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NEW PROPELLING CHARGE FOR 16-INCH, 50-CALIBER GUN

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FOREWORD

The work reported herein was performed at the Indian Head Division, Naval Surface Warfare Center, Indian Head, MD.

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INTRODUCTION

Background:

The D846 propelling charge for the 16-inch, 50-caliber gun was designed for use with the 1,900-lb projectile and makes use of single-base Pyro propellant originally manufactured for use in the 16-inch, 45-caliber gun firing a heavier projectile. As such, the performance is far from optimized, though adequate. The charge is made up of six bags of powder, each weighing nominally 100 lb. The copper from the rotating band which is deposited into the rifling grooves of the barrel is kept to an acceptable level through the use of an envelope containing 200 g of lead foil which is placed between the first and second powder bags behind the projectile.

The Pyro propellant used in the charges was made in the late forties and early fifties and thus is rather elderly for propellant. While stabilizer levels and fume times are acceptable, it is clear that there are not many years left until this propellant is no longer safe for use. Pyro was made using a solvent process with alcohol and ether. Because of the large size of the grains, high levels of residual solvent remained in that propellant when it was delivered. Over the years, some of that residual solvent was lost, the amount varying depending upon the storage and container conditions. Thus, a single lot could have a variety of solvent levels. The concentration of solvent has an effect on ballistic performance, so reproducibility suffers if solvent levels vary widely. This effect can be minimized by blending prior to loading charges.

Pyro is a fairly hot propellant which produces high barrel wear rates (from a Navy perspective). Given the scarcity of 16-inch barrels, high wear rates are unacceptable. To alleviate the high wear rate associated with firing Pyro charges, polyurethane foam jackets were developed. These jackets are simply thin (1/8 inch) sheets of polyurethane foam which are wrapped around each charge. During the combustion of the charge, the jackets burn, generating relatively cool gas which flows along the boundary between the barrel wall and the bore, thus slowing heat flow to the barrel. While effective in reducing wear, these jackets have been difficult to produce and have a fairly short shelf life before they become brittle and crack.

Objective:

The objective of this program was to develop a new charge to replace the old Pyro charge. It was to match the performance of the Pyro charge and eliminate as many of the problems associated with the old charge as possible. We also set ourselves the goal of designing in performance growth potential in the expectation that reactivation of the gun system would bring requirements for increased performance from the gun. The performance we sought to match was 2,690-ft/s (820-m/s) new gun muzzle velocity for the 1900-lb (862-kg) projectile with a breech pressure below 46,900 psi (323 MPa). Specific problems we tried to avoid were high levels of solvent, especially ether; the necessity of using wear-reducing jackets; and the use of lead for decoppering.

APPROACH

Like most programs involving the Navy's 16-inch guns, maximum use of existing resources was in order, due to the high costs associated with the large volumes of material needed for firings. Development of a totally new formulation would incur very high costs which were not within the scope of this effort, so we concentrated our search on existing formulations of energy similar to the Pyro propellant currently in use. Army artillery propellants were of particular interest since many of the same considerations went into their development. There has been limited use of triple-base powder in the 16-inch system as reduced charges, but the formulation used, Cordite-N, dates from the Second World War and is not considered optimal today. The M31 formulation is a modern triple-base which has been made in a number of modifications for application in several artillery systems. It has an energy level a bit higher than Pyro while its flame temperature is slightly below Pyro's. The formulations and thermodynamic data for each propellant are shown below in Table I. The Army has had many millions of pounds made with very good results, demonstrating the producibility of the powder. We chose it for application in the D846 round.

TABLE I. DESCRIPTION OF PYRO AND M31A1E1

Ingredient or characterisic	Pyro	M31A1E1
NC 12.6% N	100.00	21.50
Nitroglycerin		18.00
Nitroguanidine		54.70
Dibutylphthalate		3.00
Ethyl centralite		1.50
Diphenylamine	0.50	
Potassium sulfate		1.25
Carbon black		0.05
Graphite		0.05
Impetus (J/g)	977	986
Flame temperature (K)	2,688	2,615

Our first task was to design a granulation for the new propellant. We obtained a burning rate description from the Army, which took the form:

$$r_b = 9.107 \times 10^{-2} \text{ in/s/psi}^{0.79} \times P^{0.79}$$

$$= 2.313 \text{ mm/s/MPa}^{0.79} \times P^{0.79}$$

Using a Baer-Frankle-type, lumped-parameter interior ballistics code (1), we optimized the granulation for an initial muzzle velocity of 2,690 ft/s (820 m/s) at a maximum pressure of 46,500 psi (321 MPa). (We designed to a pressure slightly lower than the maximum allowable of 46,900 psi to allow a small margin of error.) The description of the gun had been validated during computer charge weight assessments for the standard D846 round, so we had confidence that our model was accurate. The calculation yielded an optimal web of 0.108 inch (2.74 mm) for a seven-perforated grain. The predicted charge weight for this web was 514 lb (233 kg). Three

10,000-lb lots of propellant were ordered with webs at the optimal value and bracketing it plus and minus 10 mils. This procedure, standard when making a new powder, allows all three lots to be probed for charge weight, then based on the probe ballistics, the optimal web can be determined.

