. The foaming agent to water mixture ratio ranges from 1:100 to 6:100 parts depending on the foam characteristics desired. These liquid foaming agents can be divided into two basic classes of foam production according to expansion ratio; i.e., one for low expansion (<100:1) and the other for high expansion (100:1 to 1000:1) foam generation.

Firefighting foams, first introduced in the latter part of the nineteenth century, were originally known as chemical foams because the foam bubble was produced by a chemical reaction. Chemical foams are now obsolete in firefighting, having been replaced by mechanical or air foams.[**] It is important to note that the chemical foams may have utility as related to potential use in a gun blast reduction device.

Several types of liquid foaming agents and commercially available foam generators were purchased for evaluation of operating principles and foam quality. It was intended to utilize one of these for the production of foam for the full-scale 5"/54 muzzle device tests. These items were purchased after a limited investigation of the available aqueous foam-making apparatus. Therefore, they do not necessarily constitute the limit of available commercial equipment that might be adaptable to an automated foam-filling system for an advanced muzzle device design.

Because smaller (hopefully negligible) effects on the gun and projectile ballistics could be expected as the foam expansion ratio increased and density decreased, equipment capable of producing high expansion foams was of major

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[*] A composition of protein, synthetic with protein additives, or pure synthetic based solutions, that when mixed with water and air will produce expanded foam when agitated.

[**] Foam produced by a physical agitation of a mixture of water, air, and foaming agent (also called airfoam).

interest. To produce moderately high expansion foam (from 100:1 to 250:1), a Rockwood "Super JET-X" foam generator and "JET-X" foaming agents were procured.* Since it was not known how high the expansion ratio of the aqueous foam could be before the sound reduction effect was diminished, the equipment had to be capable of producing a foam with expansion ratios up to 500:1. For this purpose, a Rockwood JET-X-2 foam generator was procured. Both Rockwood generators utilize an in-line solution proportioning eductor to provide the proper mixture of liquid foaming agent and water. In addition to the JET-X foaming agent, Rockwood "Aquafoam AFFF" liquid foaming agent and Rockwood "Double Strength 3 percent liquid foaming agent" were procured for experimental evaluation.

Because of the large volume of foam produced per minute, neither one of the Rockwood foam generators could be utilized in filling the muzzle device. Accurate control over filling could not be obtained to ensure that the device was at least 90 percent full. However, certain principles of operation were invaluable in developing the foam generator used in the tests. The generator is described in a later section.

Since the 7.62-mm tests were principally carried out using a 20:1 expansion ratio foam, it was necessary to produce or know how to produce a low expansion (50:1 or less) foam in sufficient quantity to fill the fullscale muzzle device in less than 3 minutes. For this purpose, a batch type foam generator system, manufactured by the Mearl Corporation, Roselle Park, New Jersey, was procured. The system is primarily designed for the production of foam for subsurface injection such as producing porous concrete. It is used for producing foams from a 10:1 to $\approx$50:1 expansion ratio. The unit is described as a model OT-10 and is capable of producing 7 to 8 feet^3 of foam per minute at a 20:1 expansion ratio. This unit operates on the principle of a premixed solution tank under pressure. The liquid foaming solution and a separate compressed air feed are metered through manually set proportioning orifice valves into a nozzle filled with an aggregate to mechanically agitate the solution. In addition to a Mearlcrete foaming agent, the Fluoro-Protein 3 percent, Ultra X-SD, and the Artic LT6(6

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* Rockwood System Corporation, 82nd Street, South Portland, Maine 04106

percent) Mearl foams were procured for evaluation. Expansion of over 30:1 could not be obtained with any of the Mearl liquid foaming agents procured when used in the OT-10 system. In attempts to use the Mearl liquid foaming agents (at various solution ratios from 1 to 6 percent) to produce higher expansion foams, the drainage rate* was very rapid. However, the low-expansion foams produced were very stable. Results using the Rockwood, double strength 3 percent and JET-X liquid foaming agents in various solution ratios from 2 to 6 percent in the Mearl OT-10 produced excessively wet foam with very poor stability. The Rockwood AFFF produced a highly stable 20 to 30:1 foam.

In summary, the Mearl OT-10 system could not be utilized effectively with existing Mearl nozzles to produce satisfactory foam with an expansion ratio greater than 30:1.

During preliminary experiments conducted to determine the effect foam in the gun barrel would have on barrel interior pressure, it was discovered that the Rockwood JET-X foam underwent a rapid physical breakdown due to an unknown reaction. The reaction was established when the foam came in contact with the powder residue (Naco) on the gun barrel walls. Oil contact was also determined to cause a rapid physical breakdown of the foam to a liquid state. For the foam-in-barrel tests, a small generator was fabricated to produce high expansion Rockwood JET-X foam in expansion ratios from ~200:1 to ~500:1. During the same tests, the Mearl OT-10 system was used to produce a ≈30:1 expansion foam with the Mearlcrete foaming agent. The decay rate was observed to be substantially reduced with the denser Mearl foam; however, a reaction was still present. Since this reaction would seriously hamper maintaining a full muzzle device, it became imperative that a foam be produced that would be stable under these conditions. The foam would have to exhibit the ability to retain structure and water content in the gun/muzzle device environment.

To study the decay of foam at different expansions, several fired Naco powder cases (5"/54) were obtained to facilitate observations of foam stability. The general results are tabulated in Table A-1.

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* The rate at which liquid drains from the foam.

Table A-1. Decay of Foam at Different Expansions

Liquid Foam Concentrate	Base	Stability with Powder (Naco) Residue		Stability on Clean Steel
		Low Expansion* (≦30:1)	High Expansion** (>100:1)†	
Mearlcrete	Protein	Slow breakdown	Could not obtain high expansion foam	Stable
Arctic Mearlfoam	Protein	Breaks down rapidly	Could not obtain high expansion foam	Stable
Ultra X-SD	Believed to be synthetic with protein additives	Did not try	Breaks down	Stable
Fluoro-Protein	Protein with flurochemical surfactants	Did not try	Breaks down	Stable
JET-X	Synthetic with protein additives	Slow breakdown	Breaks down	Stable
Double strength	Hydrolized Protein	Did not try	Breaks down	Stable
Aquafoam AFFF	Synthetic	Stable	Stable	Stable
Besco No. 98	Synthetic detergent	Stable	Unknown	Stable

* The Mearl OT-10 system was used to produce the foam.

** The foam generator developed for use in filling the 5"/54 full-scale muzzle device was used to produce the foam.

† Could not produce foam in excess of 106:1 expansion ratio. At ~100:1 the natural decay on drainage rate was very rapid.

It can be seen that all the foams of either protein base or containing protein additives typically break down. The Rockwood Aquafoam AFFF, however, did not exhibit any reaction characteristics in either low- or high-expansion foam. This foam is purely synthetic based and has no protein content. To further verify that a synthetic based foam would exhibit stability under the condition described, a heavy-duty cleaning detergent (purely synthetic) was used to produce a foam for observation. The detergent is identified as Besco No. 98. The foam produced in a low-expansion condition also was stable. Difficulty in producing a high-expansion foam was encountered; therefore, the stability was not observed.

During the process of determining the various foams' stability with gun powder residue, an important discovery was made. As various foams were produced, a trial muzzle device fill-up was attempted using a full-scale transparent plastic mockup of the 5"/54 muzzle device. This mockup conformed to the 5"/54 device internal diameter and length dimensions as well as to the inside diameters of the gun barrel and baffles. The mockup is shown in Figure A-1. It was determined that a low-expansion foam of between 10:1 and 80:1 expansion ratio would not fill the device. The foam would flow over itself and run out the baffle and muzzle openings when the device was approximately five-eighths filled. A principal property of aqueous mechanical firefighting foams is the ability for the foam to flow freely over itself to facilitate spreading.

