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ANALYSIS OF WEAR DATA FOR THE 155MM XM198

US ARMY ARMAMENT COMMAND

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

MAY 1975

TECHNICAL REPORT

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THIS TEST ATTEMPTS TO DETERMINE WHICH CHARACTERISTICS OF TUBE OR PROJECTILE CAUSE OR INFLUENCE MUZZLE WEAR, PARTICULARLY FOR THE 155MM XM198 HOWITZER FAMILY OF COMPONENTS (XM199 CANNON, XM549 PROJECTILE, XM123 PROPELLING CHARGE). THE TEST WAS LIMITED TO AN EVALUATION OF CONDITIONS WHICH EITHER ARE KNOWN OR ARE SUSPECTED TO HAVE AN IMPACT ON MUZZLE WEAR. THE ASSUMPTION WAS MADE THAT THE EXTENT OF SHELL BODY ENGRAVING IS DIRECTLY PROPORTIONAL TO THE EXTENT OF MUZZLE WEAR. NO SINGLE VARIABLE UNDER OBSERVATION WAS FOUND WHICH
(SEE REVERSE SIDE)

20. CONTROLS THE PRESENCE OF BODY ENGRAVING; IT WAS CONCLUDED THAT A NUMBER OF CAUSES, PERHAPS IN SPECIFIC COMBINATIONS, PRODUCE THIS EFFECT. SEVERAL PARAMETERS WERE FOUND, HOWEVER, WHICH INCREASE EITHER THE INCIDENCE OR THE EXTENT OF BODY ENGRAVING INCLUDING COPPERING, PROJECTILE SEATING AS INFLUENCED BY THE FORCING CONE, DYNAMIC INSTABILITY, PROJECTILE IMBALANCE, AND ESCAPE OF PROPELLANT GASES AHEAD OF THE ROTATING BAND. BASED SOLELY ON THE RESULTS OF THIS TEST, A HYPOTHESIS IS PROPOSED CONCERNING THE MECHANISM OF MUZZLE WEAR.

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BACKGROUND:

DURING DEVELOPMENT TESTS OF THE 155MM XM198 HOWITZER, ADVANCED DEVELOPMENT PROTOTYPE, EXCESSIVE MUZZLE WEAR WAS EXPERIENCED WITH ONE TUBE, AND THERE WERE INDICATIONS OF HIGH MUZZLE WEAR ON A SECOND TUBE. SUBSEQUENT INVESTIGATION INDICATED THAT A NUMBER OF XM549 SLUGS USED FOR THESE TESTS SHOWED EVIDENCE OF HEAVY BODY ENGRAVING. FURTHER INVESTIGATION REVEALED THAT SLUGS FIRED DURING AN EARLIER TEST ALSO SHOWED SOME EVIDENCE OF BODY ENGRAVING. ALL OF THE TUBES IN QUESTION HAD SOME DEGREE OF COPPERING ON THE BORE SURFACE AT THE TIME THE SLUGS WERE BEING FIRED. THE IMMEDIATE CAUSE OF THESE CONDITIONS COULD NOT BE DETERMINED, THUS THE MOTIVE FOR THIS TEST.

MUZZLE WEAR IS AN ENLARGEMENT OF THE BORE IN THE VICINITY OF THE MUZZLE. AS WITH WEAR IN GENERAL, THE MECHANISM WHICH CAUSES MUZZLE WEAR IS NOT THOROUGHLY UNDERSTOOD. THE PROBLEM HAS BEEN OBSERVED FOR SOME TIME, HOWEVER, AND SOME PHENOMENA HAVE BEEN NOTICED WITH REGARDS TO IT. THE FOLLOWING HAVE BEEN EXTRACTED FROM PROCEEDINGS OF THE INTERSERVICE TECHNICAL MEETING ON GUN TUBE EROSION AND CONTROL, A WATERVLIET ARSENAL PUBLICATION EDITED BY I. AHMAD OF WATERVLIET ARSENAL AND J. P. PICARD OF PICATINNY ARSENAL, P. I. 3-7:

(1). MUZZLE WEAR TENDS TO OCCUR IN MODERATELY HIGH VELOCITY GUNS FIRING COPPER BANDED SHOT.

(2). BORE ENLARGEMENT IS MORE EXTENSIVE THAN THAT OCCURRING AT THE BREECH END OF THE RIFLED BORE.

(3). IT USUALLY DEVELOPS OVER A BORE LENGTH OF 20 CALIBRES OR MORE, BECOMING GREATER AS THE MUZZLE IS APPROACHED.

(4). IT IS ALMOST ENTIRELY CONFINED TO THE LANDS, THERE BEING LITTLE OR NO WEAR IN THE GROOVES.

(5). VERY FREQUENTLY MUZZLE WEAR IS ASYMMETRICAL: THAT IS, A FEW ADJACENT LANDS ARE WORN TO A GREATER EXTENT THAN THE REST. THIS ASYMMETRY TENDS TO BE ASSOCIATED WITH THE SAME GROUP OF LANDS THROUGHOUT THE REGION OF MUZZLE WEAR AND IS OFTEN REFERRED TO AS "SPIRAL WEAR."

(6). THE RATE OF MUZZLE WEAR INCREASES EXPONENTIALLY WITH THE MUZZLE VELOCITY OF THE PROJECTILE.

PURPOSE:

THE PURPOSE OF THIS TEST WAS TO DETERMINE WHICH CHARACTERISTICS OF TUBE OR PROJECTILE CAUSE OR INFLUENCE THE MUZZLE WEAR CONDITION.

METHOD:

THE TEST WAS LIMITED TO AN EVALUATION OF CONDITIONS WHICH EITHER ARE KNOWN TO HAVE OR ARE SUSPECTED TO HAVE AN IMPACT ON MUZZLE WEAR. IT IS ASSUMED THAT EXCESSIVE MUZZLE WEAR WILL BE ACCOMPANIED BY AN ABNORMAL AMOUNT OF BODY ENGRAVING AND/OR ASYMMETRIC ROTATING BAND ENGRAVING, SO THESE CONDITIONS WILL BE CONSIDERED VALID RESPONSE VARIABLES. MUZZLE WEAR ITSELF IS A RELATIVELY SLUGGISH VARIABLE AND WAS NOT CONSIDERED SUFFICIENTLY SENSITIVE FOR THE PURPOSES OF THIS TEST.

THE TEST PLAN IS SHOWN IN FIG. 1. ALL DECISIONS ON TERMINATING OR CONTINUING A GROUP WERE MADE BY PICATINNY AND WATERVLIET ARSENAL REPRESENTATIVES AT THE SITE. NO GROUP WAS TO HAVE CONSISTED OF LESS THAN TWO OR MORE THAN SEVEN ROUNDS. DATA WERE TAKEN FOR FOUR SEPARATE TUBES: XM181 TUBE S.N. 14 WHICH WAS A SOMEWHAT WORN TUBE WITH STANDARD FORCING CONE; XM199 TUBE S.N. 1 WHICH WAS A SOMEWHAT WORN TUBE WITH STEEP FORCING CONE; XM181 TUBE S.N. 17 WHICH WAS A RELATIVELY NEW TUBE WITH STEEP FORCING CONE; AND XM199 TUBE S.N. 4 WHICH WAS A RELATIVELY NEW TUBE WITH STANDARD FORCING CONE. IT SHOULD BE NOTED THAT THE CONFIGURATION OF XM181 TUBES IS VERY SIMILAR TO THAT OF XM199 TUBES. COPPER WAS PRESENT IN TUBES S.N. 14 AND S.N. 1 AND, AS CALLED FOR IN THE TEST PLAN, COPPER REMOVAL WAS ACCOMPLISHED ABOUT MIDWAY THROUGH THEIR RESPECTIVE TEST PHASES UNDER THE GUIDANCE OF THE PICATINNY ARSENAL REPRESENTATIVE.

