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155MM XM198 HOWITZER MUZZLE WEAR

R. G. Hasenbein

Watervliet Arsenal

Prepared for:

Army Armament Command

May 1975

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WVT-TR-75024

AD

155MM XM198 HOWITZER MUZZLE WEAR

R. G. HASENBEIN



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

MAY 1975

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Block No. 20. ABSTRACT(Continued)

between muzzle wear and: range percent error, wear at the commencement of rifling, and certain lots of propelling charge. On the average, muzzle wear began 175 inches from the breech face of the tube. Further, it was limited to a particular set of lands which, on the average, emerged from the muzzle at 5 o'clock (viewed from the muzzle). This set of lands can be traced back to the 12 - 1 o'clock position at the origin of rifling. A thermally altered layer was found on the top and driving edge of the lands. Since this layer is much harder than the base metal and contains many V-shaped cracks, it is susceptible to flaking and chipping. The location of the layer suggests that it is formed by abrasive action between the tube and projectile.

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Introduction

A 15,000 round Durability Test was conducted on the 155mm XM198 Howitzer system (see Fig. 1) from September 1973 to August 1974 at Camp McCoy, Wisconsin and Jefferson Proving Ground, Indiana. During the course of this test, several XM199 Cannon tubes (see Fig. 2) showed high muzzle wear and/or rates of muzzle wear.

This incidence of muzzle wear was not the first experienced with the XM198 Howitzer. During Development Tests of the Advanced Development Prototype, excessive muzzle wear was experienced with one tube, and there were indications of high muzzle wear on a second tube. This prompted a joint Watervliet/Picatinny Arsenal muzzle wear test at Malta, (N.Y.) Test Station. No single parameter observed controlled the occurrence of muzzle wear; it was concluded that a number of factors, perhaps in specific combinations, produce this condition. However, several parameters were found which increased either the incidence or the extent of muzzle wear.¹

In the meantime, the problem vanished as quickly as it had appeared, and no further work was done. During the Durability Test, the first two tubes tested showed low muzzle wear until quite late in their lives. The next four tubes in succession demonstrated relatively high rates of muzzle wear early in their lives, but the last tube tested again showed somewhat lower levels. It was felt (but not proven) that muzzle wear was detrimental to the Howitzer's ballistic performance.