It was later determined that the smooth plastic muzzle device mockup contributed to the problem because it was possible to completely fill the actual prototype steel device with the same foams. Part of the problem observed in filling the plastic mockup was that it was exposed to direct sunlight and was quite warm when the filling trials were run. The actual muzzle device was so massive that the interior walls remained relatively cool during the period of testing. It is important to note that incomplete filling of a muzzle device undergoing rapid fire may be a problem as the interior walls of the device may heat up substantially during firing.

Figure A-1. Transparent Mockup of 5"/54 Muzzle Device

FOAM GENERATOR DEVELOPMENT

As stated earlier, the basic concept of mechanical aqueous foam-making equipment is to produce a solution of water and foaming agent, in specific proportions, and to agitate the mixed solution to form an expanded foam. The water and foaming agent can be premixed or proportioned by special equipment. The solution is supplied through a line under pressure to a nozzle. At this point, air, a mechanical agitant, or both are introduced to produce the foam output. The quality (stability), quantity, bubble size, and expansion ratio are dependent on the combination of many variables. Some of the variables involved are liquid pressure and flow rate, proportioning percentage of foaming agent to water, type of foaming agent, aspirating-air pressure and flow rate, agitation mechanism, and physical nozzle configurations.

The foam generator design was developed through a trial and error approach. The variables were identified, adjustments controlled, and variables combined until a working combination was achieved that yielded the desired output.

The design of the generator (see Figure A-2), utilizes the Mearl OT-10 pressurized tank as a premixed solution dispenser. The premixed water and foaming agent are suppplied to a nozzle under regulated pressure. The nozzle is a typical house furnace oil burner nozzle, which is modified to facilitate an increased flow rate. The nozzle position is adjustable to provide uniform wetting of the screens in front of the nozzle. The wetting screen is made of four layers of conventional window screen material, formed in a conical shape, to aid in liquid film forming over the screen. In front of the wetting screens is an area of aggregate to create a mechanical solution agitation. The aggregate (not used for foams > ~150:1 expansion) is composed of small plastic hollow cylinders and is held in place by another piece of window screen. A piece of cheesecloth is located over this screen to produce a desired small bubble structure (to enhance the ability of the foam to pile upon itself). The screen and cheesecloth layers are held in place by the extension tube. The offline angular output opening of the extension tube facilitates filling of the 5"/54 muzzle device through the muzzle opening. Another piece of window screen is placed over the end of the

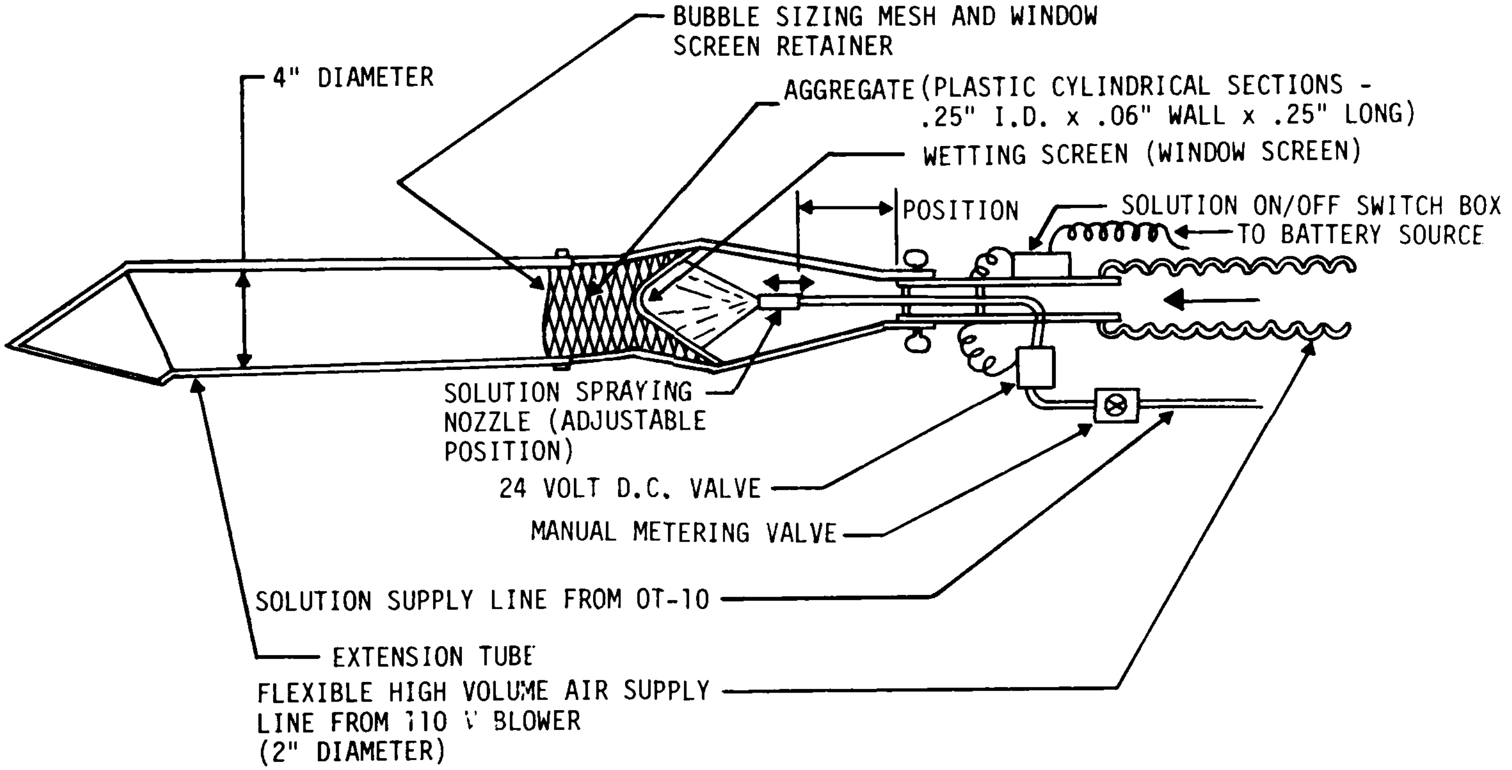

Figure A-2. Developed Foam Generator Design Schematic extension tube to create a slight back pressure or resistance to facilitate a uniform foam output. The air is supplied by a high-volume blower, through a 2-inch diameter flexible plastic tube. The air flow is controlled by a valve on the blower input. The liquid solution is turned on and off by an electrically operated valve between the OT-10 tank and the nozzle. Solution flow rate is controlled by regulated OT-10 tank pressure and a manual inline valve or the solution flow control orifice valve on the OT-10 on/off handle.

The foam expansion ratio is varied by the degree of solution agitation, air and liquid flow rates, and the size of the bubble forming screen. Also, the proportioning of the foaming agent and water affect the resultant foam density and stability.

All of the foaming agents described earlier in Table A-1 were tested in the previously described generator. Combinations of parameters (see Table A-2) were evaluated to determine foam production capability.

The stability of a foam, as discussed earlier, was the limiting factor as to how much experimentation was done with a given type of foaming agent. Once a foam was produced, with any given foaming agent that was stable in contact with a clean steel surface, the stability with burnt Naco gun powder residue was checked. If a rapid drainage rate was observed, no further work was done. As a result, the major portion of the experimentation to obtain desired expansion foams of 50, 100, 200, and 400:1 was conducted with Rockwood aquafoam AFFF, which had the highest stability factor.