PROVISIONS WERE MADE FOR QUANTITATIVELY DETERMINING MAXIMUM BORE PRESSURE, TUBE STRAIN, MUZZLE PRESSURE, AND PROJECTILE VELOCITY SHORTLY AFTER EXIT FROM THE MUZZLE. TWO HIGH SPEED PHOTOGRAPHS WERE TAKEN OF EACH PROJECTILE IN FLIGHT SHOWING OPPOSITE SIDES OF THE SHELL NORMAL TO ITS AXIS OF ROTATION; THE INTENT WAS TO OBSERVE THE PRESENCE (OR LACK OF) BODY ENGRAVING FOR EACH ROUND. WHILE THE PICTURES PROVED TO BE OF GENERALLY EXCELLENT QUALITY, NEARLY ALL SHELL SUFFERED AT LEAST A SLIGHT RUBBING AWAY OF THEIR PAINT; IT PROVED TO BE QUITE DIFFICULT TO DISTINGUISH SUCH ABRASION FROM TRUE BODY ENGRAVING. DIFFERENCES IN DEGREE OF BODY ENGRAVING WERE ALSO IMPOSSIBLE TO RELIABLY ASSESS FROM THE PHOTOGRAPHS ALONE.

IT WAS THUS DECIDED TO STAMP THE SHELL EXTERIORS WITH THEIR RESPECTIVE ROUND NUMBERS IN A GREAT MANY PLACES AND THEN TO RECOVER THE NUMBERED SHELL FRAGMENTS AFTER FIRING FOR A MORE RELIABLE OBSERVATION OF BODY (AND ROTATING BAND) ENGRAVING. IT SHOULD BE NOTED THAT THE TEST BEGAN WITH TUBE S.N. 14 RELYING SOLELY ON THE PHOTOGRAPHS. SINCE THE PHOTOGRAPHS WERE INCONCLUSIVE, DATA DERIVED FROM THIS PORTION OF THE TEST ARE NOT BEING CONSIDERED. ALL CONCLUSIONS DRAWN FROM THE TEST THUS RELY ON INSPECTION OF RECOVERED FRAGMENTS FIRED FROM TUBES S.N. 1, S.N. 4, AND S.N. 17.

SEVERAL DIFFERENT TYPES OF SHELL WERE EMPLOYED IN THIS TEST, PRIMARILY XM549 PROJECTILES AND XM549 SLUGS (SOME OF WHICH HAD THEIR CENTER OF MASS INTENTIONALLY DISPLACED RADIALLY FROM THE LONGITUDINAL AXIS OF ROTATION AND ARE THUS TERMED "UNBALANCED"). SMALL SAMPLES OF OTHER SHELL WERE ALSO FIRED INCLUDING SEVERAL SLUG VARIATIONS, M101 PROJECTILES, M107 PROJECTILES, AND XM483 PROJECTILES. A PLASTIC OBTURATOR WAS PUT ON SOME OF THE SHELL TO ASSESS ITS IMPACT ON BODY ENGRAVING.

DATA:

RAW DATA FOR THE INDIVIDUAL ROUNDS ARE SUMMARIZED IN TABLE 1.

OBSERVATIONS FROM DATA:

THE DATA WERE REDUCED INTO MANY QUALITATIVE AND QUANTITATIVE CATEGORIES IN SEARCH OF A VARIABLE WHICH WOULD SHOW A POSITIVE INFLUENCE ON BODY ENGRAVING. AS PREVIOUSLY MENTIONED, MUZZLE WEAR IS A SLUGGISH VARIABLE. SINCE BODY ENGRAVING IS INDICATIVE OF MECHANICAL ABRASION BETWEEN THE TUBE AND PROJECTILE, THE BASIC PREMISE IS THAT THE EXTENT OF MUZZLE WEAR IS DIRECTLY PROPORTIONAL TO THE EXTENT OF BODY ENGRAVING.

THUS, IF ANY OF THE OBSERVED VARIABLES SHOW AN INFLUENCE ON BODY ENGRAVING, THE ABOVE PREMISE DICTATES THAT IT INFLUENCES MUZZLE WEAR AS WELL.

1. EXTENT OF BODY ENGRAVING: THIS IS THE EFFECT WHICH IS MEASURED AGAINST ALL FOLLOWING POSSIBLE CAUSES. BODY ENGRAVING HAS BEEN BROKEN DOWN INTO FIVE SUB-CATEGORIES WHICH ARE NAMED AND EXPLAINED BELOW:

(a) PAINT - INDICATING THAT THE TUBE LANDS HAVE ONLY SCRAPED PAINT FROM THE PROJECTILE.

(b) BURN - INDICATING THAT THE TUBE LANDS HAVE ABRADED ONLY THE CIRCUMFERENTIAL MACHINE MARKS ON THE PROJECTILE EXTERIOR.

(c) LIGHT - INDICATING BODY ENGRAVING UP TO AN APPROXIMATE DEPTH OF .01".

(d) MEDIUM - INDICATING BODY ENGRAVING UP TO AN APPROXIMATE DEPTH OF .02".

(e) HEAVY - INDICATING BODY ENGRAVING IN EXCESS OF APPROXIMATELY .02".

CATEGORIES (c), (d), AND (e) ARE CONSIDERED TO BE "BODY ENGRAVING" WHEREAS (a) AND (b) ARE NOT. BODY ENGRAVING WAS PRESENT IN 35% OF THE OBSERVED PROJECTILE, OF WHICH 66% WERE LIGHT, 17% MEDIUM, AND 17% HEAVY.

2. TYPE OF PROJECTILE: ALL TYPES OF PROJECTILE OBSERVED DEMONSTRATED AT LEAST LIGHT BODY ENGRAVING AT SOME TIME DURING THE TEST, EVEN THOSE LIGHTLY SAMPLED. SOME TYPES OF PROJECTILE TENDED TO ENGRAVE MORE THAN OTHERS, HOWEVER. ON A PERCENTAGE BASIS FOR THE XM549 SLUGS AND PROJECTILES (OTHER TYPES WERE SAMPLED TOO LIGHTLY TO MAKE ANY VALID STATEMENT), TWICE AS MANY BALANCED SLUGS WERE BODY ENGRAVED AS PROJECTILES, AND TWICE AS MANY UNBALANCED SLUGS WERE BODY ENGRAVED AS BALANCED SLUGS; i.e. PROJECTILES - 17%, BALANCED SLUGS - 36%, UNBALANCED SLUGS - 70%.

3. <u>TYPE OF TUBE</u>: THE EXTENT OF BODY ENGRAVING VARIED GREATLY IN ONE OF THE THREE TUBES FROM WHICH DATA WERE EXTRACTED. TUBE S.N. 4 (NEW TUBE WITH STANDARD FORCING CONE) SHOWED BODY ENGRAVING IN ONLY ONE PROJECTILE OUT OF 23 (4%). TUBE S.N. 1 (OLD TUBE WITH STEEP FORCING CONE) AND TUBE S.N. 17 (NEW TUBE WITH STEEP FORCING CONE) SHOWED BODY ENGRAVING IN 16 OUT OF 33 (48%) AND 12 OUT OF 26 (46%) PROJECTILE RESPECTIVELY.