1. R. G. Hasenbein, "Analysis of Muzzle Wear Data for the 155mm Howitzer XM198", Watervliet Arsenal Report (1973).



Figure 1. 155mm XM198 Howitzer

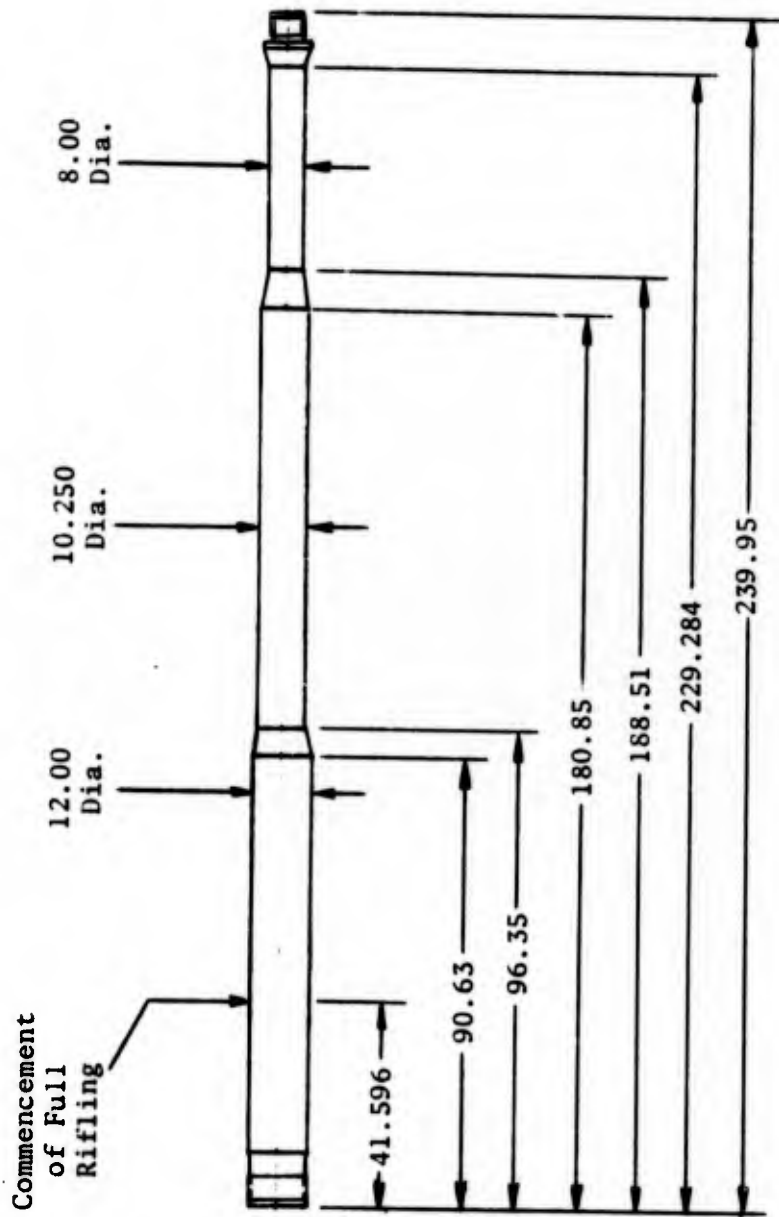


Fig. 2 155mm XM19S Cannon Tube

TABLE 1

FIRING HISTORY OF TUBES USED DURING DURABILITY TEST

<u>Tube S. N.</u>	<u>Zone</u>	<u>No. Rds.</u>		<u>XM123E2 Z8 Propelling Charge Lot No.</u>
48	8	<u>1,395</u>		IND-E-124
		1,395	Total Z-8 @ JPG	
	7	<u>13</u>	@ JPG	
		1,408	Total Rds. @ JPG	
		22	Rds. @ APG	
		<u>1,430</u>	Total Rds. on Tube	
49	8	55		IND-E-115 IND-E-124
	8	<u>515</u>		
		570	Total Z-8	
	7	<u>4</u>		
		574	Total Rds. on Tube	
51	8	729		IND-E-114 IND-E-123A IND-E-123B IND-E-123C IND-E-109B IND-E-115 IND-E-124
	8	5		
	8	5		
	8	5		
	8	249		
	8	940		
	8	<u>519</u>		
		2,452	Total Z-8	
	7	<u>25</u>		
		2,477	Total Rds. on Tube	
52	8	1,779		PA-E-01-433 IND-E-109A IND-E-114
	8	902		
	8	<u>132</u>		
		2,813	Total Z-8	
	7	<u>53</u>		
	2,866	Total Rds. on Tube		
53	8	1,007		IND-E-114 IND-E-115
	8	<u>1,663</u>		
		2,670	Total Z-8	
	7	<u>36</u>		
	2,706	Total Rds. on Tube		

TABLE 1 (Continued)

FIRING HISTORY OF TUBES USED DURING DURABILITY TEST

<u>Tube S.N.</u>	<u>Zone</u>	<u>No. Rds.</u>	<u>XM123E2 Z8 Propelling Charge Lot No.</u>
54	8	1,002	PA-E-01-433
	8	449	IND-E-82
	8	561	IND-E-88
	8	534	IND-E-114
			<u>2,546</u>
	7	36	
		<u>2,582</u>	Total Rds. on Tube
55	8	1,778	IND-E-124
	8	340	IND-E-130
		<u>2,118</u>	Total Z-8
	7	43	
		<u>2,161</u>	Total Rds. on Tube

The manufacturing and firing histories of tubes used during the Durability Test were investigated in order to determine the extent to which the tubes contributed to the muzzle wear problem. Several "fired-out" tubes from the test were cut up and studied in order to gain a better understanding of the mechanism of muzzle wear. Extensive data is included in the text for use in future muzzle wear investigations and research.

Tube Muzzle Wear Performance

It would be useful to compare the seven tubes used during the Durability Test and determine how each performed with regard to muzzle wear. All tubes were manufactured according to the same drawing (WTV-F24030) except for S.N.53 (WTV-F24245) which had a chromium plated bore and S.N.55 (WTV-F25247) which had gain twist rifling (from 1 turn in 40 calibers to 1 turn in 20 calibers). Table 1 is a recap of the firing history of each tube used.

Table 2 gives an overview of the tubes used along with number of rounds, final muzzle wear, average muzzle wear rate, and muzzle wear projected to 2,500 rounds (based on average muzzle wear rate). It is obvious from Table 2 that a considerable spread exists in average muzzle wear rates (from $.003 \times 10^{-3}$ to $.019 \times 10^{-3}$ inches per round). For 2,500 rounds, this would extrapolate from .008 to .048 inches of wear at the muzzle. From Table 2 it may be noted that tubes S.N.48, 49 and 53 had rather high wear rates, tube S.N.52 had a low wear rate, and tubes S.N.51, 54 and 55 were "somewhere in between".

