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**AFATL-TR-76-152**

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# OPTIMUM RIFLING FOR PLASTIC BANDS

AERONUTRONIC DIVISION
AERONUTRONIC FORD CORPORATION
FORD ROAD
NEWPORT BEACH, CALIFORNIA 92663

DECEMBER 1976

FINAL REPORT: APRIL-OCTOBER 1976

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A six-month program was conducted to more conclusively determine which rifling configuration is best suited for use with high velocity medium caliber projectiles with plastic rotating bands. The program consisted of fabricating a test barrel and plastic banded projectiles and conducting test firings on five different rifling designs at -65°F, ambient temperature, and +165°F using progressively narrower rotating bands. The results showed that a sawtooth configuration and a modified conventional 18-groove design were superior to the other conventional and modified conventional designs evaluated.

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# SUMMARY

The primary objective of the program was to conclusively determine which rifling configuration is best suited for use with high velocity, medium caliber projectiles with plastic rotating bands. The program was a follow-on effort to Contract F08635-75-C-0041 that provided analytical data, 20mm candidate rifling designs, test barrels, and limited test data indicating potential advantages of non-conventional rifling configurations.

The program consisted of fabricating an additional 20mm test barrel per Air Force design and applying plastic rotating bands to 20mm projectiles. The projectiles were fired at -65°F, ambient temperature, and +165°F through the new barrel, and four others which were residual from the previous contract. The barrel rifling designs tested consisted of:

(a) Conventional M61 (9 grooves)

(b) Modified conventional - 12 (12 grooves)

(c) Choked modified conventional - 12 (12 grooves)

(d) Modified conventional - 18 (18 grooves)

(e) Sawtooth (18 grooves)

A test matrix was developed to include incrementally smaller rotating band widths, such that each barrel could be rated with respect to its effects on plastic rotating band performance. Muzzle velocity, accuracy, chamber pressure, and in-flight microflash photographs were used as evaluation criteria. The data indicated that the modified conventional - 18 and the sawtooth configurations showed significant improvements with respect to band performance. The former configuration appeared to be best of all under the conditions tested. Additional data and analysis would be helpful to further develop an optimum rifling design and the methodology for extrapolating this technology to other medium caliber high performance weapons.

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# PREFACE

This report was prepared by Aeronutronic Ford Corporation, Aeronutronic Division, Newport Beach, California 92663 under Contract No. F08635-75-C-0204 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida, 32542. The report covers work performed from April 1976 to October 1976. Mr. David G. Uhrig was the program manager for the Armament Laboratory.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER:

GERALD P. D'ARCY, Colonel USAF
Chief, Guns, Rockets, and Explosives Division

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# SECTION I

# INTRODUCTION

Until recently, little attention has been devoted to the effects of rifling geometry on the performance of metal or plastic rotating bands. The traditional rectangular-shaped rifling grooves have historically been varied in number and dimensions for the numerous weapon requirements throughout the world, but departure from the rectangular shape had not been systematically evaluated until 1975 as a result of Contract No. F08635-75-C-0041 with the Air Force Armament Laboratory. During this contract, limited 20mm data were developed that indicated significant beneficial effects could be obtained from certain non-standard rifling geometries for use with plastic rotating bands, particularly a sawtooth configuration. This work also indicated that slightly choked rifling and/or an increased number of rifling grooves should be further evaluated.

In April 1976 the Air Force awarded Contract F08635-76-C-0204 with the objective of determining conclusively which rifling configuration is best suited for use with high velocity, medium caliber projectiles with plastic rotating bands. This report documents the work performed on this contract. Sections II through IV present details of the rifling configurations, barrel and projectile fabrication, laboratory tests, and test firings. Conclusions and recommendations are presented in Section V.

# SECTION II

# BARREL FABRICATION

## 2.1 RIFLING CONFIGURATIONS

The rifling design profiles utilized for this program, which are shown in Figure 1, consisted of:

a. Conventional M61 barrel (9 rectangular grooves)

b. Modified Conventional - 12 (12 grooves)

c. Choked Modified Conventional - 12 (12 grooves with decreasing groove depth)

d. Sawtooth - 18 (18 grooves)

e. Modified Conventional - 18 (18 grooves)

All these configurations (except modified conventional-18) were supplied as GFE barrels residual from Contract F08635-75-C-0041, and the rationale involved in their selection is reported in the final report for that contract, AFATL-TR-75-153, Optimum Rifling Configuration for Plastic Rotating Bands, dated November 1975.

The modified conventional - 18 configuration was produced on this contract. This 18-groove design was selected to more closely evaluate rectangular versus sawtooth groove shape effects by directly comparing rifling of each shape fabricated with the same number of grooves and the same interference ratios. The modified conventional - 18 design was also to provide a further assessment of 9 versus 12 versus 18 rectangular grooves.