4. <u>COPPER IN TUBE</u>: TUBE S.N. 1 WAS THE ONLY TUBE OBSERVED FROM WHICH DATA WERE EXTRACTED BOTH BEFORE AND AFTER DECOPPERING OF THE TUBE. BEFORE DECOPPERING, 9 OF 14 PROJECTILES (64%) WERE BODY ENGRAVED, 3 OF WHICH WERE LIGHT, 3 MEDIUM, AND 3 HEAVY. AFTER DECOPPERING, 7 OF 19 PROJECTILES (37%) WERE BODY ENGRAVED, 6 OF WHICH WERE LIGHT AND 1 HEAVY. THE ROUNDS IMMEDIATELY PREVIOUS TO DECOPPERING TENDED MOSTLY TOWARDS HEAVY AND MEDIUM BODY ENGRAVING WHEREAS THE ROUNDS IMMEDIATELY AFTER DECOPPERING TENDED, IN ALL BUT ONE CASE, NOT TO BE BODY ENGRAVED AT ALL.

4. <u>MAXIMUM CHAMBER PRESSURE</u>: A PRESSURE SPREAD FROM APPROXIMATELY 49 TO 59 KSI WAS OBTAINED; BOTH THE PRESENCE AND LACK OF BODY ENGRAVING WAS NOTED OVER THIS WHOLE SPECTRUM OF PRESSURES. HOWEVER, MEDIUM AND HEAVY BODY ENGRAVING WERE NOTED ONLY IN THE RANGE BETWEEN 54-56 KSI.

5. <u>PROJECTILE MOMENTUM</u> (SHORTLY AFTER EXIT FROM MUZZLE): PROJECTILE MOMENTUM IS LINEARLY PROPORTIONAL TO PROJECTILE ANGULAR MOMENTUM. THE MOMENTUM SPREAD OBSERVED WAS GENERALLY BETWEEN 8200-8500 SLUG-FT/SEC; BOTH THE PRESENCE AND LACK OF BODY ENGRAVING WAS NOTED OVER THIS WHOLE SPECTRUM OF MOMENTA. HOWEVER, MEDIUM AND HEAVY BODY ENGRAVING WERE NOTED ONLY IN THE RANGE BETWEEN 8200-8300 SLUG-FT/SEC.

6. <u>PROJECTILE VELOCITY</u> (SHORTLY AFTER EXIT FROM MUZZLE): PROJECTILE VELOCITY IS LINEARLY PROPORTIONAL TO PROJECTILE ANGULAR VELOCITY. THE VELOCITY SPREAD OBSERVED WAS, IN GENERAL, BETWEEN 2750 - 2850 FT/SEC; BOTH THE PRESENCE AND LACK OF BODY ENGRAVING WAS NOTED OVER MOST OF THIS SPECTRUM OF VELOCITIES. THE VELOCITY LEVELS ATTAINED IN TUBE S.N. 1 WERE GENERALLY LOWER THAN THOSE ATTAINED IN THE TWO NEWER TUBES; HOWEVER, THE EXTENT OF BODY ENGRAVING WAS GREATER IN TUBE S.N. 1 THAN IN THE OTHER TWO.

7. <u>"DYNAMIC INSTABILITY FACTOR"</u>. AN ASIDE SHOULD BE MADE AT THIS POINT TO JUSTIFY OBSERVATION OF THIS FACTOR WHICH IS: THE PRODUCT OF THE MASS OF THE PROJECTILE (SLUGS) AND THE SQUARE OF THE ANGULAR VELOCITY $(\text{RAD/SEC})^2, m\omega^2$. AS A FIRST ORDER ANALOGY, THE PROJECTILE MAY BE ENVISIONED AS A RIGID ROTOR (THE SHELL BODY) SUPPORTED BY FLEXIBLE BEARINGS (THE ROTATING BAND). ANALYSIS OF SUCH A SYSTEM IS PRESENTED ON PP. 84-86 OF <u>VIBRATION THEORY AND APPLICATIONS</u> BY W. T. THOMPSON, PRENTICE HALL INC., 1965. ASSUMING THAT THE ROTATING BAND EXERTS A SPRING-LIKE FORCE AND THAT ITS SPRING COEFFICIENT IS CIRCUMFERENTIALLY UNIFORM, THE POSITION OF THE AXIS ABOUT WHICH THE ROTOR TURNS IS DISPLACED FROM THE NOMINAL BEARING AXIS ACCORDING TO THE FOLLOWING EQUATION:

$$\boxed{R = \frac{cm\omega^2}{k - m\omega^2}\, e^{[-i\omega t]}}$$

(STEADY-STATE SOLUTION)

<u>WHERE</u>

- R = THE DISPLACEMENT (FT.)
- m = MASS OF ROTOR (SLUG)
- c = ECCENTRICITY OF ROTOR CENTER OF MASS FROM AXIS OF ROTATION. (FT.)
- ω = ANGULAR VELOCITY OF ROTOR (RAD/SEC)
- k = LINEAR SPRING CONSTANT OF BEARING (LB/FT.)
- e = THE EXPONENTIAL
- i = $\sqrt{-1}$
- t = TIME (SEC.)

THE NATURAL FREQUENCY CAN BE SEEN TO BE $\omega_n = \sqrt{\frac{k}{m}}$. AT WHICH ROTOR INSTABILITY SETS IN AND $|R| \rightarrow \infty$. IF DAMPING IS INCLUDED, $|R|$ WILL BE A GREATLY REDUCED (FINITE) NUMBER, BUT THE NATURAL FREQUENCY IS LARGELY UNALTERED. IT IS EVIDENT THAT THE AXIS ABOUT WHICH THE ROTOR TURNS WHIRLS ABOUT THE NOMINAL BEARING AXIS AT AN ANGULAR VELOCITY EQUAL TO THAT OF THE ROTOR. IF THE ANGULAR VELOCITY IS EITHER ABOVE OR BELOW THE NATURAL FREQUENCY, $|R|$ IS MINIMAL WHEREAS AT OR NEAR A NATURAL FREQUENCY, $|R|$ WOULD BE EXTREME. THIS ANALOGUE, THOUGH RATHER CRUDE, WOULD EXPLAIN SEVERAL OF THE OBSERVATIONS CITED ON P. 1 SUCH AS: THE TIME LAG TILL FULL EFFECT OF THE INSTABILITY IS NOTICED AND ITS EXTENSIVE NATURE; THE ASYMMETRY OF THE WEAR PATTERN WHICH MORE OR LESS FOLLOWS THE RIFLING TWIST; AND THE EXPONENTIAL INCREASE OF MUZZLE WEAR WITH VELOCITY (WHICH IS LINEARLY PROPORTIONAL TO ANGULAR VELOCITY). THE HERE-NAMED "DYNAMIC INSTABILITY FACTOR", $m\omega^2$, IS THUS EXTRACTED FROM THE EQUATION FOR R (ABOVE) AS A ROUGH INDICATOR OF ROTOR (i.e. PROJECTILE) INSTABILITY.

THE "DYNAMIC INSTABILITY FACTOR" IS LINEARLY PROPORTIONAL TO BOTH PROJECTILE KINETIC ENERGY AND CENTRIFUGAL FORCE. VALUES OBSERVED WERE BETWEEN 86×10^5 AND 93×10^5 (SLUG/SEC.). BOTH THE PRESENCE AND THE LACK OF BODY ENGRAVING WAS NOTICED OVER THIS WHOLE SPECTRUM. HOWEVER, MEDIUM AND HEAVY BODY ENGRAVING WERE ONLY NOTED IN THE RANGE BETWEEN $87 \times 10^5 - 89.5 \times 10^5$ (SLUG/SEC^2); OUTSIDE OF THIS RANGE, THERE IS (ON A PERCENTAGE BASIS) LESS TENDENCY FOR THE SHELL TO BODY ENGRAVE.