TABLE 2

TUBES - EXTENT OF MUZZLE WEAR

<u>Tube S.N.</u>	<u>Rounds Fired</u>	<u>* Final Muzzle Wear (in.)</u>	<u>Average Muzzle Wear Rate (x10⁻³ in./rd.)</u>	<u>Projected Wear in 2500 rds.(in.)</u>
48	**1,408	.024	** .017	.043
49	574	.011	.019	.048
51	2,477	.018	.007	.018
52	2,866	.009	.003	.008
53	2,706	.048	.018	.045
54	2,582	.018	.007	.018
55	<u>2,161</u> 14,774 rds.	.013	.006	.015

+ 226 rounds fired using instrumented tube S.N. 46

Total: **15,000 rds.** fired during Durability Test.

* All values taken from stargage readings beginning vertically at the muzzle except S.N. 55 which was horizontal.

** 22 Additional rounds were fired from this tube during a muzzle brake test at Aberdeen Proving Ground (August 1973). Total tube rounds: 1430.

TABLE 3

TUBES - RATES OF MUZZLE WEAR

<u>Tube S. N.</u>	<u>Tube Round</u>	<u>*Muzzle Wear</u>	<u>Muzzle Wear Rate(x10⁻³ in. per rd.) Between Readings.</u>
48	0	.000	---
	22	.004	.182
	1104	.022	.017
	1430	.024	.006
49	0	.004	---
	56	.020	-.071
	574	.011	.021
51	0	.000	---
	580	.017	.029
	1000	.020	.007
	1446	.019	-.002
	1808	.021	.006
	2477	.018	-.004
52	0	.001	---
	1813	.006	.003
	1916	.008	.019
	2249	.007	-.003
	2475	.009	.009
	2732	.008	-.004
	2866	.009	.007
53	0	.000	---
	560	.018	.032
	709	.024	.040
	1025	.035	.035
	1828	.042	.009
	2026	.043	.005
	2706	.048	.007
54	0	.001	---
	2042	.009	.004
	2146	.007	-.019
	2394	.012	.020
	2506	.017	.045
	2582	.018	.013

(Continued on next page)

TABLE 3 (Continued)

<u>Tube S.N.</u>	<u>Tube Round</u>	<u>*Muzzle Wear</u>	<u>Muzzle Wear Rate(x10⁻³in.per rd.) Between Readings.</u>
55	0	.001	----
	188	.002	.005
	255	.004	.030
	483	.002	-.009
	696	.008	.028
	898	.012	.020
	1088	.008	-.021
	1292	.012	.020
	1594	.018	.020
	1696	.019	.010
	1899	.021	.010
	2100	.021	.000
	2161	.013	-.131

* All values taken from stargage readings beginning vertically at the muzzle except S.N. 55 which began horizontally.

A closer look reveals that the above data (while correct) might be misleading. Table 3 shows that muzzle wear rate is not linear; rather, it varies without regard to the number of rounds on the tube. The data in Table 3 is shown graphically in Figure 3. It can be seen, for example, that S.N.51, had an extremely high wear rate at the muzzle for the first 580 rounds and then decreased drastically for the last 1,897 rounds. On the other hand, S.N.54 demonstrated a low wear rate for its first 2,146 rounds; the rate then increased considerably for the last 436 rounds. Numerous other examples of varying rates of wear can be cited.

Two conclusions can be drawn: (1) as stated before, muzzle wear rate can vary substantially during the life of the tube, apparently without regard to how many rounds have been fired. (2) Knowing the gross muzzle wear at the end of a tube's life does not give a true picture of the tube's muzzle wear performance. It is also important to know the muzzle wear rate at various times during its life.

Based on Table 3 and Figure 3, then, tubes S.N.48, 49,51 and 53 will be considered to have "high muzzle wear" because of the high rates of muzzle wear which occurred early in their lives. Tubes S.N.52 and 54 will be considered to have "low muzzle wear" since they maintained low muzzle wear rates until quite late in their lives. Tube S.N.55 apparently had a much more erratic muzzle wear pattern than the others, and a case could be made for calling it either a "high" or "low muzzle wear" tube. However, since its final value of .013 inches of wear has been confirmed twice by Jefferson Proving Grounds personnel, since it tended to show generally lower wear levels throughout its life and since several of the stargage readings were obtained while the tube was hot (thus giving