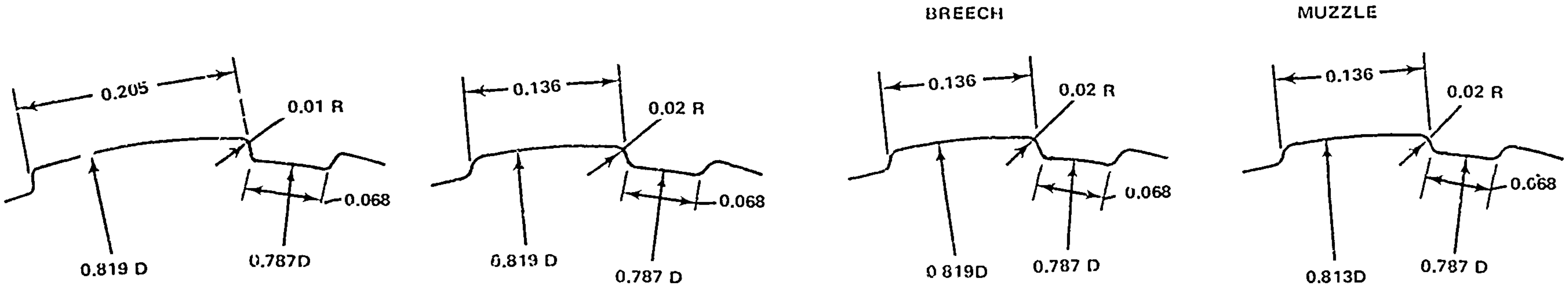
All barrels, including the new modified conventional - 18, were fabricated to include the standard M61 exponential gain twist per Rock Island Arsenal Drawing 7790801, "Barrel", dated 5 May 1960.

## 2.2 BARREL MATERIAL

In order to minimize the number of variables in generating comparative data, the same material was used for the new modified conventional - 18 barrel as was used for the GFE barrels, residual from Contract F08635-75-C-0041. The material used was purchased in the form of M61 heat treated and rough contoured gun-drilled, barrel blanks meeting MIL-S-46047. A spot check of the hardness indicated $R_c35$ which was within the $R_c$ 32-37 range specified on Rock Island Arsenal Drawing 7790801, "Barrel", dated 5 May 1960.

## 2.3 SHORT-LENGTH BARREL SECTION

A section was cut from a M61 barrel blank to provide material for producing the short length section for laboratory tests. Prior to cutting, the blank



A. CONVENTIONAL

N = 9

B. MODIFIED CONVENTIONAL - 12

(CONSTANT GROOVE DEPTH) N = 12

C. CHOKED MODIFIED CONVENTIONAL - 12

(DECREASING GROOVE DEPTH) N = 12

D. SAWTOOTH-18

N = 18

E. MODIFIED CONVENTIONAL - 18

N = 18

(N = NUMBER OF LANDS)

Figure 1. Rifling Configurations

was honed to meet the bore dimensions of the M61 barrel after chrome plating, i.e., 0.786+0.003 inch. The approach for this laboratory barrel section was not to chrome plate in the interest of economy and schedule. A conventional broaching technique utilizing a series of two-groove cutters was utilized.

## 2.4 FULL-LENGTH TEST BARREL

The standard M61 barrel blanks described in paragraph 2.2 were honed from the as-received ID of 0.779 inch to 0.783 inch and rifled by conventional broaching, utilizing the same tooling as for the short length barrel sections. The bore and rifling groove depth dimensions were adjusted to compensate for subsequent electropolishing and chrome plating to the specified dimensions.

# SECTION III

# PROJECTILE FABRICATION

## 3.1 PROJECTILE CONFIGURATION

The basic projectile and rotating band utilized for this program are shown in Figure 2. Standard 20mm M56 HEI projectile bodies with machined band seats were supplied by the government. The rotating bands were molded and cured to the proper diameter, then the forward and aft angles were machined. The narrower band widths were achieved by machining back the forward side at the same 20° angle.

The following paragraphs describe the materials and processes which were used in fabricating the adhesive bonded plastic rotating band for the 20mm projectiles which were used in this program. The process is documented utilizing a specification format.