Radford Army Ammunition Plant produced the powder for us with no production problems and ahead of schedule. The powder was shipped to the Naval Surface Warfare Center's Dahlgren laboratory for firings, and a small sample was sent here to Indian Head for characterization. To our dismay, the burning rates which we measured in our 700-cm^3 closed bomb were significantly higher than those upon which we based our granulation design. The measured burning rate expression, valid between 5,000 and 28,000 psi (34.5 to 193 MPa), was

$$\begin{aligned} r_b &= 3.566 \times 10^{-3}\ \text{in/s/psi}^{0.68} \times P^{0.68} \\ &= 9.057 \times 10^{-2}\ \text{mm/s/MPa}^{0.68} \times P^{0.68} \end{aligned}$$

When plotted together, the difference between the burning rate description from the Army and those measured in our bomb is apparent as shown below in Figure 1.

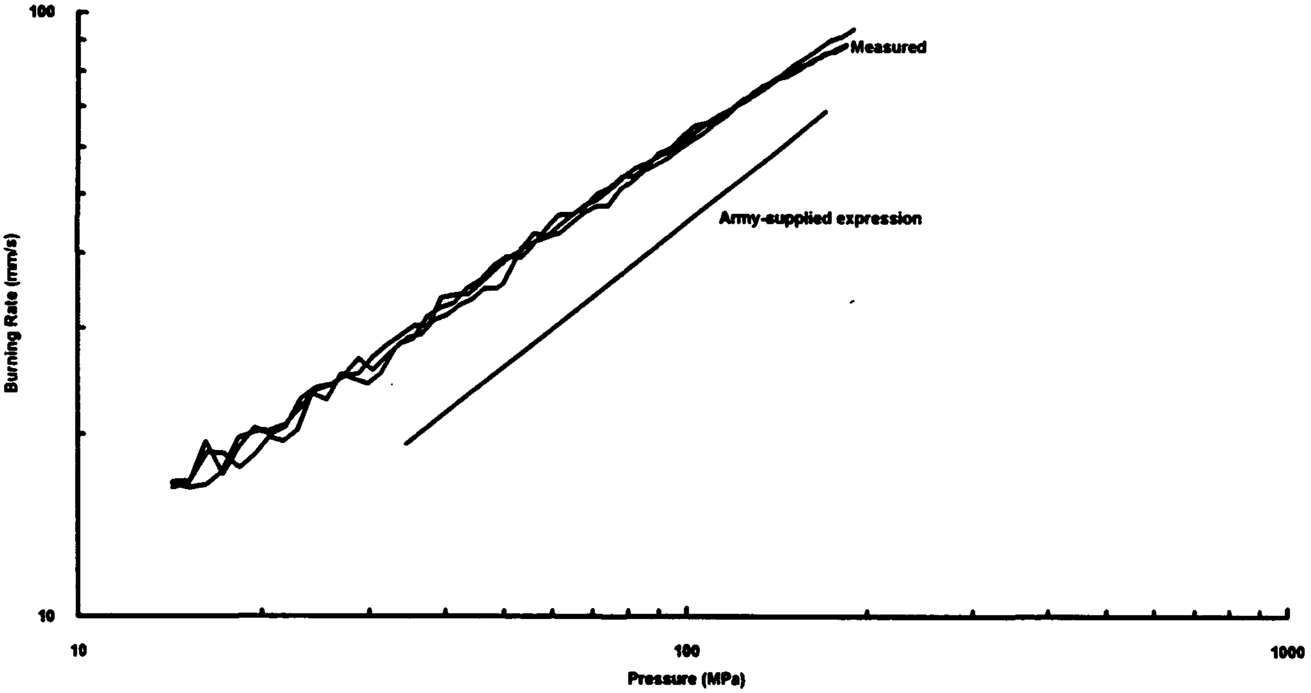

FIGURE 1. BURNING RATE DESCRIPTIONS FOR M31A1E1, MEASURED VERSUS ARMY SUPPLIED

When used in our lumped parameter code, even our largest, slowest web, 0.117 inch (2.87 mm), would yield maximum pressure at a charge weight of only 410 lb (186 kg), yielding an initial muzzle velocity below 2,500 ft/s (762 m/s). While we were quite disappointed (and baffled at the mismatch between quoted and measured burning rates), we chose to fire a probe series to check our predictions on charge weight. Our goal was to have some firing data so we could match that and predict the ballistics achievable with the correct granulation.