IF THE DATA ARE SUBDIVIDED BY INDIVIDUAL TUBES AND THEN BY INDIVIDUAL PROJECTILE TYPES, A TENDENCY TOWARDS BODY ENGRAVING BECOMES MORE PRONOUNCED FOR SOME VALUES AND DEFINITELY LESS PRONOUNCED FOR OTHERS. THUS, AS MAY BE EXPECTED, THIS IS BOTH A TUBE- AND A PROJECTILE-INFLUENCED VARIABLE.

8. PRESENCE OF STEP IN ROTATING BAND: AGAIN, AS AN ASIDE, IT WAS NOTICED THAT SOME ROTATING BANDS RECOVERED WERE MIRROR IMAGES OF THE TUBE RIFLING, THE ENGRAVING BEING PERHAPS SLIGHTLY WIDER CIRCUMFERENTIALLY THAN THE TUBE LANDS. ON THE OTHER HAND, SOME ROTATING BANDS RECOVERED EXHIBITED A STEP IN THE ENGRAVING; IT APPEARED THAT THEY HAD BEEN WIDENED SOMEWHAT AS BEFORE, THEN SUBJECTED TO AN INCREASED (ONE-SIDED) RADIAL COMPRESSIVE FORCE WHICH WORE A DEEPER GROOVE INTO THE BAND. IT WAS FELT THAT THIS PHENOMENA MAY BE CORRELATED WITH BODY ENGRAVING.

IN ALL, 31% OF THE OBSERVED ROUNDS DISPLAYED THIS STEP IN THEIR ROTATING BANDS. 35% OF ALL SHELL OBSERVED SHOWED BODY ENGRAVING, OF WHICH 41% DISPLAYED THE STEP. ON THE OTHER HAND, 64% OF ALL ROUNDS OBSERVED SHOWED NO BODY ENGRAVING, OF WHICH 25% DISPLAYED THE STEP. EXCEPT FOR THE MATCH-UP SLUG, ALL MEDIUM AND HEAVY BODY ENGRAVED SHELL HAD STEPS PRESENT ON THEIR ROTATING BANDS. NO SHELL FIRED FROM TUBE S.N. 4 WAS FOUND TO HAVE THE STEP.

9. PRESENCE OF PLASTIC OBTURATOR: IN ALL, TWENTY OF THE OBSERVED ROUNDS WERE FIRED WITH A PLASTIC OBTURATOR ASSEMBLED TO THE SHELL IN BACK OF THE ROTATING BAND; 8 OF THESE ROUNDS DISPLAYED BODY ENGRAVING.

ONLY TUBES S.N. 1 AND S.N. 17 WERE TESTED IN PART WITH SUCH SHELL; BODY ENGRAVING OCCURRED 54% (80% BEFORE DECOPPERING, 33% AFTER) AND 22% OF THE TIME, RESPECTIVELY, FOR SHELL USING THE OBTURATOR.

10. STRAIN GAGES

(a) AT ORIGIN OF RIFLING: NO PATTERN ARISES BY CORRELATING STRAIN READINGS AT THE ORIGIN OF RIFLING WITH BODY ENGRAVING. THE SHAPES OF ALL CURVES WERE ESSENTIALLY THE SAME, REGARDLESS OF THE PRESENCE OR LACK OF BODY ENGRAVING.

(b) 41.5" FROM MUZZLE: IN GENERAL, ROUNDS EXHIBITING BODY ENGRAVING SHOWED INCREASED TUBE STRAIN AHEAD OF THE ROTATING BAND. ANALYSIS OF THIS VARIABLE IS BROKEN DOWN BY TUBE:

(1) TUBE S.N. 1: BEFORE DECOPPERING, STRAIN LEVELS AHEAD OF THE ROTATING BAND WERE GENERALLY HIGHER (THAN AFTER DECOPPERING) REGARDLESS OF WHETHER THE PLASTIC OBTURATOR WAS USED. AFTER DECOPPERING, THE PRESENCE OF THE PLASTIC OBTURATOR GENERALLY REDUCED STRAIN AHEAD OF THE ROTATING BAND, BUT THIS (IN AND OF ITSELF) DID NOT ASSURE THAT BODY ENGRAVING WOULD NOT BE PRESENT. NINE ROUNDS AFTER DECOPPERING WAS ACCOMPLISHED, THE STRAIN LEVELS AHEAD OF THE ROTATING BAND APPEARED TO INCREASE AGAIN, ESPECIALLY WHEN THE PLASTIC OBTURATOR WAS NOT PRESENT.

(2) TUBE S.N. 4: STRAIN AHEAD OF THE ROTATING BAND WAS GENERALLY LOW FOR THE FIRST 17 ROUNDS. THE LAST 8 ROUNDS SHOWED SLIGHTLY HIGHER LEVELS, BUT NONE RESULTED IN BODY ENGRAVING.

(3) TUBE S.N. 17: USE OF THE PLASTIC OBTURATOR GENERALLY REDUCED THE STRAIN AHEAD OF THE ROTATING BAND. THIS IN AND OF ITSELF WAS NOT SUFFICIENT TO PREVENT BODY ENGRAVING ALTHOUGH THE TENDENCY TO DO SO WAS GREATLY REDUCED. FOR PROJECTILE NOT HAVING THE PLASTIC OBTURATOR, THE POSSIBLE CORRELATION BETWEEN STRAIN AHEAD OF THE ROTATING BAND AND BODY ENGRAVING WAS NOT ESPECIALLY EVIDENT AND, IN FACT, SHOWED A SLIGHT TENDENCY TOWARDS AN INVERSE RELATIONSHIP.

(c) 11" FROM MUZZLE: THESE CURVES WERE GENERALLY LESS SMOOTH THAN THOSE OF STRAINS FURTHER FROM THE MUZZLE, BOTH BEFORE AND AFTER THE ROTATING BAND PASSED BY. THE MEDIUM AND HEAVY BODY ENGRAVED SHELL WERE NORMALLY ACCOMPANIED BY ESPECIALLY VIOLENT TRACES; THEY WERE ERRATIC BEFORE THE ROTATING BAND'S PRESENCE WAS FELT AND DID NOT LEAD TO THE DISTINCTIVELY SMOOTH, HIGH-GRADIENT SLOPE WHICH TYPICALLY IS PRODUCED BY THE ROTATING BAND ENTERING THE AREA UNDER THE STRAIN GAGE. THE CURVES DERIVED IMMEDIATELY AFTER DECOPPERING OF TUBE S.N. 1 WERE SINGULARLY SMOOTH, ESPECIALLY COMPARED TO THOSE IMMEDIATELY BEFORE DECOPPERING WHICH WERE AMONG THE MOST VIOLENT OBSERVED. THE PLASTIC OBTURATOR TENDED TO REDUCE THE STRAIN FELT BY THE TUBE BEFORE THE ROTATING BAND PASSED BY WITH THE EXCEPTION OF THOSE ROUNDS FIRED FROM TUBE S.N. 1 BEFORE DECOPPERING.