A foam generator was calibrated, using Rockwood Aquafoam AFFF, to produce foam expansion ratios of 80, 100, 200, and 350:1, as measured directly out of the generator. This represents the range over which a full column steady flow of foam, without excessive air blowing, could be produced from the extension tube of the generator. Excessive air blowing causes nonuniform filling of the muzzle device. The generator produces 80:1 foam at a rate of over 6 feet^3/minute and requires a maximum of 2.0 minutes to fill the muzzle device through the muzzle opening. The muzzle device can be filled to over 90 percent volume (see Figure A-3) with foams $\geq$ ~80:1 expansion ratio. The bubble size produced varies with density, but appeared to range from ~1/32-inch diameter for 80:1 foam up to 3/32-

Figure A-3. Developed Foam Generator Filling 5"/54 Muzzle Device with 200:1 Expansion Ratio Foam

Table A-2. Controlled Foam Generator Parameters

A. Type of foaming agent (Table A-1)

B. Foaming agent percent or proportion (1 to 6 percent foaming agent to water)

C. Nozzle size (three sizes used)

D. Nozzle tip distance from wetting screens

E. Number of wetting screens

F. Aggregate volume, type, and size

G. Number of layers and kind of material in bubble forming mesh

H. Solution orifice valve setting (OT-10 on/off handle)

I. Solution tank regulated pressure

J. Manual solution valve position

K. Expansion blower flow rate (regulated by intake valve positions)

inch diameter for 200:1 foam. For 350:1, it ranges upwards to ~1/4 inch. This is an observation and not an exact measurement. Because of the involved procedures, equipment, and a large setup cost, measurements of bubble size and wall thickness were not accomplished. The OT-10 system, using a standard nozzle, was calibrated to produce expansion ratios of 20:1 to 50:1 using the Aquafoam AFFF.

The foam produced with Rockwood Aquafoam AFFF is nonreactive with the burnt Naco powder residue created from 5"/54 gun firing. The foam has a uniform bubble structure at all densities, and its synthetic base has a claimed minimal environmental impact (i.e., fish toxicity, chemical and biological oxygen demand, and total organic carbon). It can be produced with either fresh or salt water.

All aqueous foams have a certain drainage rate that causes the expansion ratio and bubble size to increase progressively. The Rockwood Aquafoam AFFF yields the slowest drainage rate observed of all the foaming agents tested for any given high-expansion ratio (~100:1 or greater). The low-expansion foams generally had very low natural drainage rates, regardless of foaming agent. This drainage rate in effect means that, due to the delay from the time of muzzle device filling to gun firing, the expansion ratio of the foam has increased. The quarter life of the 200:1 Aquafoam AFFF produced was observed to be ≈3 minutes. During the first 2 minutes after production, very little drainage was observed.

To determine the expansion ratio of the generated foam at the time of gun firing, a simple procedure can be followed. Using a known volume container with a lowest point drain hole (see Figure A-4), the expansion ratio of a given foam can be obtained at any time after production by monitoring the foam weight.* The muzzle device must also have a lowest point drain hole to allow drained solution to drain from the device. As observed in experimental tests, the foam volume does not begin to decay until ~50 percent or more of the solution has drained out of foam suspension.

In order to fire the gun with a foam of a specific desired expansion ratio, the muzzle device is filled with a slightly denser (lower expansion ratio) foam. Halfway through filling the muzzle device, the bucket is filled with the same foam. The weight of the foam is monitored in the bucket and when it reaches that which corresponds to the desired expansion ratio, the gun was fired.

RECOMMENDATIONS

In the event that further development beyond the testing of the full-scale 5"/54 muzzle device is carried out, it is recommended that consideration be given to development of an automated foam-filling system. Existing industrial expertise should be utilized for such a project, particularly if a chemical foam is contemplated.

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* The bucket volume must be large enough to yield foam expansion ratio accuracy, when considering the accuracy of the weight measurements. The weight of the bucket must also be known.

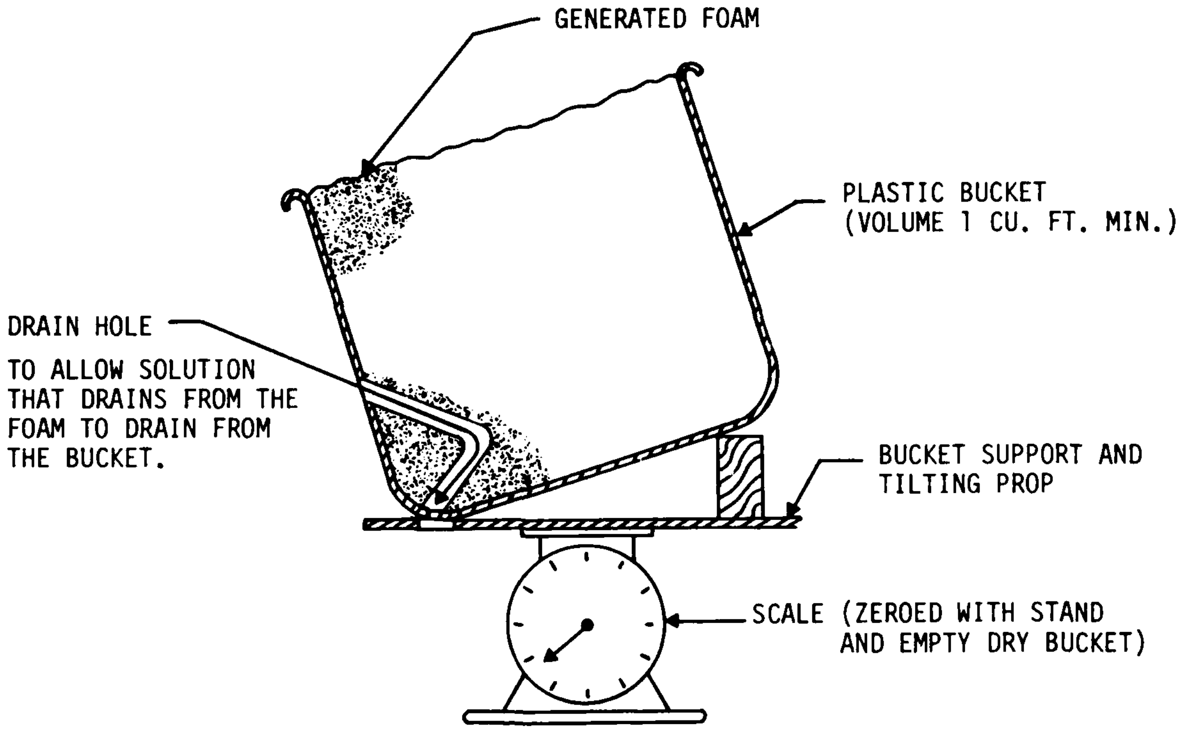

Figure A-4. Acquiring the Expansion Ratio of a Given Foam

APPENDIX B

BALLISTIC EFFECTS OF FOAM IN THE MUZZLE OF A 5"/54 GUN

INTRODUCTION

One concern with the development of a full-scale foam-containing muzzle device is the effect of foam seeping into the muzzle of the barrel. The purpose of this test was to investigate the effects of the foam seepage on interior ballistics.

BACKGROUND

A 5"/54 foam test was initiated in August 1978. The plans were to fire several rounds, with increasing amounts of foam in the muzzle. A protein-based foam with an expansion ratio of 20:1 was used. This is a relatively dense foam with a consistency similar to shaving cream. After firing one round with 40 inches of foam in the muzzle, excessive pressures were measured at 12 and 50 inches from the muzzle. The program was halted at this point for further analysis. Star gauging of the barrel indicated a 0.025-inch permanent expansion, 20 inches from the muzzle.