Charges were loaded at 350 lb up to 440 lb (157 to 200 kg). Because the grains were quite a bit smaller than the usual 16-inch powder, the stacking machines could not be readily used, so a dumped charge was used. For the lower charge weights, the smaller bags from reduced charges were used. When the actual firings were done, there was a pleasant surprise: pressures were much lower than expected, allowing us to fire up to a charge weight of 480 lb (218 kg) to yield a velocity of 2,628 ft/s (801 m/s). It should be noted that all calculations were made on the basis of an unworn barrel and that charge weights are assessed to yield expected *new* barrel initial velocity. When corrected for the wear state of the barrel, we found that a charge weight of 476 lb (216 kg) would give us the required D846 velocity.

While we were happy to have been able to meet our performance goals, we were troubled at the failure of our predictions to match the actual firing data. Our lumped parameter model had been so successful in predicting performance of the standard D846 charge that we were able to load out lots of ammunition based upon these predictions. What was so different here? Our charge was six bags, like the standard, but each bag held only 79 lb of dumped powder rather than 94 lb of stacked grains. Thus, our new charge had decreased permeability through the charge and larger ullage volume. Keeping in mind that each bag had a black powder ignition patch on one end, one could see that the assumption of simultaneous ignition of all surfaces incorporated in the lumped parameter code was probably far from the actual case. Simulator and NOVA code studies of artillery charge ignition and flamespread had shown some interesting effects related to ullage volumes and distributed ignition systems. Ignition did not always move from the rearmost increment forward, and significant delays between ignition of certain increments were common. Delayed ignition of some of our bags could explain the lower pressures that we saw. The lumped parameter code was exercised with fractions of the charge having various ignition delays and the calculations started to resemble the measured performance. Hopeful that this was the right tack, we applied XNOVAK to the problem and achieved a much better simulation of the performance. XNOVAK is the simple, one-dimensional express version of the NOVA code (2). The simulation shown below was achieved with no complex manipulation of inputs, thus demonstrating the importance of accounting for flamespread in large weapons with a lot of ullage. Figure 2 shows the plots of charge weight versus pressure for the actual data and the lumped parameter prediction and NOVA simulation. The lumped parameter points are as originally calculated without any ignition delays between bags.

Having been successful in the probe series of firings, we did a limited temperature coefficient series at the charge weight assessment temperature, 90 °F, and a lower firing temperature, 60 °F. Unlike Army or Air Force ammunition for which operational temperature ranges are far greater than the controlled storage conditions aboard ship, these mild temperature conditions are all that are needed to cover anticipated situations. The standard D846 round shows a temperature coefficient of 2.3 ft/s/°F, yielding a velocity decrease of 26 ft/s for this temperature differential. When we fired four rounds at each temperature, we saw only a 6-ft/s velocity decrease, giving a temperature coefficient of 0.1 ft/s/°F. This flatter temperature coefficient should make the round more forgiving of temperature variations (which should be entered into the fire control system) and thus more accurate.

The manner in which lead serves to decopper barrels is not well understood. In 1975, Robertson proposed a mechanism to explain the process (3). According to this theory, copper will be removed because the lead melts at the temperatures reached in the gun and is swept downbore, where it is deposited on the coppered bore surface. There it forms a low-melting alloy with the copper, which can be swept from the barrel by the passage of the next round. If one accepts this theory, which we did, a suitable replacement for lead would be liquid in the range of 800 to 2,200 K or so, would form a low-melting alloy with copper, and, most important, would not pose any significant safety or toxicity problems. Robertson had provided some hints of other materials which should be effective decoppering agents, though he had not considered toxicity in his criteria. One of these materials was bismuth. An examination of the literature revealed that, based upon the percentage of bismuth in low-melting bismuth/copper alloy, bismuth should prove a more efficient decoppering agent than the lead. Scanning the listings of material safety data sheets showed no significant toxic effects for bismuth or its organic salts. Indeed, bismuth compounds were often found in medicines and cosmetics. Another candidate identified by Robertson was tin, though his assessment was that bismuth should be much more effective. The Army was examining the use of tin for decoppering in the 155-mm howitzer, so we felt that our effort should not duplicate that one.