11. KISTLER GAGE: NO CONSISTENT CORRELATION WAS OBSERVED BETWEEN MUZZLE PRESSURE AND BODY ENGRAVING. THE PRESENCE OF THE PLASTIC OBTURATOR ON PROJECTILE GENERALLY LOWERED THE PRESSURE AHEAD OF THE ROTATING BAND (EXCEPT IN TUBE S.N. 1 BEFORE DECOPPERING), BUT THIS SHOWED NO TREND TOWARDS ELIMINATING BODY ENGRAVING.

DISCUSSION OF OBSERVATIONS:

THE MOST OBVIOUS CONCLUSION TO BE DRAWN IS THAT NO SINGLE VARIABLE UNDER OBSERVATION APPEARS TO CONTROL THE PRESENCE OF BODY ENGRAVING. THUS, A NUMBER OF CAUSES, PERHAPS IN SPECIFIC COMBINATIONS, PRODUCE THIS EFFECT.

BY FAR, THE OUTSTANDING CAUSE FOR HOPE IN DETERMINING THESE CAUSES RESTS WITH OBSERVATION OF TUBE S.N. 4 WHICH SHOWS BODY ENGRAVING IN ONLY 1 OF 23 ROUNDS FIRED (4%). EVIDENTLY, CONDITIONS WERE PRESENT WHICH WERE NOT AT ALL CONDUCIVE TO BODY ENGRAVING. THE TUBE ITSELF WAS RELATIVELY NEW; HOWEVER, TUBE S.N. 17, WHICH PRODUCED BODY ENGRAVED SHELL 46% OF THE TIME (COMPARED WITH 48% FOR TUBE S.N. 1, A RELATIVELY OLD TUBE) WAS ALSO A NEW TUBE. THUS IT DOES NOT APPEAR THAT, SIMPLY BECAUSE A TUBE IS NEW, IT WILL PRODUCE LESS BODY ENGRAVING. IT MAY BE NOTED THAT TUBE S.N. 4 HAD A STANDARD FORCING CONE WHEREAS THE OTHER TWO (WHICH PRODUCED ABOUT THE SAME PERCENTAGE OF BODY ENGRAVING) HAD STEEPER CONES. THIS MAY INDICATE THAT THE NATURE OF THE PROJECTILE SEATING HAS AN EFFECT ON REDUCING BODY ENGRAVING. THE PRESENCE OF THE STEEP CONE BY NO MEANS ASSURES BODY ENGRAVING SINCE TUBES S.N. 1 AND S.N. 17 ONLY PRODUCED THIS EFFECT ABOUT HALF THE TIME; HOWEVER, THE INFERENCE IS THAT THE STEEP FORCING CONE APPEARS TO HAVE PROVOKED BODY ENGRAVING WHEREAS THE STANDARD CONE DID NOT.

THE PERFORMANCE OF SHELL BEFORE AND AFTER DECOPPERING IN TUBE S.N. 1 INDICATES A DEFINITE CORRELATION BETWEEN COPPERING AND BODY ENGRAVING.

BEFORE DECOPPERING, MOST SHELL WERE HEAVILY BODY ENGRAVED, AND THE INSTRUMENTATION SHOWED VIOLENT, ERRATIC STRAIN AND PRESSURE TRACES ACCOMPANYING THE ROUNDS. IMMEDIATELY AFTER DECOPPERING, HOWEVER, THESE TRACES BECAME HIGHLY STABLE AND THE INCIDENCE OF BODY ENGRAVING WAS REDUCED TO ABOUT NIL; AFTER NINE ROUNDS THE INCIDENCE INCREASED AGAIN, ALTHOUGH MOST SHELL WHICH BECAME BODY ENGRAVED WERE ONLY LIGHTLY SO. THUS, SINCE THIS SMALL AMOUNT OF RECOPPERING QUICKLY INCREASED THE TENDENCY TO BODY ENGRAVE, IT WOULD SEEM THAT BODY ENGRAVING IS A FAIRLY SENSITIVE FUNCTION OF COPPERING.

THE PHYSICAL PARAMETERS (VELOCITY, MOMENTUM, MAXIMUM CHAMBER PRESSURE) SHOWED NO CONCRETE CORRELATION WITH BODY ENGRAVING OVER THEIR RESPECTIVE OBSERVED RANGES, ALTHOUGH THE MORE EXTENSIVE BODY ENGRAVING WAS GENERALLY CONFINED TO A SPECIFIC RANGE OF VALUES. THE "DYNAMIC INSTABILITY FACTOR" ALSO SHOWED LITTLE OVERALL CORRELATION; HOWEVER, WHEN DATA WERE SUBDIVIDED BY INDIVIDUAL TUBES AND THEN BY INDIVIDUAL PROJECTILE TYPES, BOTH THE TENDENCY TOWARDS AND THE EXTENT OF BODY ENGRAVING BECAME MORE PRONOUNCED FOR SOME VALUES AND DEFINITELY LESS PRONOUNCED FOR OTHERS. IT SHOULD BE NOTED THAT $m\omega_n^2$ (WHERE ω_n IS THE NATURAL FREQUENCY) IS EQUAL TO THE SPRING CONSTANT OF THE BEARING, i.e. ROTATING BAND. THE $m\omega^2$ VALUE WHICH APPEARED TO PRODUCE THE MOST EXTENSIVE BODY ENGRAVING WAS $8.75 \times 10^6 \frac{(lb)}{(ft)} = .73 \times 10^6 \frac{(lb)}{(in.)}$. AS A FIRST APPROXIMATION, ONE MIGHT EXPECT THIS SPRING CONSTANT VALUE TO BE (NUMERICALLY) ON THE ORDER OF THE ELASTIC MODULUS OF COPPER, WHICH IS $17 \times 10^6 \frac{lb}{in^2}$ (NOTE: THE ROTATING BAND, HOWEVER, UNDERGOES A PLASTIC DEFORMATION, AND ITS "INSTANTANEOUS PLASTIC MODULUS" WOULD BE SOMEWHAT BELOW THIS LATTER VALUE).

IT IS QUITE POSSIBLE THAT THE NUMERICAL PROXIMITY OF THE "DYNAMIC INSTABILITY FACTOR" AND THE DEFORMATION MODULUS IS MORE THAN A PASSING COINCIDENCE AND THAT THE PROJECTILE MAY INDEED ACT AS A RIGID ROTOR ON FLEXIBLE BEARINGS.

THE XM549 SLUGS, ESPECIALLY THOSE WHICH WERE UNBALANCED, TENDED TO INCREASE THE TENDENCY TO BODY ENGRAVE. IT WOULD APPEAR THAT, ON A PERCENTAGE BASIS, THE MORE UNBALANCED THE SHELL, THE GREATER THE TENDENCY TO BODY ENGRAVE.

IN GENERAL, ROUNDS EXHIBITING BODY ENGRAVING ALSO SHOWED A SOMEWHAT INCREASED TUBE STRAIN AHEAD OF THE ROTATING BAND. THIS MAY LEAD ONE TO BELIEVE THAT GAS LEAKAGE INCREASES THE PRESSURE (AND THEREFORE THE TUBE STRAIN) AHEAD OF THE ROTATING BAND; WE SHOULD THUS SEE A CORRELATION BETWEEN MUZZLE PRESSURE AND BODY ENGRAVING. THE KISTLER GAGE READINGS, HOWEVER, DID NOT YIELD A CONSISTENT CORRELATION. ON THE OTHER HAND, SHELL WHICH INCORPORATED THE PLASTIC OBTURATORS GENERALLY KEPT BOTH THE STRAIN AND THE PRESSURE AHEAD OF THE ROTATING BAND AT LOWER LEVELS AND ALSO SHOWED A TENDENCY TOWARDS REDUCED INCIDENCE AND EXTENT OF BODY ENGRAVING. IT SHOULD BE NOTED THAT, BEFORE DECOPPERING OF TUBE S.N. 1, THE PLASTIC OBTURATOR WAS NOT ABLE TO REDUCE EITHER THE PRESSURE, THE STRAIN, OR THE EXTENT OF BODY ENGRAVING.