## 3.2 PROJECTILE SURFACE PREPARATION

1. Vapor degrease in perchloroethylene (250°F).

2. Grit blast the recessed band seat with clean dry #120 alumina using clean dry air.

3. Vapor degrease in perchloroethylene (250°F for 5 minutes minimum).

4. Ultrasonic clean in prebond 700 caustic solution (283 grams/gallon of water) for a minimum of 5 minutes at 200 ±10°F.

5. Rinse in deionized water with ultrasonic agitation for a minimum of 5 minutes at 190 ±10°F.

6. Rinse twice in acetone.

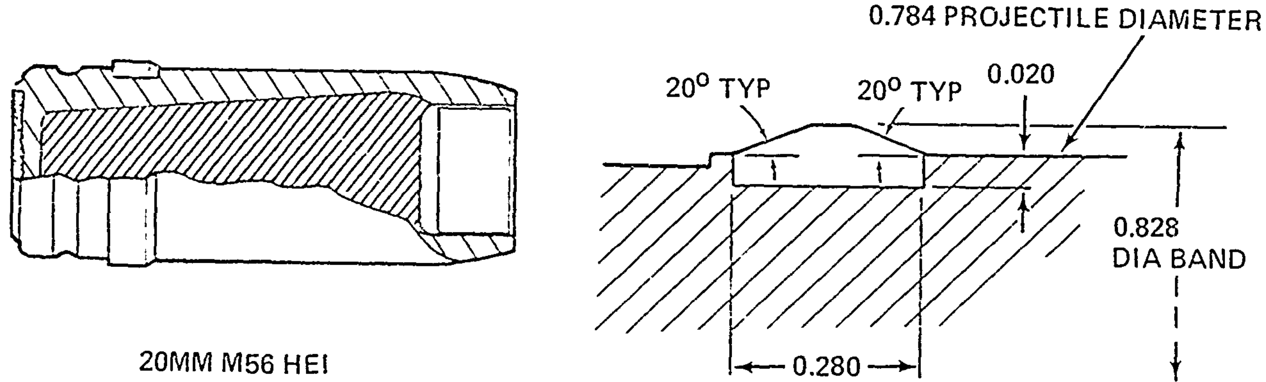
7. Apply a uniform coating of DuPont's P-5 10 percent solids primer to projectile recessed band seat area by dipping. A thickness of 0.003 inch to 0.004 inch is recommended.

NOTE: Paragraphs 3 through 7 should be conducted in a continuous operation. The projectile should not be allowed to dry between any step of the processing.

8. Store projectiles in a non-contaminated atmosphere for a minimum of 24 hours and a maximum of 72 hours.

## 3.3 ADHESIVE APPLICATION

1. Apply one ply of American Cyanamid FM1000 film adhesive to the recessed area band seat. The film thickness is 0.003 inch and weighs



20MM M56 HEI
PROJECTILE WITH
PLASTIC BAND

BASELINE BAND
PHYSICAL CONFIGURATION

Figure 2. Projectile and Band Configuration

$0.015\ lb/ft^2$. The adhesive may be butt-overlapped a maximum of 0.060 inch. Heat tack the overlapped film area together.

2. Store the adhesive-covered projectile in a contamination-free package below 80°F until injection molded. Injection molding must occur within 3 days after adhesive application.

## 3.4 INJECTION MOLDING

1. Vacuum-dry Zytel 158 nonlubricated nylon to 0.060 ±0.02 percent moisture content.

2. Preheat the adhesive-coated projectile at 150 ±10°F for a total time of 10 minutes.

3. Position the adhesive-coated projectile in a 150 ±10°F mold and injection mold using processing conditions which are applicable to the particular injection molding machine and the Zytel 158.

4. Remove projectile from mold and cool to room temperature. Place the projectile in the steel retaining ring, fill cavity with glass beads, and cure in a preheated oven for 90 minutes at 345 ±10°F.

5. Cool to room temperature, remove retaining ring, and final machine the plastic band to the required dimensions.

## SECTION IV

## TESTING AND EVALUATION

### 4.1 TEST PROCEDURE

The testing phase of the program was planned to provide extensive firing data with varying band widths and band soaking temperatures in order to compare the ballistic performance associated with each of the five barrel designs described in Section II. The barrels were installed in a firing fixture (Figure 3) at the contractor's range facility. The instrumentation for the tests illustrated in Figure 4 included barrel pressure, velocity screens, microflash camera, and a target at 1000 inches.

Evaluation of the test results included comparisons of accuracy, muzzle velocity, projectile stabilization, and evaluation of rotating band condition from microflash photographs.

The general plan was to initially fire a series of projectiles with the standard 0.280-inch rotating band width illustrated in Figure 2 through each barrel. Following this, additional series were fired with narrower rotating bands (reduced an additional 0.020 inch for each successive series), and so on, until at least 50 percent of the bands failed.

The tests were conducted according to the matrix shown in Table 1. Initially, the 0.280-inch band width was tested; then in order to more quickly bracket the acceptable/nonacceptable band performance, the 0.180-inch width was fired. Following this, the additional matrix was developed to determine the minimum acceptable width for each barrel at each test temperature.

The projectiles were fired at a weight of ~84 grams which was achieved by attaching M505 metal fuze parts to the tip. The standard M61 20mm cases were hand-loaded with 42 grams of WC870 propellant. A microflash unit was utilized to simultaneously take photographs with a standard Polaroid camera as well as 35mm. Velocity measurements were taken at two ten-foot locations (and averaged for reporting purposes).

### 4.2 TEST RESULTS AND ANALYSIS

The candidate rifling configurations were evaluated based upon assessment of accuracy, muzzle velocity, band integrity, and projectile stability which is primarily an indicator of gross band failure. Under all test conditions, all rifling configurations delivered comparable accuracy and muzzle velocity performance. The summary of velocity performance and chamber pressure obtained for all shots is contained in Table 2. The average velocity spread at each of the three test temperatures between all barrel configurations and