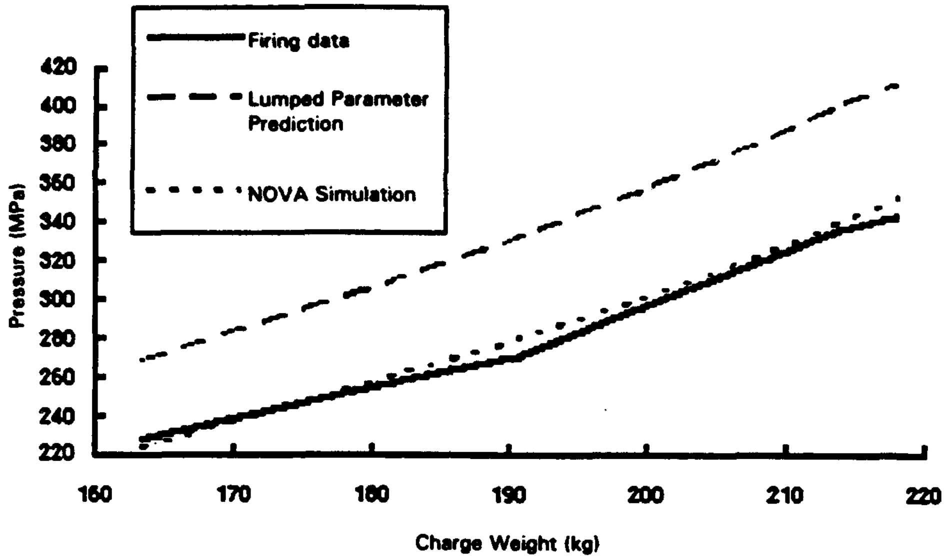

FIGURE 2. ACTUAL, PREDICTED, AND SIMULATED CHARGE WEIGHT VERSUS PRESSURE PLOTS FOR M31A1E1 IN 16-INCH, 50-CALIBER GUN

We were making new propellant for this program, so had the opportunity to include the decoppering agent in the propellant formulation as is done with NACO propellant. Our belief is that this is an inefficient way of introducing the decoppering agent. Only that material which comes in contact with the barrel surface can actually work to remove any copper, and a decoppering agent incorporated in the propellant will be evenly distributed across the bore. We believe it is better to place the decoppering agent toward the front of the charge near the chamber wall so as to introduce as much as possible into the boundary layer. Opposing arguments say that insufficient heat is transferred to the foil to melt it quickly enough to get the metal into the boundary layer; however, to our knowledge, no evidence has been presented to support this theory, while Canadian experiments in the 1950s showed that placing the lead foil in a loose do-nut [sic] improved the decoppering action (4).

Given our limited budget of time and resources, we chose to include our decoppering agent as a foil packet similar to the lead. In searching for suppliers of metallic bismuth, we discovered that pure bismuth is a rather brittle material and not suitable for making into a foil. Alloyed with 42% of tin, a foil may be made, so we purchased ribbon of this alloy from the Indium Corporation. Because of a miscalculation of the amount required for the program, we had only enough of the bismuth/tin foil decoppering agent to fire with the probe series. Two hundred grams of ribbon were used with each of the triple-base charges during the first firing series. All other shots used 400 g of lead foil. The 200-g decoppering agent weight was based upon a calculation of the amount needed to alloy the same amount of copper as alloyed by 400 g of lead.

Instrumentation used in these firings was as extensive as possible. Pressure was measured by copper crusher gauges and a piezoelectric gauge through the mushroom (in the breech). No 16-inch gun is available with pressure gauge ports along the barrel as are most other guns. An array of eleven blast gauges was placed around the muzzle of the gun to record blast overpressure against time. The nature of the flash was characterized through coverage by color video, near infrared, 3- to 5-μm forward looking infrared (FLIR) and 8- to 14-μm FLIR. Before and after each firing series, the bore of the barrel was star gauged to obtain a measure of the wear experience. Photographs were also taken of the interior of the bore, 39 inches from the origin of bore, to try to determine the effect of the bismuth/tin decoppering agent.

RESULTS AND DISCUSSION

The ballistic performance of the triple-base charge was discussed above. Little else can be said due to the very limited number of shots fired. Pressure-time curves were quite smooth as is shown in Figure 3. The velocity and standard deviation of the four low temperature shots was 2,580 ± 3.6 ft/s, while that for the four higher temperature shots was 2,586 ± 1.9 ft/s. (Remember that these are data obtained in a worn gun, hence the velocities lower than 2,690 ft/s.) These numbers, albeit based upon scant data, may be compared to the specification of ±10 ft/s. Thus, performance goals were met. What variability we saw was less than the standard charge, and the variation of performance with temperature was also less than with the standard D846 charge.