Simple calculations show that a foam with an expansion ratio of 20:1 translates into approximately 1 inch^3 of water per inch of length of barrel in the foam region. If all of this foam was reduced to its liquid state (void of air) and distributed evenly on the interior surface of the barrel, the liquid film would be approximately 0.064 inches thick. It is then theorized that the projectile rode over some portion of the fluid contained in the foam and caused the over stressing of the barrel near the muzzle. It was concluded that introducing 40 inches of 20:1 aqueous foam would cause significant damage to the gun barrel. It is also believed, however, that the amount of foam seeping into the muzzle could be limited to considerably less than 40 inches of penetration in practical application. Insignificant effects were observed for penetrations less than $\approx$30 inches. Also, foam of greater expansion ratios introduces less fluid into the muzzle.

Experiments were conducted with a full-scale plexiglass model of the muzzle device to determine how much foam seepage into the gun barrel could be expected. The results showed that a maximum of about 20 inches of foam would extrude into the gun muzzle before flow developed out of the larger muzzle opening of the device. This, however, is only true for the filling rate used. It would be expected that a more rapid filling rate would produce a higher back pressure and result in further penetration into the gun barrel.

OBJECTIVE

The purpose of this test was to investigate effects of aqueous foam on interior ballistics when the gun muzzle was filled to lesser degrees than previously tested and foams of various expansion ratios were used.

TEST DESCRIPTION

For completeness, the test results of both August 1978 and March 1979 are included. In this appendix, they are referred to as Test I and Test II, respectively.

A 5"/54 Mk 18 Mod 0 Gun, Serial No. 16155, machined to accept pressure gauges along its length, was used. The gun was star gauged before Test I, between Tests I and II, and after Test II.

Barrel pressures, along with muzzle velocities, were measured for all rounds. The muzzle velocities were measured by Doppler radar with an accuracy of ±5 feet/second.

For Test I, eight Kistler 607A pressure transducers were installed in the gun barrel at the lettered stations (as shown in Figure B-1). For each pressure station along the barrel, there are two opposing pressure ports available. The

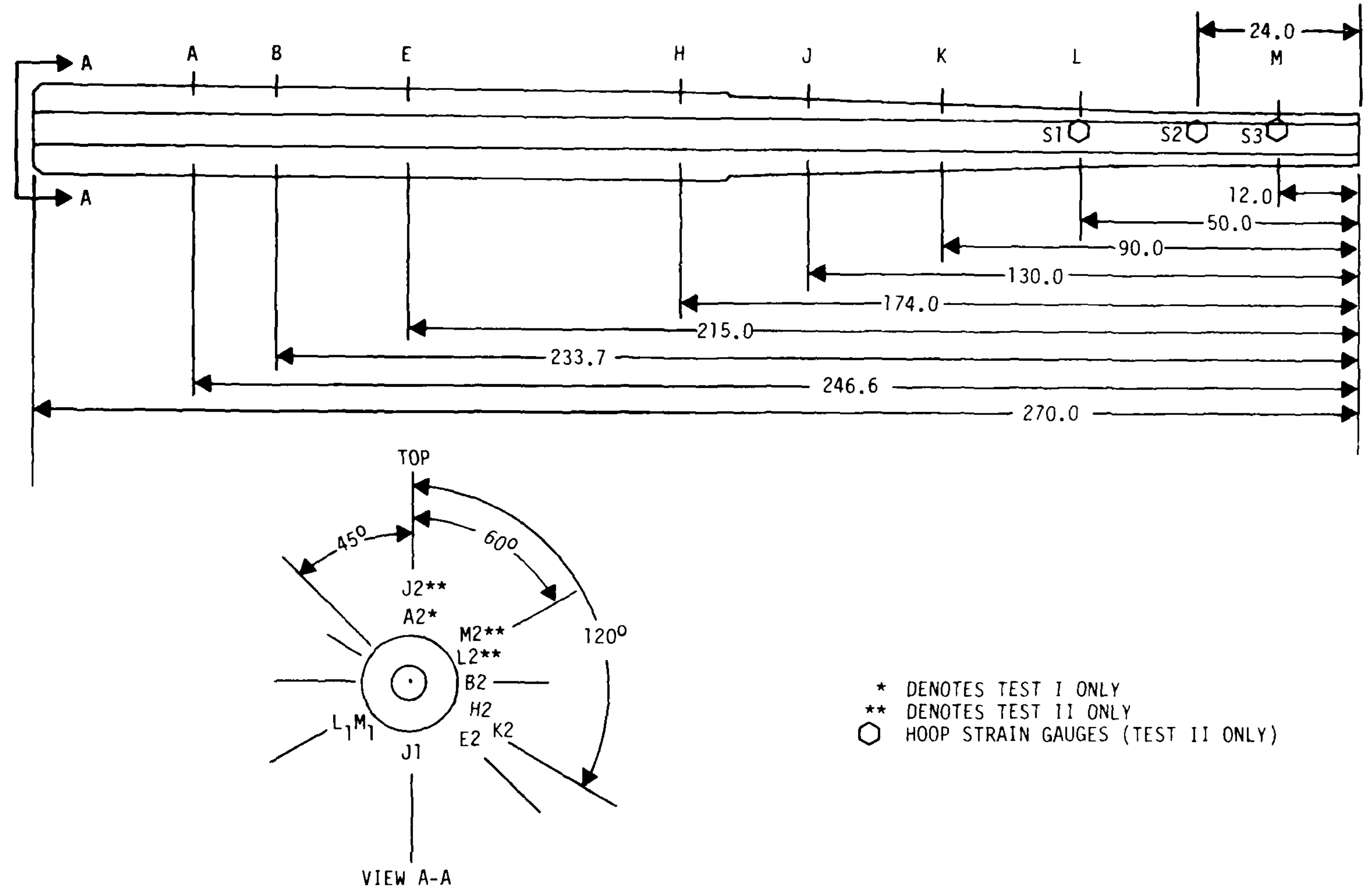

Figure B-1. Gun Barrel Instrumentation

clocked positions of the pressure taps are provided in Figure B-1. For Test I, one of the two pressure taps at each lettered station was arbitrarily selected.

For Test II, the pressure measurement at Station A was deleted. Also, additional pressure gauges were installed in the opposing pressure taps at Stations J, L, and M to provide additional data in these critical areas.

For Test II, three strain gauges were installed on the barrel to measure hoop strain. These gauges were positioned 12, 24, and 50 inches from the muzzle as shown in Figure B-1.

The various foam densities were prepared from commercial concentrates and the foam was generated with either a commercial or an NSWC-designed nozzle. Samples of the foam were weighed in a known volume to determine the exact expansion ratio. The foam expansion ratios, foam type, solution mix, and nozzle type are provided in Table B-1.

RESULTS AND DISCUSSION

The results of Tests I and II are provided in Tables B-2 and B-3, respectively. The first three rounds fired in Test I were reduced charge. The next three rounds of Test I and the first three rounds of Test II were fired at full charge with no foam to establish baseline data. The first round fired on a given day is considered a warming round; it exhibits a data variance.

The impact of foam density and the length of foam in the barrel on the muzzle velocity were analyzed. It was assumed that the muzzle velocity, as a function of length of foam for a given foam density, is

$$V = V^0 - B\ell^2$$

where

V is the muzzle velocity (feet/second)

V^0 is the muzzle velocity with no foam (feet/second)

B is a constant to be determined

ℓ is the length of foam (inches)

Table B-1. Aqueous Foam Expansion Ratios

Nominal Expansion Ratio	Foam Concentration Type	Solution Mix (%)	Nozzle Type	Measured Expansion Ratio
20:1	Rockwood Jet-X	2.5	Mearl 2.1 cFm*	20.1:1
35:1	Mearlfoam 5	3	Mearl 6cFm*	34.8:1
200:1	Rockfoam Jet-X	1	NSWC Design	222:1
500:1	Rockwood Jet-X	6	NSWC Design	497:1

* Mearl OT-10 system described in Appendix A.