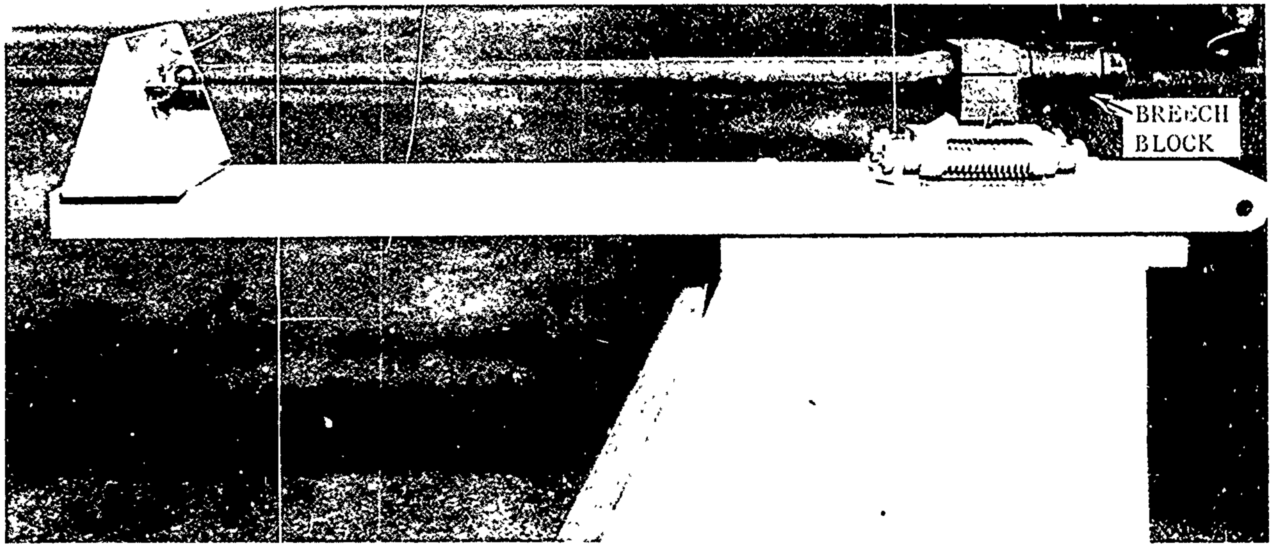


Figure 3. Test Firing Fixture

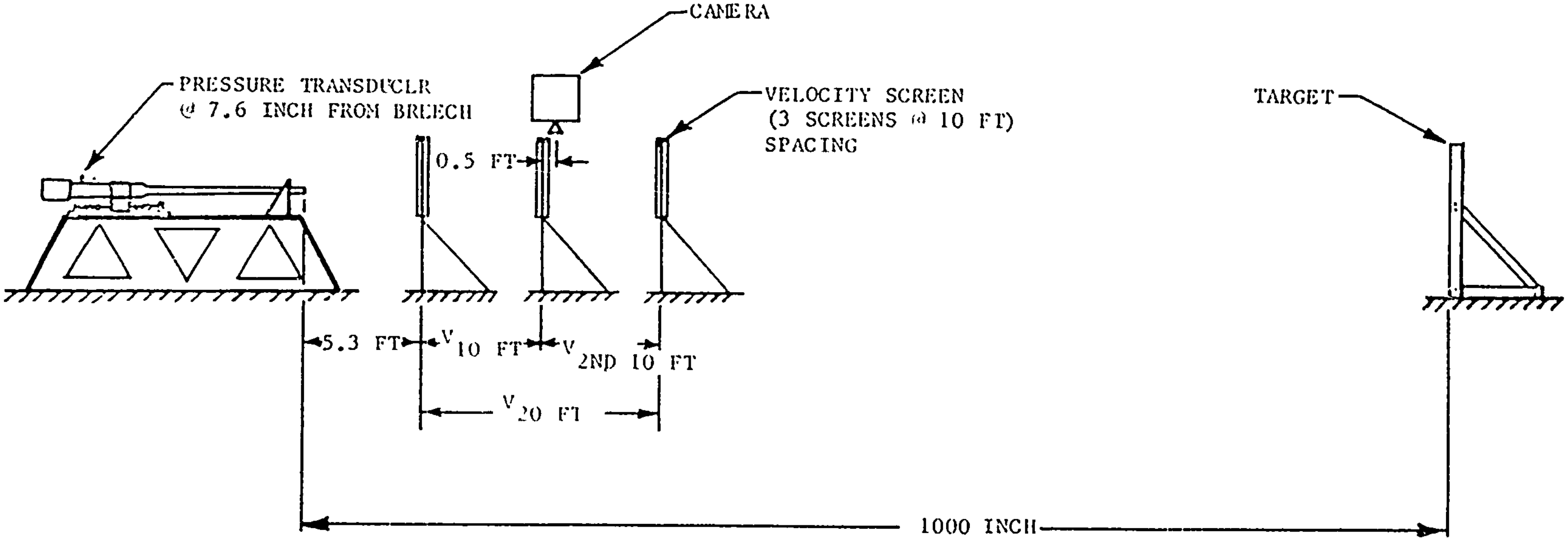


Figure 4. Test Set-up

## TABLE 1. TEST MATRIX

| | TEST TEMPERATURE | | | NUMBER OF PROJECTILES FOR EACH ROTATING BAND WIDTH | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Barrel | -65°F | +70°F | +165°F | 0.280" | 0.260" | 0.240 | 0.220" | 0.180" | 0.160" | 0.140" |
| Conventional | X | | | 10 | | | | 10 | 10 | 10 |
| | | X | | 10 | | | | 10 | 10 | 10 |
| | | | X | 10 | 10 | 10 | | 10 | | |
| Modified Conventional - 12 | X | | | 10 | | | 10 | 10 | 10 | 10 |
| | | X | | 10 | | | | 10 | 10 | 10 |
| | | | X | 10 | 10 | 10 | 10 | 10 | | |
| Choked Modified Conventional - 12 | X | | | 10 | | | 10 | 10 | | 10 |
| | | X | | 10 | | | 10 | 10 | 10 | 10 |
| | | | X | 10 | 10 | 10 | 10 | 10 | | |
| Modified Conventional - 18 | X | | | 10 | | | | 10 | | 10 |
| | | X | | 10 | | | | 10 | | 10 |
| | | | X | 10 | | | 10 | 10 | 10 | 10 |
| Sawtooth - 18 | X | | | 10 | | | | 10 | 10 | 10 |
| | | X | | 10 | | | | 10 | | 10 |
| | | | X | 10 | | | | 10 | 10 | 10 |

## TABLE 2. TEST FIRING RESULTS

| BARREL | BAND WIDTH (in.) | MEAN VELOCITY (fps) | MEAN PRESSURE (ksi) | PHOTO (*) | MEAN VELOCITY (fps) | MEAN PRESSURE (ksi) | PHOTO (*) | MEAN VELOCITY (fps) | MEAN PRESSURE (ksi) | PHOTO (*) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | -65°F | | | ambient | | | 165°F | | |
| CONVENTIONAL - 9 | 0.280 | 3417 | 39 | OK | 3624 | 47 | OK | 3765 | 60 | OK |
| | 0.260 | | | | | | | 3775 | 49 | OK |
| | 0.240 | | | | | | | 3691 | 49 | M |
| | 0.180 | 3406 | 43 | OK | 3620 | 53 | OK | 3767 | 62 | P |
| | 0.160 | 3352 | 38 | OK | 3602 | 51 | OK | | | |
| | 0.140 | 3374 | 36 | OK | 3606 | 50 | P | | | |
| CONVENTIONAL - 12 | 0.280 | 3432 | 41 | OK | 3651 | 55 | OK | 3780 | 61 | OK |
| | 0.260 | | | | | | | 3774 | 59 | OK |
| | 0.240 | | | | | | | 3770 | 60 | M |
| | 0.220 | 3448 | 37 | OK | | | | 3795 | 58 | M |
| | 0.180 | 3434 | 41 | OK | 3647 | 51 | OK | 3770 | 60 | P |
| | 0.160 | 3388 | 38 | OK | 3650 | 54 | OK | | | |