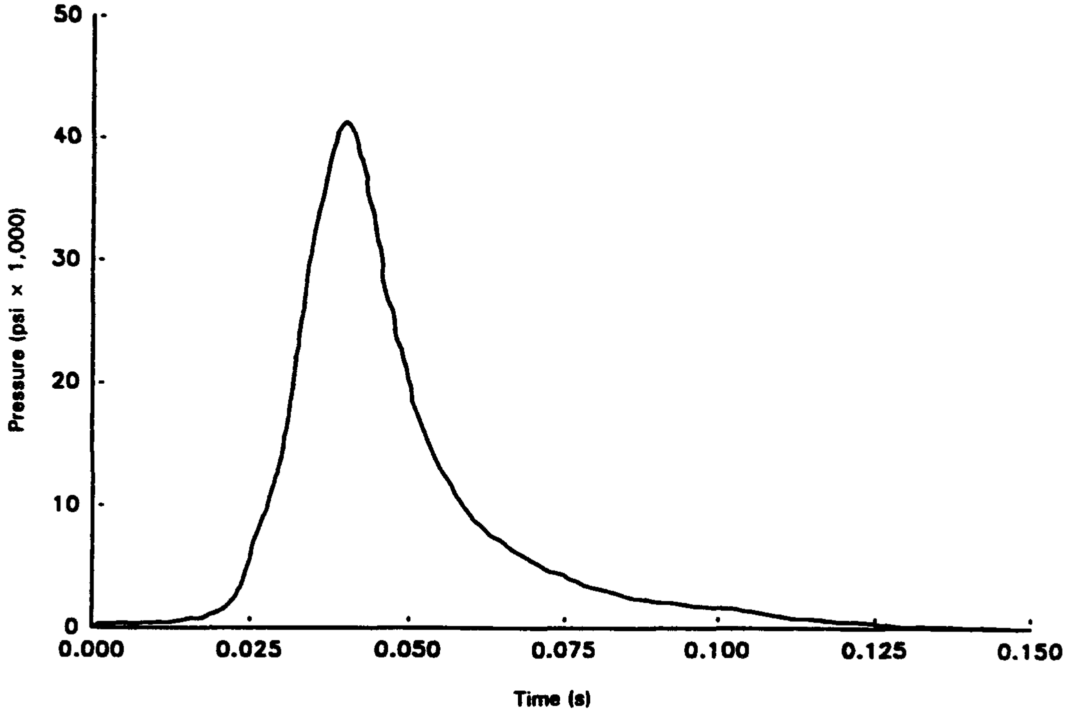

FIGURE 3. SAMPLE PRESSURE-TIME CURVE FROM 90 °F FIRING

Having fired as few rounds using the bismuth/tin foil as we did, drawing conclusions about the efficacy of that system for decoppering is difficult. Star gauge reports show that the smallest bore measurement, or bore restriction, became a bit smaller after the bismuth/tin shots were fired. After the next series of shots, the restriction opened up somewhat. The technicians who did the boroscopic examination of the barrel reported that there was some copper on the bore surface, not visibly different in amount between the different occasions, but in a different location. This observation is not supported by the star gauge reports as shown in Figure 4 which plots the measured bore diameter against the distance from the bore face for the region near the bore restriction. The deepest "valleys" on the plot are for the measurements taken after the probe firings wherein the bismuth/tin foil was used for decoppering.

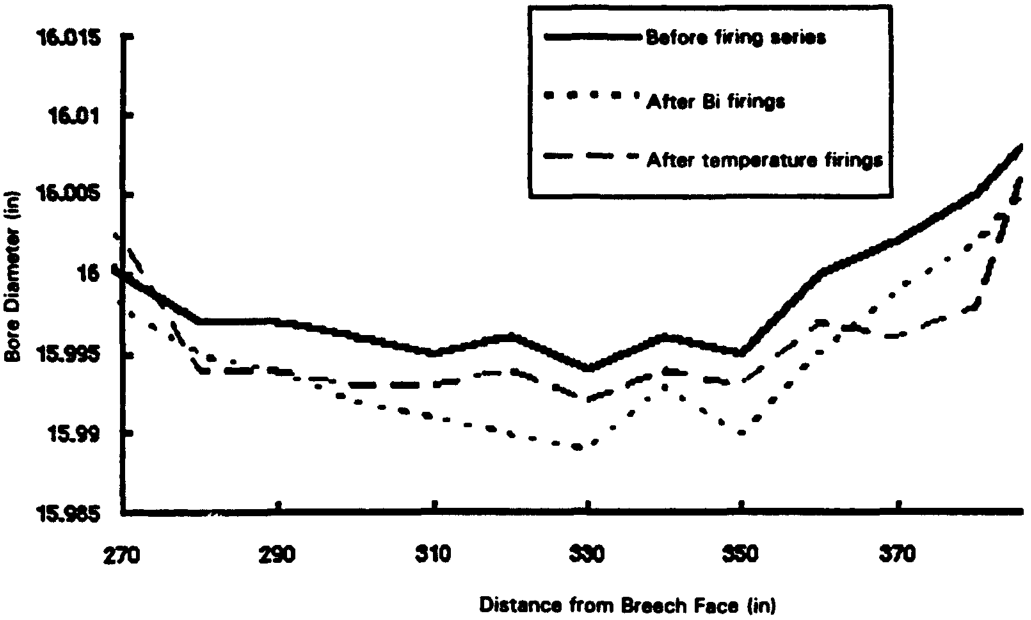

FIGURE 4. BORE DIAMETER IN REGION OF BORE RESTRICTION

The state of wear of the barrel is measured in terms of bore enlargement at the origin of bore, the position of greatest erosion. For indirect fire weapons, prediction of muzzle velocity is extremely important in achieving accurate performance. Erosion of the gun changes where the projectile seats and thus the interior ballistics for the round. If the actual state of wear is known, the fire control system can account for the wear state in determining the ballistic solution. Clearly, measuring the bore diameter accurately before every shot is impractical, so the Navy has instituted a system of shot counting to estimate the accumulated wear on the barrel. For each type of charge, a value is assigned to describe the contribution made by that round to barrel wear. These values refer to the wear incurred in firing the most erosive charge (D839) and are expressed as equivalent service rounds (ESRs). Thus, a charge's ESR may be viewed as a relative measure of its erosivity.