Table B-2. Results of Foam in Muzzle Test of August 1978

Rd. No.	Date	Ratio	Inches Foam	Peak Pressure (K psig)											Muzzle Velocity (ft/sec)
				A1	B2	E2*	H2*	J1*	J2	K2	L1*	L2	M1*	M2	
1**†	8-17	NA	0	28.8	28.6	24.3	21.6	16.1	--	10.1	10.6	--	9.6	--	2228
2**	8-17	NA	0	25.7	28.8	26.1	21.1	15.4	--	9.2	8.7	--	8.9	--	2246
3**	8-17	20:1	40	--	26.4	25.5	21.4	14.3	--	8.3	8.6	--	--	--	2185
4	8-17	NA	0	--	43.6	42.5	30.7	20.4	--	11.8	10.2	--	10.5	--	2629
5	8-17	NA	0	31.5	42.9	38.8	29.8	20.1	--	11.4	10.0	--	10.9	--	2632
6	8-17	NA	0	44.4	42.7	35.8	29.5	19.7	--	11.4	10.3	--	9.9	--	2637
7	8-17	20:1	40	41.9	40.4	32.5	29.6	18.0	--	12.0	46.7	--	40.6	--	2542

* Denotes gauge locations on lower half of barrel
** Denotes rounds fired at reduced charge
† Denotes conditioning round

Table B-3. Results of Foam in Muzzle Test of March 1979

Rd. No.	Date	Ratio	Inches Foam	Peak Pressure (K psig)											Muzzle Velocity (ft/sec)
				A1	B2	E2*	H2*	J1*	J2	K2	L1*	L2	M1*	M2	
1**	3-14	NA	0	--	46.0	36.7	38.9	21.7	29.7	20.5	21.5	22.3	10.4	10.9	2596
2	3-14	NA	0	--	38.9	36.2	39.0	18.8	18.3	12.9	9.6	10.1	10.4	7.8	2621
3	3-14	NA	0	--	39.2	36.0	38.3	19.6	18.9	14.4	10.2	10.2	9.9	7.8	2611
4	3-14	500:1	30	--	40.8	36.0	35.0	18.6	18.6	13.0	10.7	9.4	9.8	7.8	2616
5	3-14	500:1	30	--	42.5	38.8	40.0	18.9	17.7	12.6	9.8	10.0	11.2	8.1	2608
6	3-14	500:1	30	--	42.5	39.5	38.0	18.7	17.8	13.1	10.2	10.0	10.8	7.8	2634
7	3-14	500:1	60	--	42.8	38.8	40.5	19.6	17.7	12.6	10.0	10.1	10.7	8.1	2624
8	3-14	500:1	60	--	42.8	40.9	38.6	19.7	17.4	12.9	10.2	10.0	10.2	8.1	2625
9	3-14	500:1	60	--	41.2	38.1	38.6	19.7	18.1	13.4	10.7	10.5	10.1	8.1	2623
10	3-14	500:1	90	--	40.5	38.5	38.3	18.6	--	12.9	10.2	9.4	10.1	8.8	2598
11	3-14	500:1	90	--	40.6	36.1	39.0	19.4	18.0	13.2	9.9	10.5	9.9	8.7	2593
12	3-14	500:1	90	--	41.2	37.4	38.2	19.6	17.8	13.2	9.5	10.0	9.6	8.4	2591
13**	3-15	NA	0	--	39.9	36.8	36.0	18.3	17.2	13.4	10.2	10.6	11.1	8.7	2600
14	3-15	200:1	30	--	39.9	42.4	44.1	31.5	28.5	29.6	26.9	25.7	22.0	17.8	2576
15**	3-16	NA	0	--	41.2	38.9	39.6	19.3	19.6	13.9	9.7	9.4	11.1	9.2	2594
16	3-16	200:1	30	--	42.6	40.3	38.7	30.7	17.8	20.5	25.4	23.4	13.5	14.3	2598

* Denotes gauge locations on lower side of barrel

** Denotes conditioning round

Table B-3. Results of Foam in Muzzle Test of March 1979 (Continued)

Rd. No.	Date	Ratio	Inches Foam	Peak Pressure (K psig)											Muzzle Velocity (ft/sec)
				A1	B2	E2*	H2*	J1*	J2	K2	L1*	L2	M1*	M2	
17	3-16	200:1	60	--	42.3	39.9	43.5	27.6	18.0	23.6	26.3	27.8	17.2	12.6	2583
18	3-16	200:1	60	--	43.2	42.1	42.8	35.1	30.9	32.6	29.3	27.6	12.4	10.3	2583
19	3-16	200:1	90	--	44.3	42.1	46.4	39.0	33.4	35.1	35.4	32.5	17.3	8.6	2577
20	3-16	NA	0	--	44.8	40.3	42.3	19.3	17.8	13.1	9.9	9.8	9.5	7.9	2623
21	3-16	200:1	90	--	42.7	45.7	46.3	32.6	29.2	30.3	29.6	29.6	11.6	10.8	2577
22	3-16	35:1	20	--	41.5	39.3	31.6	19.3	18.3	12.9	9.6	9.7	9.7	8.0	2608
23	3-16	35:1	20	--	42.8	38.9	37.0	18.0	17.7	11.6	10.6	10.5	9.5	8.0	2617
24	3-16	35:1	30	--	41.9	38.9	37.0	17.4	17.4	12.8	11.4	10.9	9.9	7.8	2612
25	3-16	35:1	30	--	42.9	38.9	37.1	18.1	16.7	12.8	10.6	10.9	10.0	7.3	2615
26	3-16	35:1	40	--	44.5	38.2	35.5	19.0	16.5	11.1	10.6	10.6	30.2	11.6	2613
27	3-16	35:1	40	--	42.6	37.5	37.0	17.7	16.4	13.0	11.1	11.5	20.6	--	2593
28	3-16	35:1	50	--	41.9	37.1	34.4	18.7	18.1	12.8	10.9	10.9	34.2	17.5	2577
29	3-16	35:1	50	--	43.9	37.8	36.3	18.1	17.0	12.5	11.1	10.1	36.4	13.5	2591
30	3-16	35:1	60	--	43.2	35.5	34.8	17.8	16.4	13.1	10.6	10.9	31.8	11.6	2569

* Denotes gauge locations on lower side of barrel
** Denotes conditioning round

V^0 was found by taking the average velocity of the round with no foam and was found to be 2,618 feet/second. The B constants were determined by a least-square curve fit for each of the foam densities which are

$$B_{35} = 0.01312$$

$$B_{200} = 0.00601$$

$$B_{500} = 0.00216$$

It was further found that the B constants may be expressed as a function of the foam density ratio

$$B = C10^{-KZ}$$

where

C and K are constants to be determined

Z is the foam density ratio

From a least-square curve fit

$$C = 0.0141$$

$$K = 0.00165$$

Thus,

$$V = 2{,}618 - 0.0141{*}\ell^2\ 10^{-0.00165Z}$$

Muzzle velocity, as a function of length of foam for each round, is plotted along with the calculated curves in Figure B-2. The standard deviation for acceptance of a powder lot is ±10 feet/second. Also, the error in the muzzle velocity is ±5 feet/second. Thus, the measured velocity of a given round could vary ±15 feet/second from nominal. From the 35:1 curve of Figure B-2, a ±15 feet/second deviation translates into 32 inches of foam.