| | 0.140 | 3391 | 42 | OK | 3594 | 51 | P | | | |
| CONVENTIONAL - 12 CHOKED | 0.280 | 3425 | 40 | OK | 3692 | 55 | OK | 3783 | 58 | OK |
| | 0.260 | | | | | | | 3763 | 62 | OK |
| | 0.240 | | | | | | | 3773 | 63 | M |
| | 0.220 | 3435 | 37 | OK | 3641 | 54 | OK | 3788 | 57 | P |
| | 0.180 | 3429 | 39 | OK | 3618 | 48 | OK | 3791 | 63 | P |
| | 0.160 | | | | 3650 | 52 | M | | | |
| | 0.140 | 3402 | 43 | OK | 3647 | 53 | P | | | |
| CONVENTIONAL - 18 | 0.280 | 3413 | 40 | OK | 3623 | 50 | OK | 3771 | 63 | OK |
| | 0.220 | | | | | | | 3682 | 57 | OK |
| | 0.180 | 3421 | 43 | OK | 3630 | 50 | OK | 3760 | 62 | OK |
| | 0.160 | | | | | | | 3775 | 58 | M |
| | 0.140 | 3425 | 43 | OK | 3594 | 51 | OK | 3771 | 62 | M |
| SAWTOOTH - 18 | 0.280 | 3440 | 43 | OK | 3618 | 51 | OK | 3788 | 68 | OK |
| | 0.180 | 3430 | 42 | OK | 3617 | 50 | OK | 3767 | 67 | OK |
| | 0.160 | 3428 | 49 | OK | | | | 3793 | 61 | M |
| | 0.140 | 3406 | 40 | OK | 3646 | 55 | OK | 3744 | 58 | P |

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*OK = satisfactory
P = poor
M = marginal

band widths was of the order of 40 fps. Even those projectiles with narrow bands that showed lack of stability showed velocities comparable with the others. Similarly, no trends could be observed by analysis of the chamber pressure data.

Table 3 presents a summary of the data taken from the individual targets for each series positioned at 1000 inches from the muzzle. The dispersion was calculated by circumscribing a minimum diameter circle around all the holes on each target. The yaw was determined by counting eliptically shaped holes of dimensions that indicated $\geq 15^\circ$ yaw. As can be seen from the data, no trend could be observed from the dispersion data. The variations that were observed probably could be best explained by the soft mount that was used, and that the barrels were flight weight rather than Mann barrels. The yaw data generally showed less projectile stability at decreasing band widths and at the +165°F test temperatures as would be expected.