To assess the erosivity of our triple-base charge, we examined the star gauge records for the barrel before firing the probe series, between the probe and temperature coefficient series, and after the temperature coefficient series. By accounting for the wear imposed by the non-experimental rounds through use of their ESRs and the table of bore enlargement versus ESR, a value for the wear imparted to the barrel from the triple-base charge was determined. Between the first star gauging and the last, the following rounds were fired: four D846 rounds loaded with Pyro and equipped with wear-reducing jackets, nine triple-base rounds of varying weights, ten triple-base rounds of the assessed weight, and two D839 rounds loaded with Pyro and also sporting wear-reducing jackets. (The D839 rounds were fired to do some routine tests which are difficult to schedule, but are unrelated to this study.) The ESRs for the D846 and D839 charges, when jacketed, are 0.11 and 0.26 respectively. The original bore enlargement (difference between the actual bore diameter and 16.000 inches) was 0.230 inches; between the probe series and the temperature series, 0.234 inches; and after all the above rounds were fired, 0.246 inches.

The expected wear for an ESR of two is five-thousandths of an inch. Calculating:

0.230 in	Original bore enlargement
+0.002 in	4 (D846 × ESR of 0.11) + 2 (D839 × ESR of 0.26), which is approximately equal to 1 ESR which yields 0.002-in enlargement
0.232 in	Expected bore enlargement exclusive of triple-base charge wear
0.246 in	Measured bore enlargement after full series

Therefore 0.014 inch of wear, equivalent to 5 ESR, is attributable to the triple-base rounds. If this wear is evenly attributed to all 19 rounds, an ESR of 0.26 is found for the triple-base rounds. This number is reasonable when one considers that the ESR for an equivalent round loaded with Cordite-N (also a triple-base propellant) is 0.15. One could argue that the lower charge weight shots would not contribute as much to the wear and so should be treated differently. Indeed, reduced charges, which use about half the charge weight for shorter range, have ESRs assigned which are about one-tenth the value for the full charge. Even if one attributes all the unaccounted wear to only those charges which weighed over 440 lb, the calculated ESR is still only 0.36. Since the triple-base charges were fired without jackets, the erosivity of the charge could be fairly compared to the wear expected from *unjacketed* standard charges, which have ESRs of 0.43 and 1.00 for the D846 and D839 charges respectively. If it is desired to maintain the wear characteristics of the present rounds, some jacket or liner would be necessary.

Blast data were taken by gauges placed at the locations shown in Figure 5. The gun was elevated to three degrees for these firings, which is as low as possible to limit range while avoiding excessive ricocheting. Some gauges were lost in each firing series due to the rather rugged environment in which they are asked to operate; thus, a complete record is not available for each shot. Data were averaged over all shots at each location with only the data from the full charge weight shots being used for the triple-base shots.

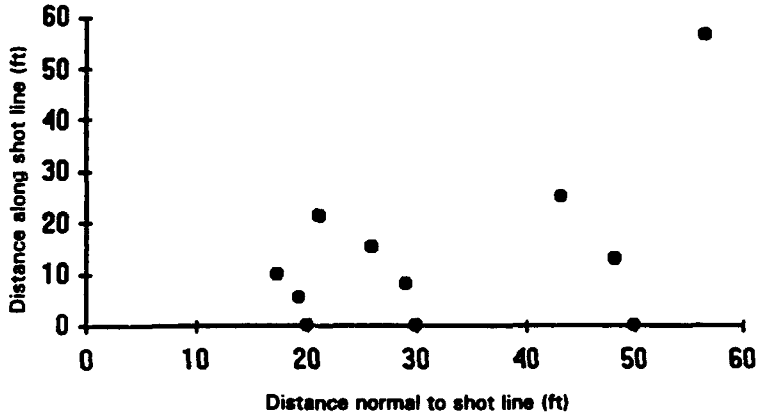

FIGURE 5. BLAST GAUGE LOCATIONS WITH RESPECT TO MUZZLE

The blast measured at each location was expressed both as the maximum pressure and the total impulse. Data were compared to unpublished isobars generated in 1981. At that time, the battleships were just coming back into service and questions arose about the effects of the gun blast on the newer, more sensitive equipment such as the Phalanx. The test series performed at that time consisted of 36 varied rounds, covering all the in-service ammunition fired from the gun at that time (which did not include the D846 charge). A more extensive blast gauge array, consisting of some 20 gauges, was used which collected data over a much greater area, both more distant and closer to the shot line as well as in the quadrant behind the muzzle. None of the gauges used in that series was as close as the gauges placed at 20 feet in our testing. Comparing our data to the 1981 data, we found that the near blast field was less severe for the 1991 shots while the farther field data were a bit higher. This may be a function of the data manipulation performed to generate isobars from rather spotty blast gauge data or from actual differences in the blast generated by these different charges. The data from the D846 shots and the triple-base shots were quite close, though the triple-base data were a bit lower. No gauge measured a pressure higher than 22 psi. Table II provides the averaged blast overpressures by gauge location for each type of round.