CONCLUSIONS:

IT IS OBVIOUS THAT NO SINGLE VARIABLE UNDER OBSERVATION HAS BEEN FOUND WHICH CONTROLS THE PRESENCE OF BODY ENGRAVING. THUS, A NUMBER OF CAUSES, PERHAPS IN SPECIFIC COMBINATIONS, PRODUCE THIS EFFECT.

BASED ON THIS TEST, HOWEVER, SEVERAL PARAMETERS WERE FOUND WHICH INCREASE THE INCIDENCE OR EXTENT OF BODY ENGRAVING:

1. COPPERING, WHICH APPEARS TO BE A FAIRLY SENSITIVE VARIABLE.

2. THE NATURE OF PROJECTILE SEATING AS INFLUENCED BY THE FORCING CONE.

3. "DYNAMIC INSTABILITY FACTOR", $m\omega^2$; i.e. FOR A SPECIFIC TUBE CONFIGURATION, A GIVEN PROJECTILE MASS HAS AN ASSOCIATED ANGULAR VELOCITY (AND, THEREFORE, LINEAR VELOCITY) CLOSE TO WHICH THE TENDENCY TO BODY ENGRAVE IS INCREASED AND AWAY FROM WHICH THIS TENDENCY DIMINISHES.

4. THE DEGREE OF IMBALANCE OF THE PROJECTILE.

5. THE DEGREE TO WHICH HOT GASES ESCAPE AHEAD OF THE ROTATING BAND.

IT IS CONCEDED THAT OTHER FACTORS MAY ALSO HAVE AN IMPACT ON BODY ENGRAVING AND THE MUZZLE WEAR PROBLEM IN GENERAL. HOWEVER, FURTHER TESTS IN THE AREA OF MUZZLE WEAR SHOULD, AT A MINIMUM, ADDRESS THE FIVE INFLUENCING FACTORS MENTIONED ABOVE IN ORDER TO CONFIRM THESE FINDINGS OR DETERMINE THE EXTENT TO WHICH EACH FACTOR PROVOKES MUZZLE WEAR.

A PROPOSED THEORY OF MUZZLE EROSION BASED ON RESULTS OF THIS TEST:

IT IS FELT THAT AN ATTEMPT SHOULD BE MADE TO CORRELATE THE FINDINGS OF THIS TEST BY PROPOSING A HYPOTHESIS CONCERNING CAUSATION OF MUZZLE WEAR. THIS HYPOTHESIS IS BASED SOLELY ON THE OBSERVATIONS DRAWN FROM THIS TEST AND IS BY NO MEANS DEFINITIVE. SUBSEQUENT INVESTIGATIONS IN THE AREA OF MUZZLE WEAR SHOULD FURTHER TEST THE CREDIBILITY OF ALL STATEMENTS MADE.

HYPOTHESIS

MUZZLE WEAR IS DIRECTLY ASSOCIATED WITH BODY ENGRAVING. IT WOULD BE DIFFICULT TO REFUTE THAT, FOR BODY ENGRAVING TO OCCUR, THE AXIAL CENTERLINE OF THE PROJECTILE MUST DEPART FROM THE AXIAL CENTERLINE OF THE GUN TUBE. THIS BRINGS THE SHELL BODY IN CONTACT WITH THE LANDS OF THE GUN TUBE RIFLING THUS CAUSING A MECHANICAL ABRASION BETWEEN THE TWO. THE RESULTS ARE MANIFEST IN DAMAGE TO BOTH TUBE AND PROJECTILE: TUBE LAND WEAR AND PROJECTILE BODY ENGRAVING (i.e. SCRIBING OF THE PROJECTILE BODY).

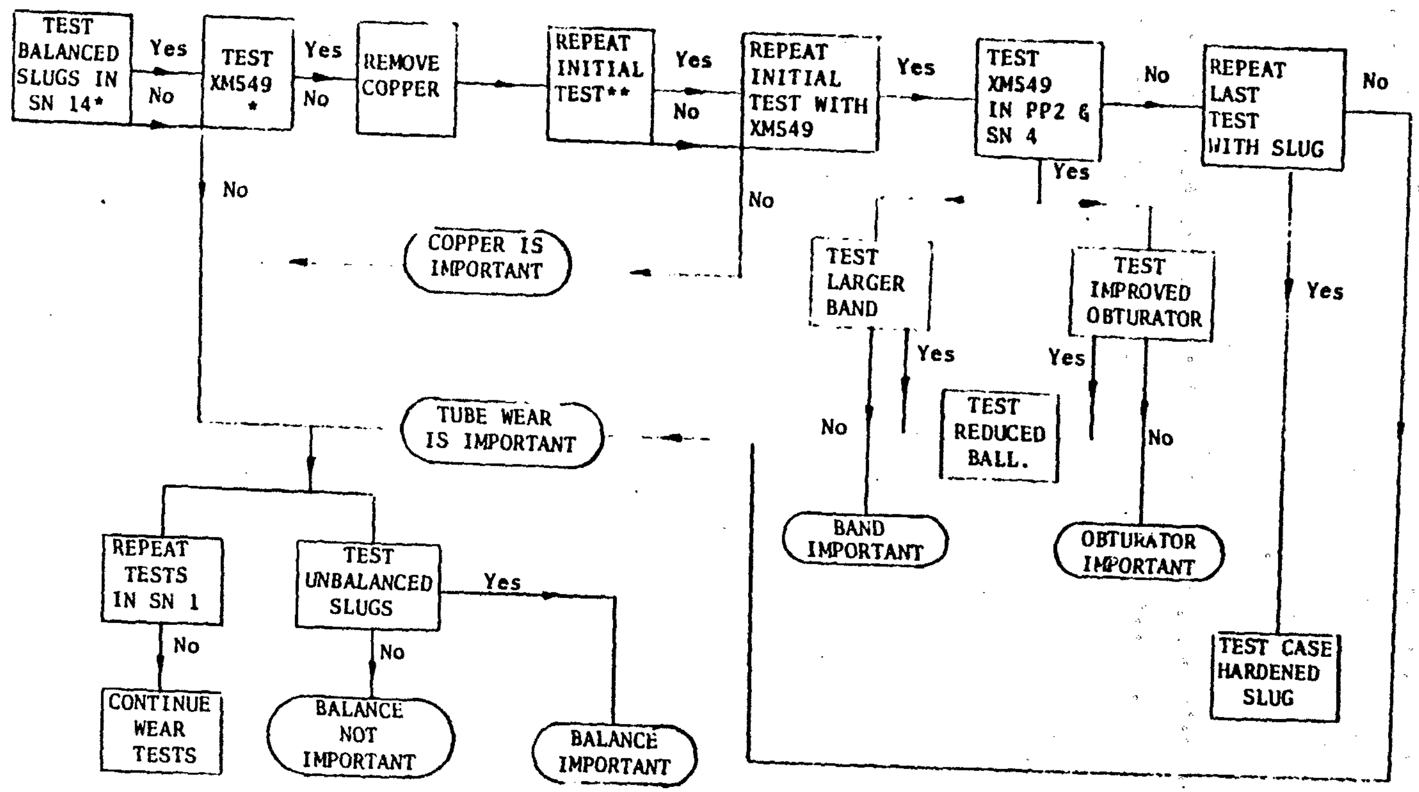
EVIDENCE WOULD INDICATE THAT THE DAMAGE TO TUBE AND PROJECTILE INCREASES AS THE SHELL PROCEEDS DOWNBORE. TUBE WEAR WHICH IS BOTH EXCLUSIVE TO THE LANDS AND BY-AND-LARGE MECHANICAL IN NATURE HAS, IN THE PAST, BEEN EVIDENT MAINLY IN THE MUZZLE REGION. FURTHER, MANY BODY ENGRAVED PROJECTILE EXHIBIT A STEP IN THEIR ROTATING BAND ENGRAVINGS; THIS INDICATES THAT THEY INITIALLY HAD BEEN WEARING IN A CIRCUMFERENTIAL MANNER (DUE TO ABRASION WITH THE DRIVING EDGE OF THE LANDS) BUT BECAME HEAVILY LOADED IN THE RADIAL DIRECTION NEAR THE END OF THEIR IN-BORE FLIGHT.