The most meaningful data were the in-flight microflash photographs summarized in Table 2. Figure 5 shows typical effects of band width for each of the five barrels. This typical ambient temperature series showed uniform distinct grooves in the 0.180-inch wide bands from all barrels with no evidence of slippage or shearing, but the 0.140-inch showed poorly defined grooves and evidence of incomplete spin-up on the conventional, modified conventional -12, and choked modified conventional -12 barrels. The other two barrels showed good band performance at ambient temperature, even at the minimum (0.140-inch) band width. Figure 6 shows typical effects of test temperature. The +165°F test temperature revealed considerable wiping and/or smearing of the bands, again showing the improved performance of the sawtooth and modified conventional - 18 barrels. Since in all cases, the sawtooth and modified conventional - 18 barrels outperformed the other three, careful attention was paid to ranking these two barrels with respect to each other. Figure 7 shows that the modified conventional - 18 barrel gave better results at +165°F, all other comparisons being equivalent. Further work to determine which barrel could best accommodate larger diameter bands would be beneficial. (Maximum diameter bands offer a greater potential for compensating for barrel erosion and thermal growth.) Contract F08635-75-C-0041 indicated that sawtooth rifling was effective over a broader range of band diameters than the others.

To summarize, the data in Table 2 indicate that the 18-groove modified conventional and sawtooth barrels result in significantly better performance with respect to temperature and band width than the other three configurations. For these particular conditions, the modified conventional - 18 barrel appears to offer the best overall performance, although more testing to determine relative acceptable band diameters and erosion life effects would be of value.

## TABLE 3. ACCURACY DATA

| Band Width (in.) | Test Temp. (°F) | Conv -9 Disp.* (in.) | Conv -9 Yaw (% ≥15) | Mod. Conv. - 12 Disp.* (in.) | Mod. Conv. - 12 Yaw (% ≥ 15) | Choked Mod. Conv. - 12 Disp.* (in.) | Choked Mod. Conv. - 12 Yaw (% ≥ 15) | Mod. Conv. - 18 Disp.* (in.) | Mod. Conv. - 18 Yaw (% ≥ 15) | Sawtooth -18 Disp.* (in.) | Sawtooth -18 Yaw (% ≥ 15) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.280 | -65 | 4.6 | - | 5.8 | - | 3.5 | - | 4.9 | - | 3.7 | - |
| | Ambient | 4.8 | - | 3.9 | - | 3.0 | - | 4.6 | - | 3.6 | - |
| | +165 | 4.4 | - | 3.0 | 10 | 4.4 | - | 5.2 | - | 4.0 | - |
| 0.260 | -65 | | | | | | | | | | |
| | Ambient | | | | | | | | | | |
| | +165 | 6.5 | - | 5.7 | 10 | 5.3 | - | | | | |
| 0.240 | -65 | | | | | | | | | | |
| | Ambient | | | | | | | | | | |
| | +165 | 5.3 | - | 3.9 | - | 5.4 | 10 | | | | |
| 0.220 | -65 | | | 4.5 | - | 4.1 | 10 | | | | |
| | Ambient | | | | | 4.4 | - | | | | |
| | +165 | | | 4.3 | - | 6.3 | 10 | 3.3 | - | | |
| 0.180 | -65 | 4.8 | 10 | 2.25 | 10 | 4.8 | 10 | 6.2 | 10 | 6.3 | 10 |
| | Ambient | 4.1 | 20 | 3.87 | 20 | 4.2 | 10 | 4.3 | 20 | 5.9 | 20 |
| | +165 | 4.6 | - | 2.5 | 20 | 3.6 | 10 | 4.5 | 30 | 4.0 | 30 |
| 0.160 | -65 | 4.3 | 10 | 6.5 | - | | | | | 4.4 | 10 |
| | Ambient | 4.5 | 20 | 5.4 | 20 | 4.4 | 10 | | | | |
| | +165 | | | | | | | 4.7 | 30 | 5.8 | 20 |
| 0.140 | -65 | 5.3 | 20 | 5.7 | 20 | 5.8 | 20 | 5.8 | 20 | 6.6 | 10 |
| | Ambient | 4.7 | - | 5.2 | 30 | 6.2 | 20 | 4.3 | 10 | 8.4 | 20 |
| | +165 | | | | | | | 4.4 | 20 | 4.9 | 20 |