TABLE II. AVERAGE BLAST OVERPRESSURE

Gauge No.	Overpressure (psi)	
	Pyro	M31A1E1
P1	–	21.00
P2	15.40	12.90
P3	21.20	–
P4	10.40	8.20
P5	6.90	5.20
P6	10.90	9.30
P7	16.50	12.20
P8	5.60	4.80
P9	–	10.40
P10	10.00	8.20
P11	5.90	4.50

Characterization of the flash generated by the triple-base charges was strictly qualitative. The color video coverage seemed to be the most useful. The near infrared camera showed some difference between the two, as did the 8- to 14-μm FLIR, though no signal at all was registered by the 3- to 5-μm FLIR. Figure 6 shows the color video, near IR, and 8- to 14-μm FLIR images from the two charges at the frame in which the flash was most fully developed. The flash from the D846 charge began at the muzzle and extended for several lengths of the barrel. The triple-base charge effluent did not ignite at the muzzle, but rather some distance from it, then the somewhat spherical region of intense flame moved out from the muzzle. The triple-base flash was of noticeably shorter duration. The flame temperatures of the two propellants were similar, so the difference in behavior must lie elsewhere. M31A1E1 includes 1.25% of potassium sulfate, a flash reducer, while Pyro does not. The triple-base charge is also about 100 lb lighter than the D846, so there is less gas to burn, helping to explain the smaller volume of flash. The lower signature of the triple-base charge could not be called "flashless," but ought to be helpful in minimizing any effects on ship's sensors.