A similar numerical analysis of the effect of foam on barrel pressures could not be easily obtained. In general, as more foam is introduced into the barrel, large pressure spikes appear which, in some cases, exceed design limits. These pressure excursions are reflected as maximum pressures in Tables B-2 and B-3. The pressure spikes measured on the low side of the barrel were sometimes higher than

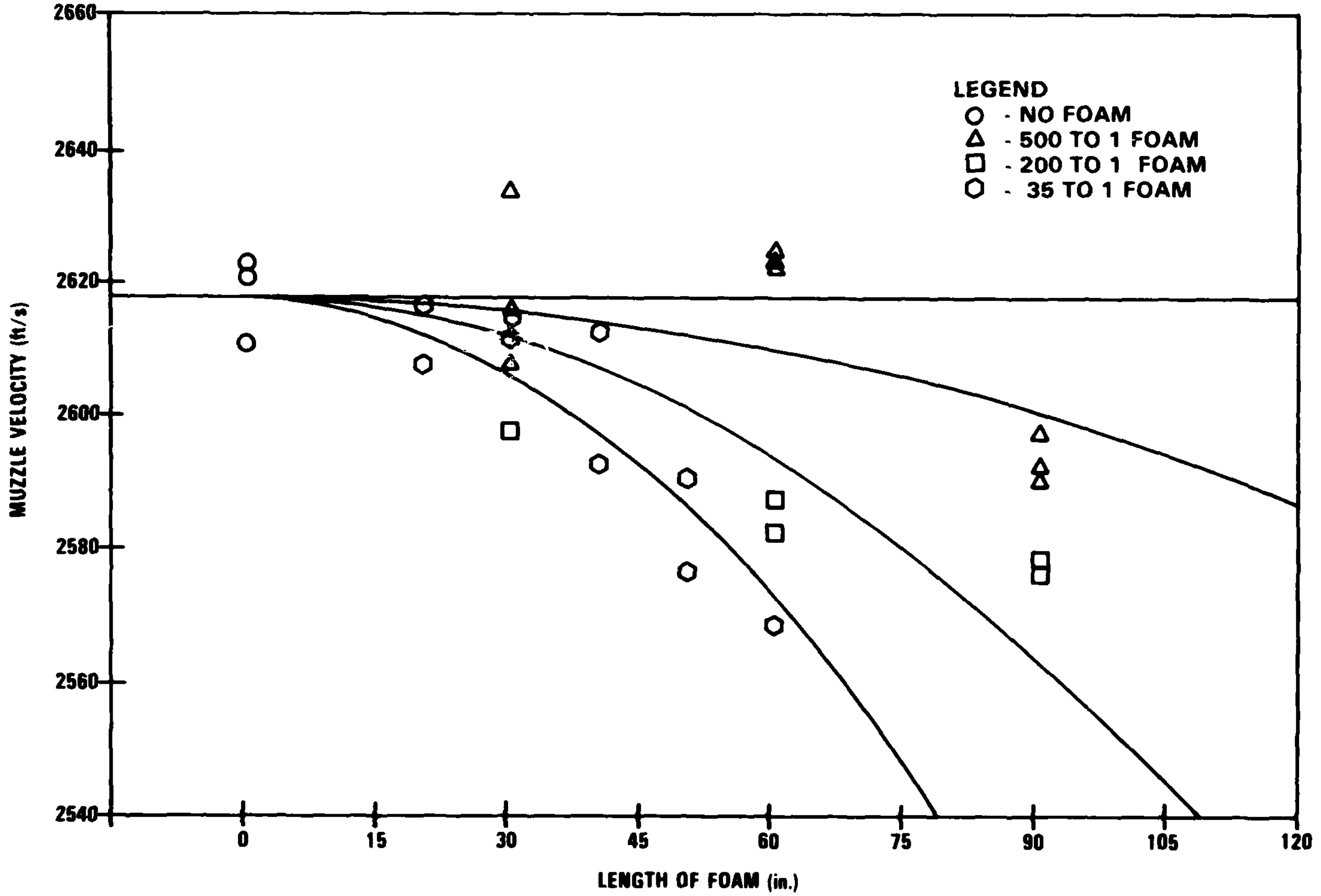

Figure B-2. Effect of Foam Density and Length of Foam on Muzzle Velocity their counterparts measured on the upperside of the barrel. This is probably due to fluid draining from the foam and accumulating on the low side of the barrel or in the recessed pressure portholes. This accumulated fluid then creates hydraulic shock when the bourrelet of the projectile passes over the pressure tap. Examples of this are the pressure traces at locations J-1 and J-2 with no foam (round 20) and with foam (round 17). (See Figures B-3 through B-6.)

It was noted during the 200:1 foam portion of the test that the foam was unstable; i.e., the foam degenerated to a liquid form quickly. Therefore, more foam was introduced into the barrel than nominally required for a given stable foam length. In general, this caused a pressure spike for relatively short lengths of foam in the barrel.

With the exception of rounds 14 and 16 (which used 200:1 foam), 30 inches of foam or less in the muzzle caused no significant change in barrel pressures.

Analysis of the strain-gauge data showed no permanent distortion of the barrel at their respective locations. However, star gauging of the barrel (Table B-4) showed a permanent distortion of the barrel resulting from both test series. For Test I, there was a 0.025-inch bulge of the interior diameter (I.D.) 20 inches from the muzzle. For Test II, there was a 0.015-inch bulge of the I.D. 2 inches from the muzzle, as well as a 0.011-inch I.D. bulge 30 inches from the muzzle. From the pressure records, it is plausible to assume that the damage occurred from the tests where foam penetration exceeded ≈30 inches; however, the test results do not conclusively prove that extended foam was the cause for the bulge observed after the conclusion of testing.

CONCLUSION

If the length of 35:1 foam in the muzzle of a 5"/54 gun is less than ≈30 inches, the reduction of muzzle velocity of a given round will be within the uncertainty band of ±15 feet/second. If care is taken not to introduce surplus liquid into the barrel, ≈30 inches of 35:1 foam in the muzzle will not affect chamber pressures.