* Dispersion

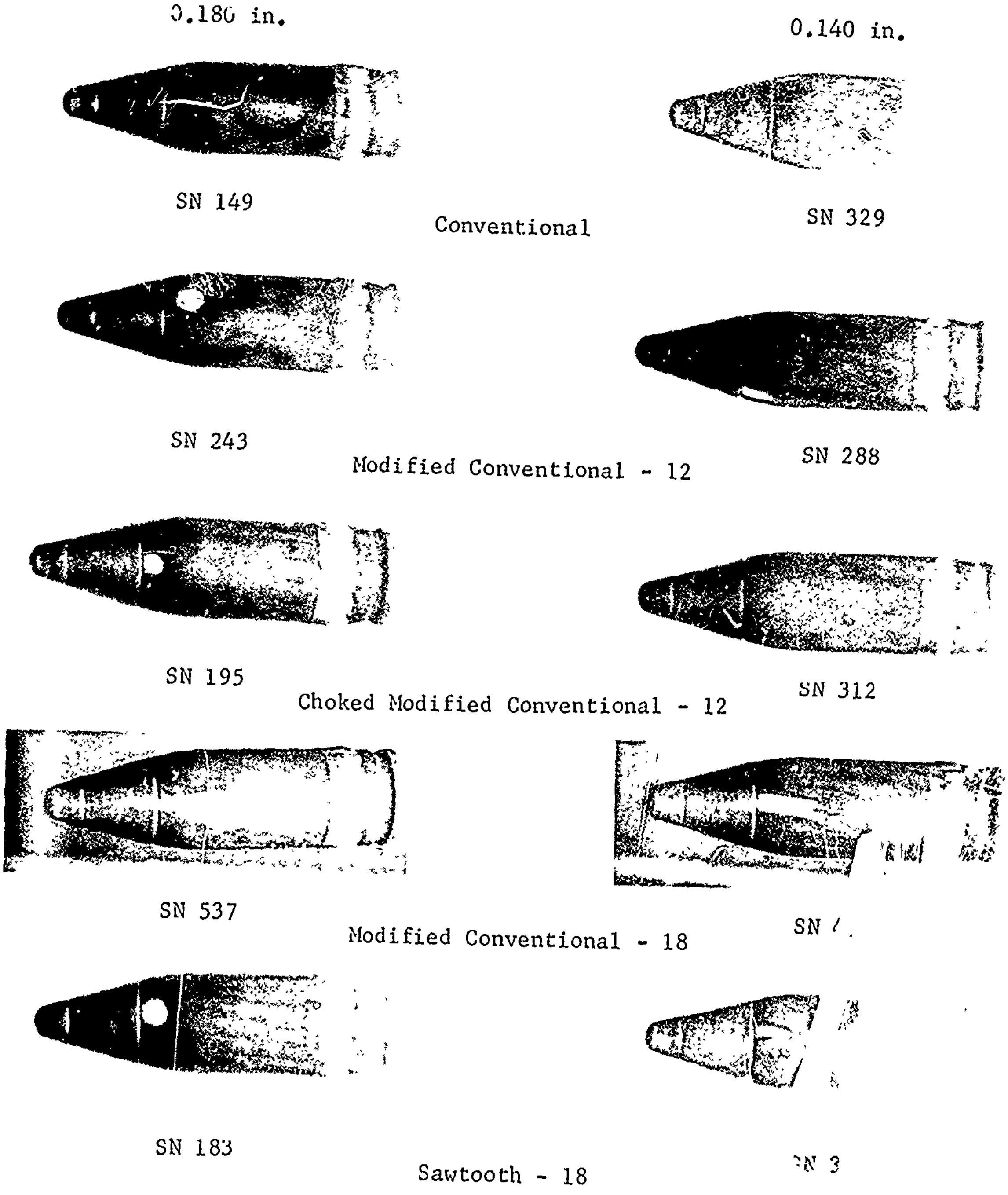
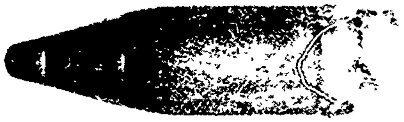


Figure 5. Effects of Band Width (Ambient Temperature)