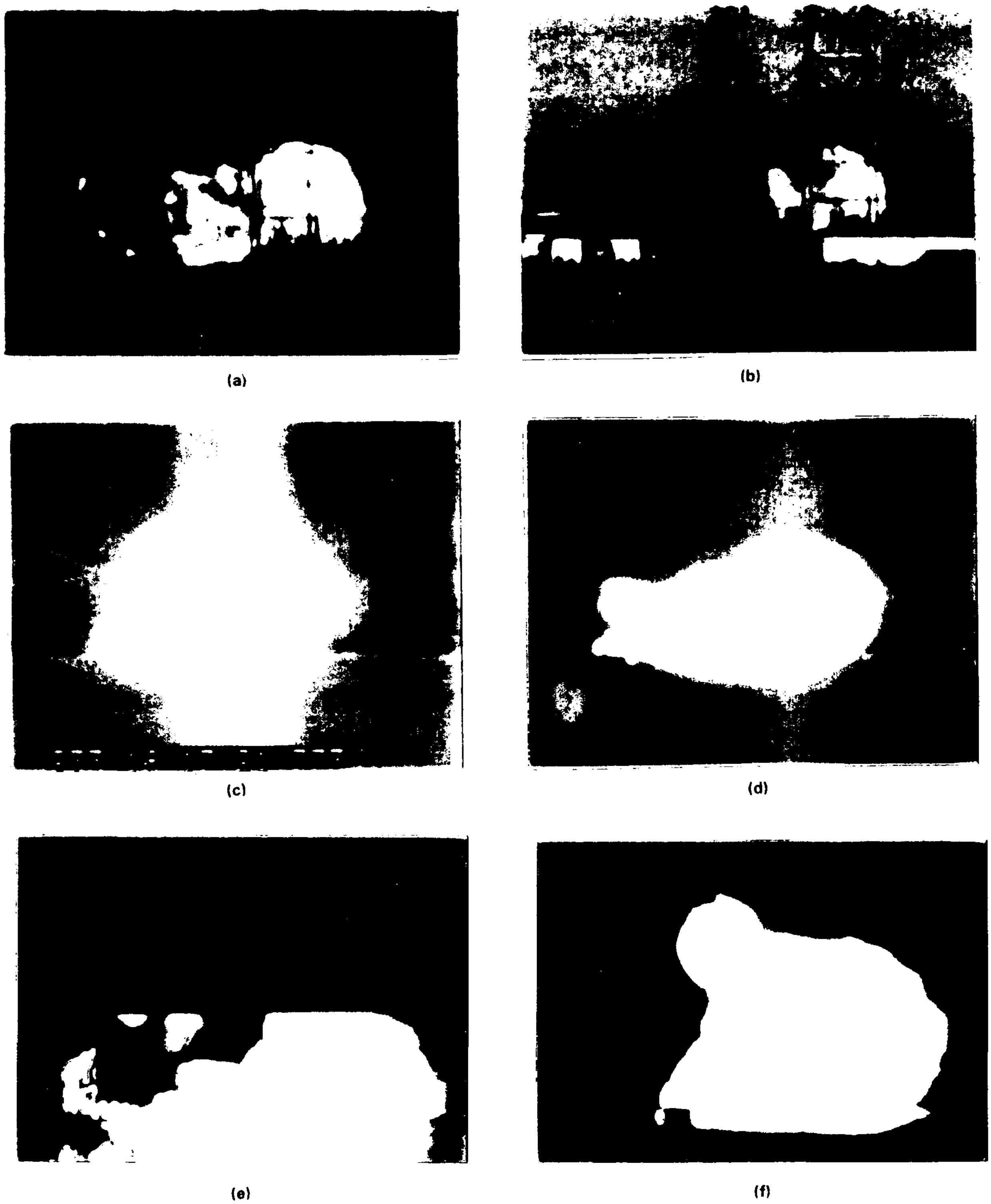

FIGURE 6. (a) PYRO CHARGE FLASH, COLOR VIDEO, (b) TRIPLE-BASE CHARGE FLASH, COLOR VIDEO, (c) PYRO CHARGE FLASH, NEAR IR, (d) TRIPLE-BASE CHARGE FLASH, NEAR IR, (e) PYRO CHARGE FLASH, 8- TO 14-μm FLIR, (f) TRIPLE-BASE CHARGE FLASH, 8- TO 14-μm FLIR

CONCLUSIONS AND RECOMMENDATIONS

Within the limited scope of this study, the triple-base propellant, M31A1E1, worked quite well as a potential replacement for Pyro in a D846 charge. The velocity of the D846 charge was achieved with a significantly lower charge weight due to the granulation's being designed for the round. The temperature coefficient was lower, which should aid in accuracy and improve performance in ambient temperature firings, since the magnitude of correction for the difference in temperature between assessment and actual firings will be lower than for the standard charge. The limited reproducibility data available are promising. The very low level of solvent in the propellant also speaks well for long-term reproducibility and predictability. The good performance achieved here at low charge weight means that greater performance [illegible]sible at the cost of a new grain design and modifications to the fire control system.

The level of wear observed was less than that of a bare Pyro charge, but more than for a jacketed charge. Use of a jacket or, preferably, a liner with the M31A1E1 charge is recommended to extend the life of the barrels. The bismuth/tin alloy *was not ineffective* in decoppering the barrel, though the data are so scarce, little more can be said. Inclusion of the decoppering agent in the form of powdered bismuth as part of a liner would seem an excellent approach, since this would put the decoppering agent in the boundary layer where it can do the most good. It would eliminate one step in the loading of the gun, the placing of the lead foil between the two forward bags. Putting the decoppering agent into a liner would also allow the use of pure bismuth, which should be more effective than its alloy with tin. Thus the liner would serve to not only reduce wear to the barrel, but coppering as well, making it a *barrel-conditioning* liner.

It appears that a simple lumped parameter model must be used with caution when changing charge weights and configurations significantly. Here we altered charge weight and thereby ullage, while at the same time we lowered the bed permeability because of the change from a stacked to a dumped charge. The more sophisticated calculation carried out by XNOVAK was able to simulate the long ignition delays between bags and, so, the lower peak pressures that we actually saw. Had we had the insight to do this calculation prior to firing, we could have saved ourselves some effort.

Should the need arise to provide the battleships with a new charge to fire the 1,900-lb projectile, M31A1E1 would be an excellent choice. The granulation should be revisited based upon the firings done under this study, but that is a routine matter, done as a matter of course when a lot of propellant is made which has been out of production for some time. Dumped charges loaded into bags with bismuth-containing, barrel-conditioning liners offer savings in logistics as well as improvements in performance and environmental aspects.

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Dahlgren, VA 22448 1

Commander
Naval Surface Warfare Center
Dahlgren Division
Attn: Technical Library
Dahlgren, VA 22448 1

Director
Army Research Laboratory
Attn: Technical Library
Aberdeen Proving Ground, MD 21005-5066 1

Commander
U.S. Army Armament Research,
Development and Engineering Center
Attn: SMCAR-AEE-BR (Rutkowski)
Picatinny Arsenal, NJ 07806-5000 1

Commander
U.S. Army Armament Research,
Development and Engineering Center
Attn: Technical Library
Picatinny Arsenal, NJ 07806-5000 1

Commander
Naval Sea Systems Command
Attn: SEA-91W2
Washington, DC 20361 1

Hercules, Inc.
Technical Library
Radford, VA 24141 1

Administrator
Defense Technical Information Center
Attn: DTIC-OCC
Cameron Station, Bldg. 5
Alexandria, VA 22304-6145 2

JHU/CPIA
Attn: Security Officer
10630 Little Patuxent Parkway, Ste. 202
Columbia, MD 21044-3200 1

Internal:

102	1
6210	5
8510	3
8530	3