BODY ENGRAVING ITSELF IS INITIALLY A PROJECTILE INSTABILITY PROBLEM WHICH MAY BE PROVOKED BY MANY FACTORS. PRIMARILY, HOWEVER, IT IS INITIATED WHEN THE MASS CENTER OF THE PROJECTILE DOES NOT LIE ON THE CENTERLINE OF THE GUN TUBE. FOR EXAMPLE, THIS MAY OCCUR: IF THE PROJECTILE IS UNBALANCED (NEARLY ALL PROJECTILE, DUE TO MANUFACTURING DIFFICULTIES, SETTLING OF FILLER, ETC., ARE AT LEAST SLIGHTLY UNBALANCED); IF, DURING RAMMING, THE SHELL STRIKES AND BOUNCES (WITH A SUFFICIENT RADIAL DISPLACEMENT COMPONENT) OFF THE FORCING CONE AND IS NOT ABLE TO TOTALLY RE-CENTER ITSELF BEFORE SEATING; IF COPPERING IS PRESENT ON THE BORE SURFACE; IF THE TUBE IS WORN PRIMARILY IN A LIMITED CIRCUMFERENTIAL REGION; ETC. SINCE THE PROJECTILE IS, IN EFFECT, A VERY HIGH SPEED ROTOR, EVEN A MINUTE DEPARTURE OF THE MASS CENTER OF THE PROJECTILE FROM THE TUBE CENTERLINE HAS THE POTENTIAL OF CAUSING DYNAMIC INSTABILITY. IF WE CONSIDER THE PROJECTILE TO BE A RIGID ROTOR ON A FLEXIBLE CIRCUMFERENTIAL BEARING (i. e., ITS ROTATING BAND), IT CAN BE SHOWN THAT, FOR A PARTICULAR TUBE AND PROJECTILE, THERE IS A SPECIFIC ANGULAR VELOCITY AT AND AROUND WHICH THE SHELL WILL BE HIGHLY UNSTABLE. THIS VELOCITY DEPENDS ON INDIVIDUAL SHELL WEIGHT AND THE DEGREE TO WHICH THE ROTATING BAND ATTEMPTS TO PUSH THE PROJECTILE BACK TOWARDS THE TUBE CENTERLINE (i.e., THE SPRING CONSTANT OF THE ROTATING BAND WHICH IS COMPRESSED BETWEEN THE SHELL BODY AND THE BORE). DUE TO MANUFACTURING TOLERANCES IN BOTH THE SHELL AND THE TUBE, THIS ANGULAR VELOCITY WILL NOT BE EXACTLY THE SAME FOR ALL SHELL OF A GIVEN SPECIES WHEN FIRED IN TUBES OF A GIVEN SPECIES; A SMALL DISPERSION SHOULD BE EVIDENT.

WHEN A SHELL IS FIRED, ITS VELOCITY RAPIDLY INCREASES AS IT PROCEEDS DOWNBORE (PRODUCING A "CONCAVE DOWNWARD" VELOCITY-DISPLACEMENT CURVE); DUE TO THE UNIFORM TWIST OF THE RIFLING, ANGULAR VELOCITY INCREASES IN DIRECT LINEAR CORRELATION. AT LOWER VELOCITIES, THE PROJECTILE AXIS OF ROTATION WILL MILDLY WHIRL ABOUT THE CENTERLINE OF THE TUBE WITH THE SAME ANGULAR VELOCITY AS THE SHELL'S. HOWEVER, AS THE ANGULAR VELOCITY INCREASES, A NATURAL FREQUENCY MAY BE APPROACHED. THE EFFECTS INCURRED ARE ENTIRELY TIME DEPENDENT. IF ANGULAR VELOCITY INCREASES QUICKLY THROUGH THE NATURAL FREQUENCY, THE MILD WHIRL OF THE PROJECTILE AXIS WILL CONTINUE. IF, HOWEVER, THE ANGULAR VELOCITY IS NOT CHANGING AS RAPIDLY AS BEFORE (AS WOULD BE THE CASE FURTHER DOWNBORE NEAR THE MUZZLE), THE EFFECTS OF THE INSTABILITY WILL HAVE SUFFICIENT TIME TO MAKE THEIR PRESENCE FELT. THE PROJECTILE AXIS OF ROTATION WOULD WHIRL VIOLENTLY ABOUT THE TUBE CENTERLINE. THE WHIRL FREQUENCY WOULD BE THE SAME AS THE SHELL ROTATIONAL FREQUENCY, WITH THE NET EFFECT THAT ONE SIDE OF THE PROJECTILE WOULD TEND TO BE PRESSED HEAVILY AGAINST THE TUBE BORE. THIS WOULD LEAVE A SMALL, CRESCENT SHAPED SPACE ON THE REVERSE SIDE OF THE SHELL THROUGH WHICH PROPELLANT GASES COULD ESCAPE AHEAD OF THE ROTATING BAND. THE RESULTING DIFFERENCE IN RADIAL PRESSURE ON OPPOSITE SIDES OF THE PROJECTILE WOULD TEND TO REINFORCE THE TRANSVERSE FORCE ALREADY CREATED BY THE DYNAMIC INSTABILITY. THE TOTAL TRANSVERSE FORCE WOULD INCREASE AS THE PROJECTILE APPROACHES THE MUZZLE DUE TO INCREASING INSTABILITY EFFECTS AND ONE-SIDED RADIAL WEARING OF THE ROTATING BAND.

THUS, MUZZLE WEAR MAY HAVE A VARIETY OF (SOMETIMES SUPPORTING, SOMETIMES OFF-SETTING) INITIATORS, BUT THE PRIMARY MECHANISM IS DYNAMIC INSTABILITY FOLLOWED BY A SUPPORTIVE GAS LEAKAGE PAST THE ROTATING BAND. THIS INTERPLAY MAKES MUZZLE WEAR A HIGHLY COMPLEX INTERFACE PROBLEM WHICH INVOLVES ALL THREE COMPONENTS UNDER SCRUTINY: THE TUBE, THE CHARGE AND THE PROJECTILE.

AGAIN, IT MUST BE STRESSED THAT THE FOREGOING IS A HYPOTHESIS BASED SOLELY ON RESULTS OF THIS TEST AND IS BY NO MEANS DEFINITIVE. SUBSEQUENT INVESTIGATIONS IN THE AREA OF MUZZLE WEAR SHOULD FURTHER TEST THE CREDIBILITY OF ALL STATEMENTS MADE.