AMBIENT

+165°F

SN 149



SN 176

Conventional

SN 243

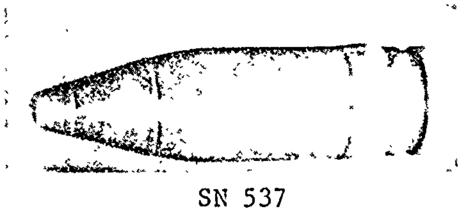
SN 265

Modified Conventional - 12

SN 195

SN 213

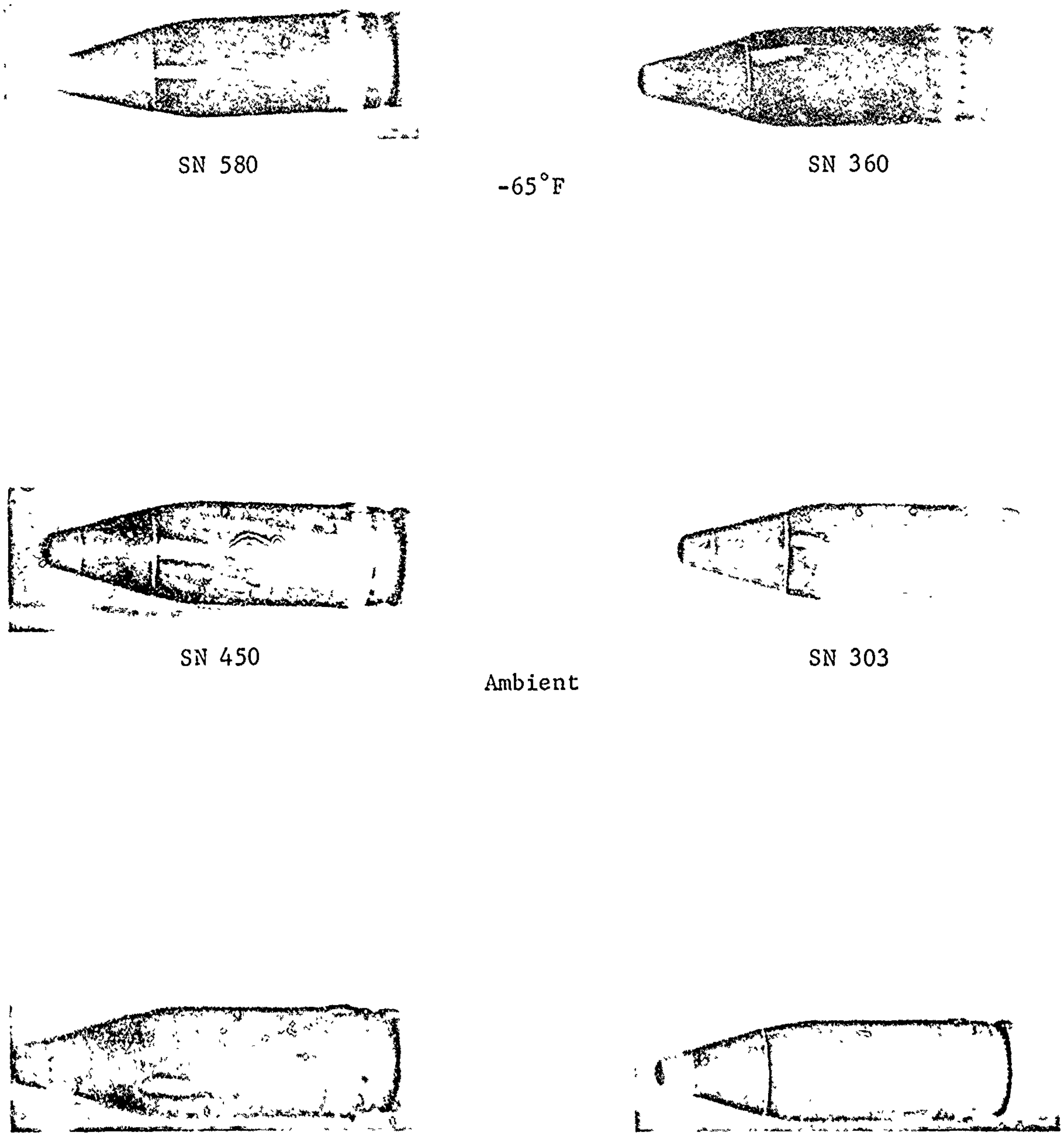
Choked Modified Conventional - 12



SN 537

SN 681

Modified Conventional - 18


Modified Conventional - 18

Sawtooth-18

SN 580

-65°F

SN 360

SN 450

Ambient

SN 303

SN 681

+165°F

SN 728

Figure 7. Comparison of Modified Conventional - 18 and Sawtooth - 18 (0.140 Band Width)

## 4.3 LABORATORY TESTS

In order to supplement the test data discussed above, laboratory testing of plastic rotating bands within short barrel sections of the sawtooth and modified conventional - 18 configurations was conducted under low and high strain rate conditions. Two basic types of tests were conducted: (a) engraving tests and (b) torsion tests. Previous data and a description of the testing apparatus are given in AFATL-TR-75-153, Optimum Rifling Configuration for Plastic Rotating Bands, dated November 1975.

The data, shown in Table 4 indicated slightly higher engraving stresses for the sawtooth barrel compared to the modified conventional - 18 at high and low strain rates, although the torsion results were nearly identical. More data including elevated temperature effects may be worthwhile for future related efforts.

TABLE 4. LABORATORY TEST RESULTS OF MODIFIED CONVENTIONAL - 18 AND SAWTOOTH - 18

Engraving Tests

| | Strain Rate (in./min) | Load (lb) | Energy (ft-lb) | Travel (in.) | Ratios (lb/in.) | Ratios (ft-lb/in.) |
|---|---|---|---|---|---|---|
| Sawtooth - 18 | 11,500 | 2150 | 169 | 2.88 | 746 | 62 |
| | 0.5 | 2765 | * | * | * | * |
| Mod. Con. - 18 | 11,500 | 1500 | 174 | 2.37 | 632 | 53 |
| | 0.5 | 2250 | * | * | * | * |

Torsion Tests

| | Strain Rate (rad/sec) | Load (lb) | Peak Torque (ft-lb) |
|---|---|---|---|
| Sawtooth - 18 | 64 | 820 | * |
| | 0.4 | * | 146 |
| Mod. Con. - 18 | 64 | 850 | * |
| | 0.4 | * | 150 |

*Not applicable to this test method.

## SECTION V

## CONCLUSIONS AND RECOMMENDATIONS

Based on the effort summarized above, the following conclusions and recommendations were drawn:

1. Beneficial effects with respect to plastic rotating band performance are achieved by optimizing the number of rifling grooves to minimize stress on the bands. The work showed that 18 grooves in two different configurations outperformed either 9 or 12 grooves.

2. Based on the conditions tested, a modified conventional - 18 configuration was slightly better than an 18-groove sawtooth. However, additional tests with varying band diameters would be helpful in further evaluating these observations.

3. Further sensitivity stress analysis to determine effects of groove shape (modified conventional or sawtooth) for any given number of grooves is necessary to achieve an optimized rifling design for plastic rotating bands. Thermostructural effects should also be considered.

4. High rate multishot firing tests are recommended to more conclusively evaluate effects of rifling configuration on plastic band performance and also on barrel erosion life.

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