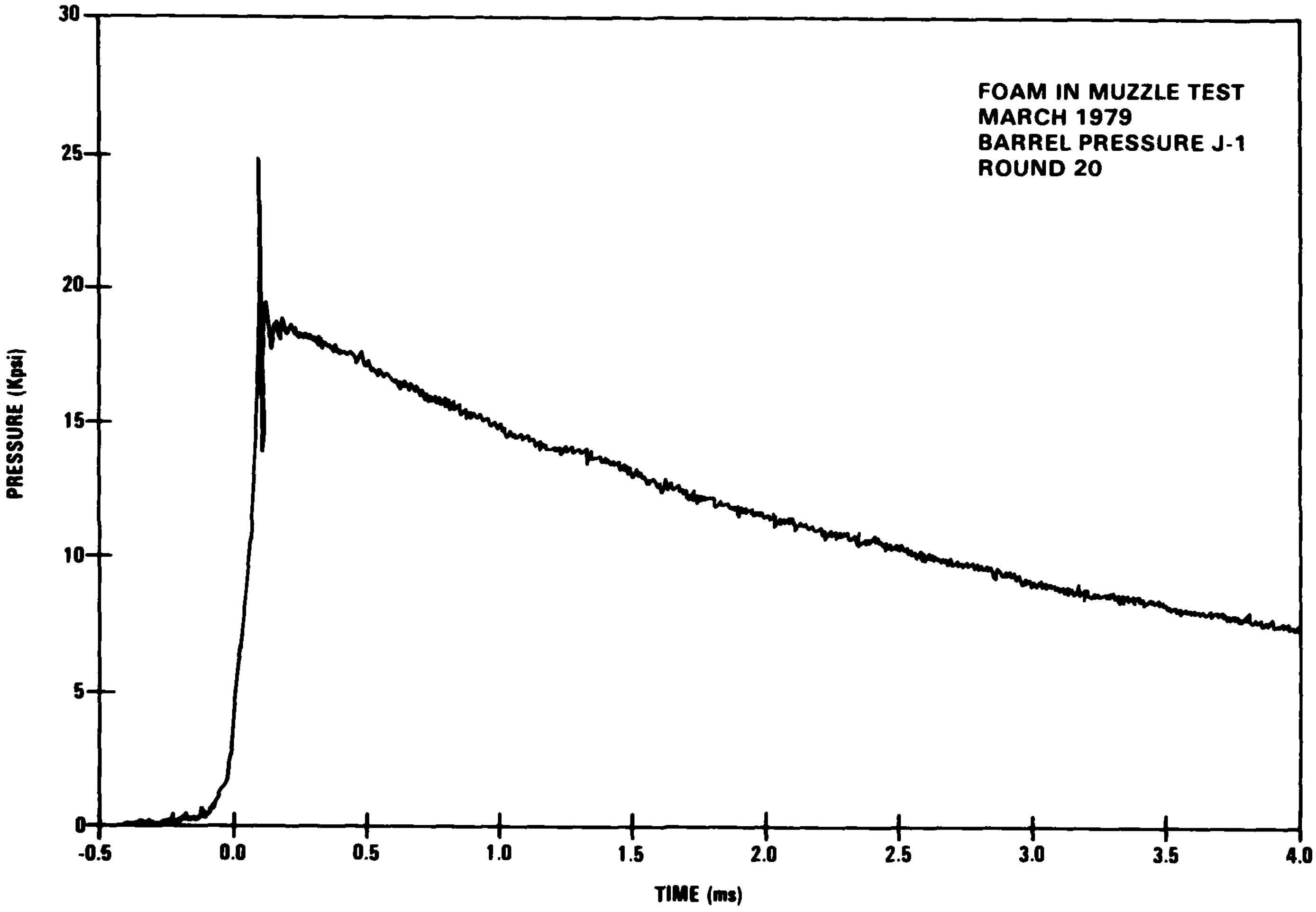

Figure B-3. Typical Barrel Pressure Trace at J-1 with No Foam

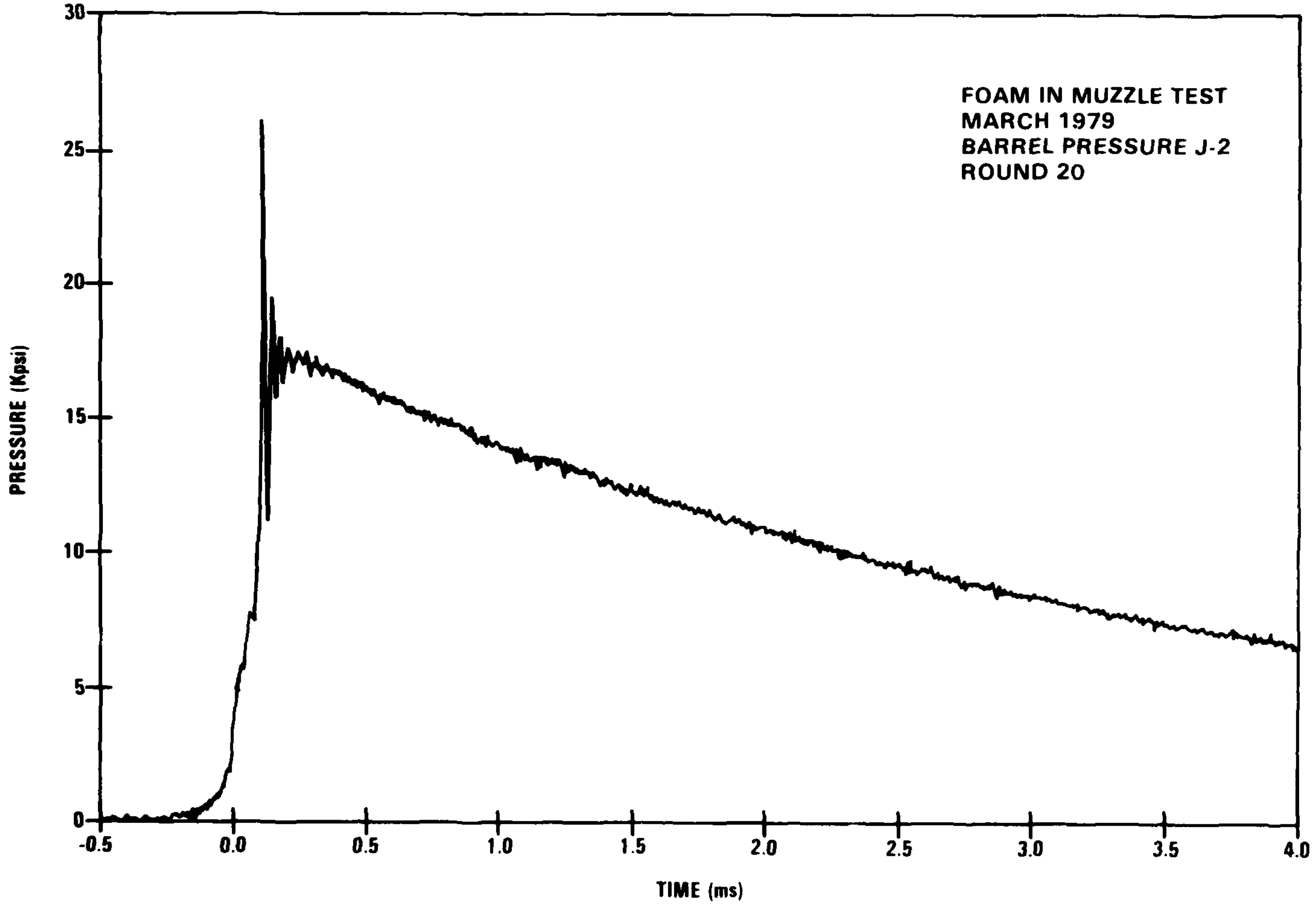

Figure B-4. Typical Barrel Pressure Trace at J-2 with No Foam

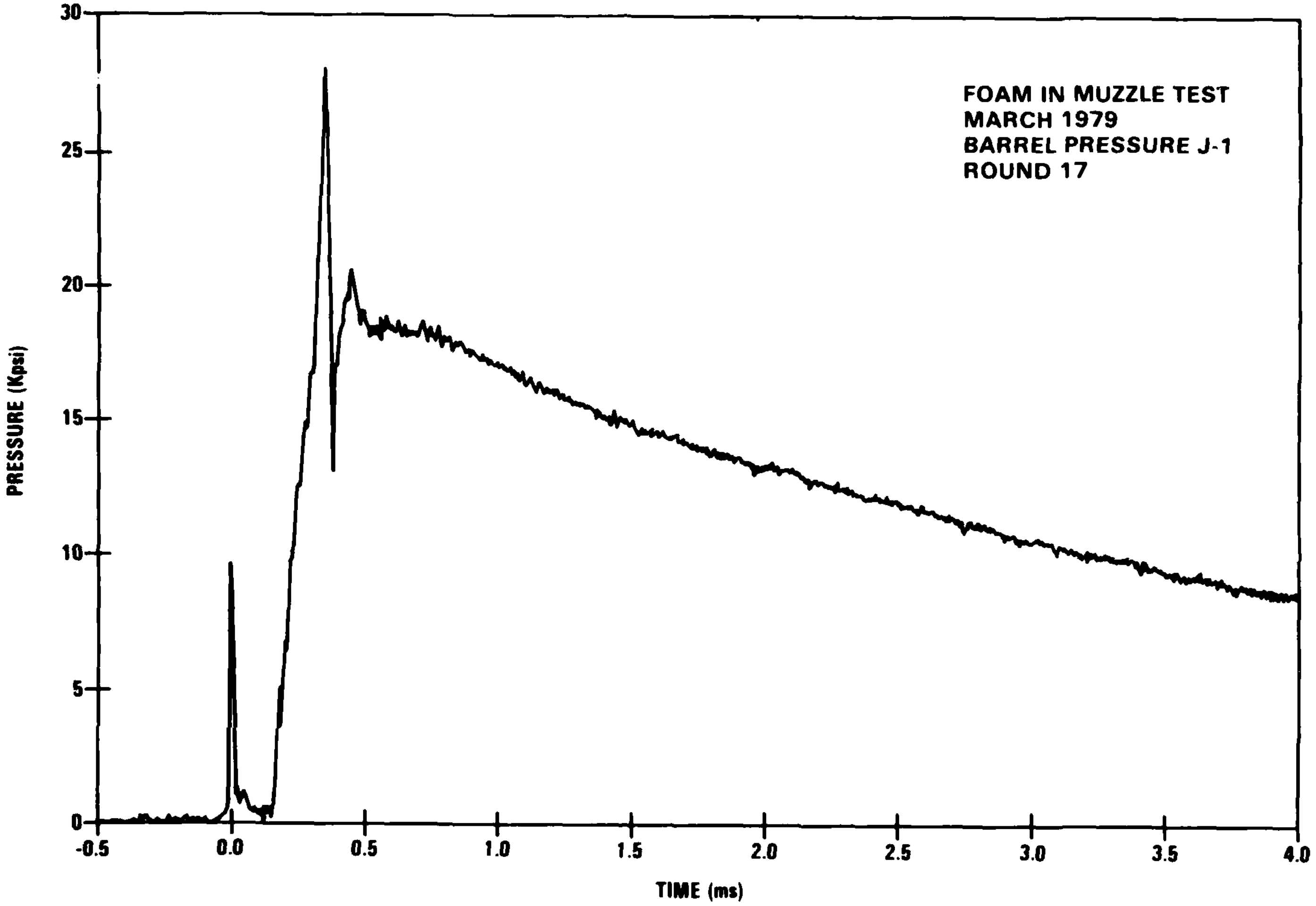

Figure B-5. Typical Barrel Pressure Trace at J-1 with Foam

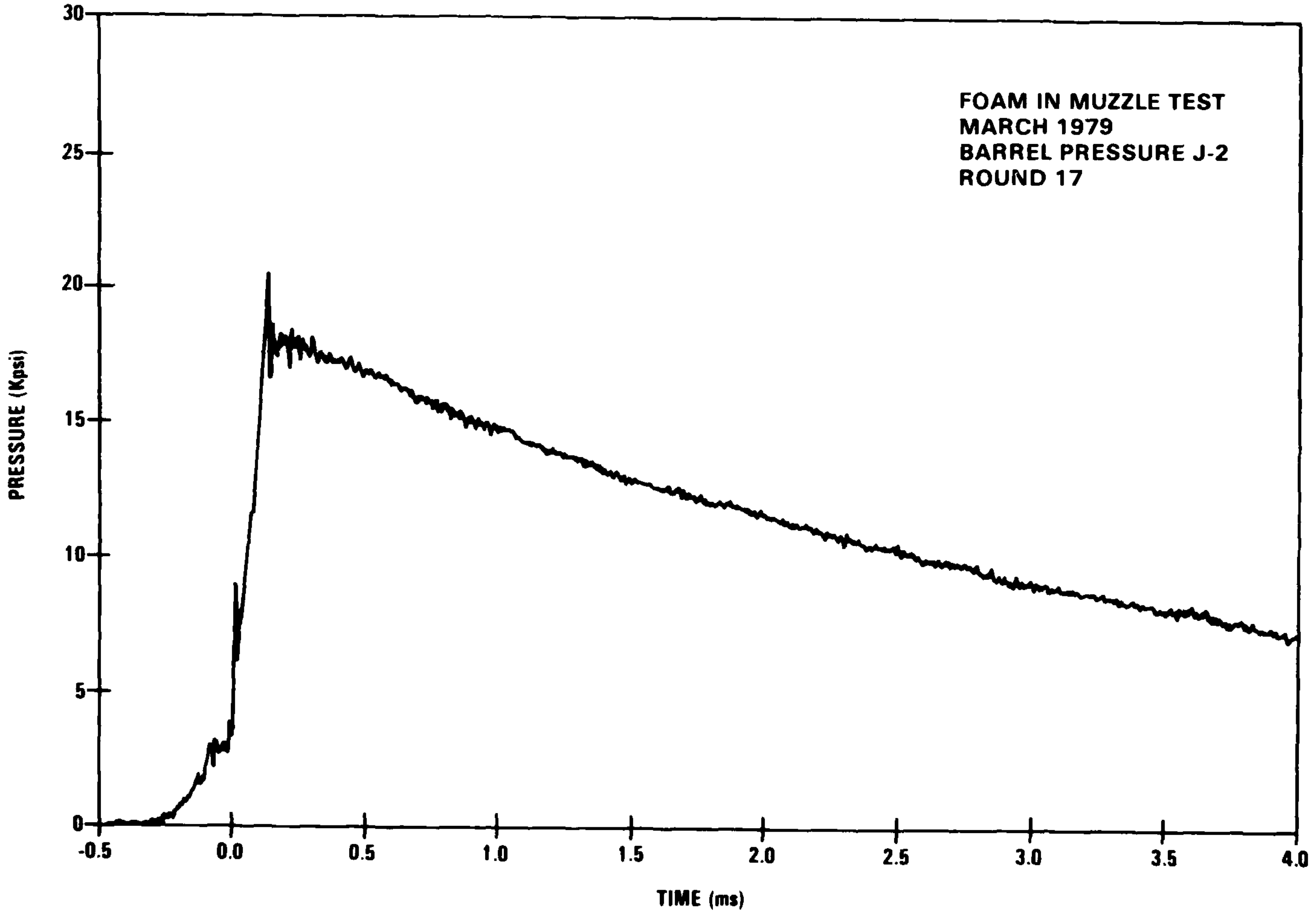

Figure B-6. Typical Barrel Pressure Trace at J-2 with Foam

Table B-4. Star Gauge Readings (Inches)

Distance from Muzzle	Before Test I 6-29-78	After Test I 9-11-78	Difference	After Test II 3-28-79	Difference
0	5.003	5.001	-0.002	5.015	0.014
1	5.003	5.001	-0.002	5.020	0.019
2	5.009	5.022	0.013	5.037	0.015
10	5.011	5.032	0.021	5.028	-0.004
12	5.009	5.027	0.018	5.026	-0.001
15	5.002	5.022	0.020	5.018	-0.004
20	5.001	5.026	0.025	5.024	-0.002
25	5.001	5.014	0.013	5.016	0.003
30	5.001	5.005	0.004	5.015	0.011
35	5.001	5.003	0.002	5.007	0.005
40	5.001	5.003	0.002	5.003	0.000
45	5.001	5.001	0.000	5.001	0.000
50	5.001	5.000	-0.001	5.000	0.000
55	5.001	5.000	-0.001	5.000	0.000
60	5.001	5.000	-0.001	5.000	0.000
65	5.001	5.000	-0.001	4.999	-0.001
70	5.001	5.000	-0.001	4.999	-0.001
75	5.001	5.000	-0.001	5.000	0.000
80	5.001	5.000	-0.001	5.000	0.000

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