*XM123 CHARGE WITH 17 1/2 OZ (TiO_2 + WAX)
**AS ABOVE WITH LEAD FOIL ADDED

YES = INDICATIONS OF BODY ENGRAVING, PRESSURE DIFFERENTIALS, ETC.
NO = NO INDICATIONS OF BODY ENGRAVING PRESSURE DIFFERENCES, ETC. FOR 7 ROUNDS

FIGURE 1 - TEST PLAN

TABLE I - RAW DATA

I. 155MM XM199 CANNON TUBE S.N. 14

Test rounds 1 - 48. Data not included for reasons cited in "Methods"

II. 155MM XM199 CANNON TUBE S. N. 1

Round	Charge	Projectile *	Body Engraving	Max.Chamber Pressure (ksi)	Projo. Wt. (lbs.)	Velocity (ft-sec-1)	Comments
49 ↑ to ↓ 53							Check-out round ↑ " "
54	M4A2	7	-	-	-	-	Warmer round
55	XM123	3	-	-	-	-	
56	"	"	Light	54.4	95.38	2797	
57	"	"	-	-	-	-	
58	"	5	-	-	-	-	
59	"	"	Burn	55.4	95.75	2825	
60	"	"	Light	52.3	95.75	2792	
61	"	"	Paint	53.4	95.81	2798	
62	"	5 @	Light	52.9	95.56	2795	
63	"	"	Paint	53.4	95.89	2798	
64	XM123	5 @	-	-	-	-	
65	"	4	Burn	54.6	95.38	2794	
66	"	"	Medium	55.5	95.50	2791	
67	"	"	Medium	56.0	95.23	2798	

Continued

Round	Charge	Projectile	Body Engraving	Max.Chamber Pressure (ksi)	Projo. Wt. (lbs.)	Velocity (ft-sec -1)	Comments
68	XM123	4 @	Heavy	54.7	95.50	2771	
69	"	"	Heavy	54.4	95.50	2784	
70	"	"	Heavy	55.2	95.34	2774	
71	"	3	Medium	55.2	95.33	2786	
72	"	8	Burn	56.4	95.06	2837	
73	M4A2	7					Decoppering round
74	"	"					"
75	"	"					"
76	"	"					"
77	"	"					"
78	"	"					"
79	"	"					"
80	"	"					"
81	"	"					"
82	"	"					"
83	"	"					"
84	"	"					"
85	"	"					"
86	"	"					"
87	XM123	5	Burn	54.0	95.31	2801	
88	"	"	Paint	49.6	96.43	2744	
89	"	"	-	-	-	-	
90	"	"	Burn	50.7	95.94	2764	
91	"	"	Light	51.7	96.00	2773	
92	"	"	Burn	53.4	95.94	2794	
93	"	4	Paint	52.9	95.96	2755	
94	"	4 @	Paint	54.8	95.48	-	
95	"	2	Burn	53.3	94.18	2788	
96	"	"	Heavy	55.7	94.18	2796	
97	"	4	Paint	55.8	95.63	-	
98	"	"	Light	56.1	95.68	2802	
99	"	7 @	Light	57.0	94.56	2796	
100	"	"	Burn	55.8	94.56	2839	
101	"	"	-	-	-	-	
102	"	8	Light	59.5	94.69	2876	
103	"	"	Light	58.9	95.00	2874	

Continued

Round	Charge	Projectile *	Body Engraving	Max.Chamber Pressure (ksi)	Projo. Wt. (lbs.)	Velocity (ft-sec -1)	Comments
104	XM123	8	Paint	58.6	95.12	2867	
105	"	6 @	Light	53.3	104.25	2686	
106	"	"	Paint	53.6	104.23	2710	
107	"	"	Burn	54.5	104.01	-	

III. 155mm XM181 Cannon Tube S.N. 4

Round	Charge	Projectile *	Body Engraving	Max.Chamber Pressure (ksi)	Projo. Wt. (lbs.)	Velocity (ft-sec -1)	Comments
108	M4A1	7	-	-	-	-	Warmer round
109	XM123	5	-	-	-	-	
110	"	"	Paint	56.7	95.94	2825	
111	"	"	Paint	56.0	96.00	2821	
112	"	"	Light	56.7	96.36	2823	
113	"	4	Burn	56.8	95.75	2807	
114	"	"	Burn	-	95.75	2803	
115	"	"	Burn	56.1	95.56	2800	
116	"	"	Paint	55.8	95.88	-	
117	"	"	Paint	55.5	95.75	-	
118	"	"	Paint	55.8	95.75	2795	
119	"	"	Paint	55.9	95.56	2803	
120	"	"	Paint	56.8	95.75	2798	
121	"	5	Burn	56.3	96.12	2823	
122	"	"	Paint	54.7	95.94	2819	
123	"	"	Burn	56.2	96.18	2827	
124	"	"	Paint	55.8	96.06	2821	
125	"	"	Paint	56.4	96.26	2818	
126	"	"	Paint	56.3	96.06	2831	
127	"	"	Burn	56.0	96.09	2820	
128	"	"	Paint	56.6	96.62	2820	
129	"	"	Burn	56.2	96.37	2817	
130	"	"	Burn	51.7	96.17	2776	
131	"	3	Paint	58.6	95.38	2817	
132	"	"	Burn	58.7	95.73	2825	

Continued

IV. 155mm XM181 Cannon Tube S.N. 17

Round	Charge	Projectile*	Body Engraving	Max. Chamber Pressure (ksi)	Projo. Wt. (lbs.)	Velocity (ft-sec -1	Comments
133 ↕ to ↕ 141							Check-out round ↕ "
142	M4A1	7	-	-	-	-	Warmer round
143	XM123	4	Paint	57.3	95.63	2834	
144	"	"	Burn	58.1	95.69	2828	
145	"	"	Medium	55.5	95.63	2805	
146	"	"	Light	59.1	95.81	2835	
147	"	"	Light	56.0	95.63	2810	
148	"	3	Burn	58.0	95.75	2823	
149	"	"	Light	58.4	95.52	2830	
150	"	"	Light	57.7	95.75	2817	
151	"	"	Light	58.4	95.98	2818	
152	"	"	Light	55.3	95.63	2798	
153	"	"	Light	58.3	95.75	2822	
154	"	1	Paint	56.1	94.44	2824	
155	"	"	Medium	54.9	94.25	2811	
156	"	1@	Heavy	56.0	94.50	2822	
157	"	"	-	-	-	-	
158	"	5@	Paint	57.8	96.25	2842	
159	"	"	Light	57.8	96.19	-	
160	"	"	Burn	55.3	95.81	2831	
161	"	"	Burn	55.9	96.36	2824	
162	"	"	Paint	54.9	95.89	2828	
163	"	"	Paint	56.7	96.11	2843	
164	"	"	Paint	57.0	96.25	2843	
165	"	4	Burn	56.3	95.94	2799	
166	"	"	Paint	57.4	95.53	2823	
167	"	"	Burn	58.6	95.81	2825	
168	"	"	Paint	57.6	95.81	2824	
169	"	"	Light	56.8	95.81	2815	

Continued

KEY @ Indicates plastic obturator used.

* Projectile are numbered as follows:

1. Match-up Slug
2. XM549 Slug with Nose
3. XM549 Slug (Unbalanced)
4. XM549 Slug (Balanced)
5. XM549 Projectile
6. XM483 Projectile
7. M107 Projectile
8. M101 Projectile

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