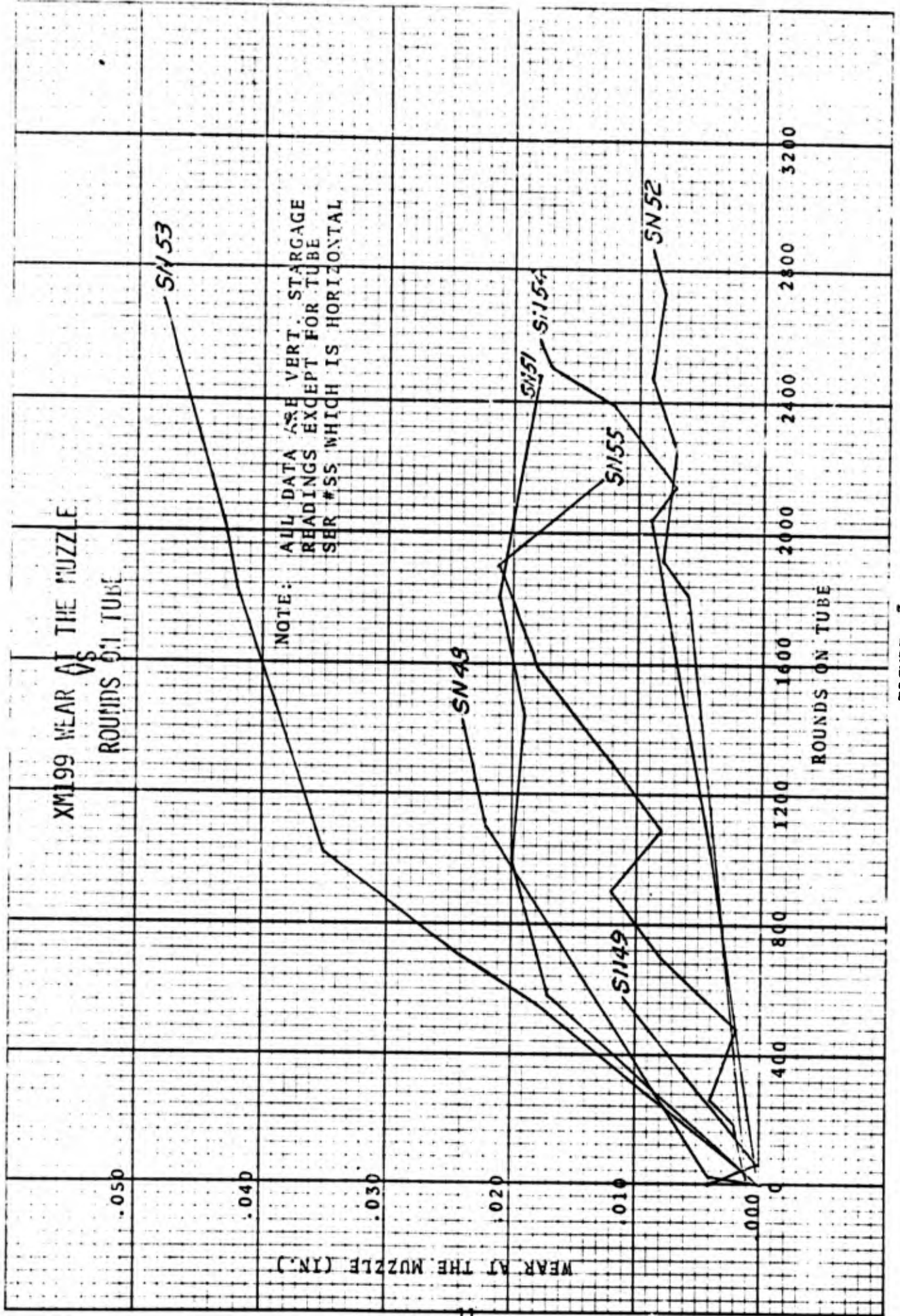


FIGURE 3

TABLE 4

TUBE WEAR AND BALLISTIC PERFORMANCE

<u>Tube S.N.</u>	<u>Tube Rds. Ballistic Data Taken</u>	<u>Wear at Muzzle (in.)</u>		<u>Wear at Commencement of Rifling (in.)*</u>		<u>RPE (%)</u>	<u>Avg.Velo- city (fps)</u>	<u>Ave. Pres- sure (ksi)</u>
		<u>V</u>	<u>H</u>	<u>V</u>	<u>H</u>			
48	No Ballistic Data Available							
49	No Ballistic Data Available							
51	7-16	.000	.000	.003	.002	.29	2731	46.2
	1005-1015	.020	.013	.058	.054	.40	2724	46.7
	1456-1465	.019	.008	.070	.077	.24	2711	45.3
	1814-1824	.021	.012	.093	.083	.44	2711	46.3
52	1906-1915	.008	.008	.084E	.085E	.22	2696	45.0
	2255-2264	.007	.008	.090	.089	.16	2708	44.6
	2466-2475	.009	.009	.095	.091	.24	2685	43.6
	2723-2732	.008	.009	.108	.104	.39	2665	42.8
53	5-14	.000	.000	.001	.001	.31	2756	49.1
	566-576	.018	.013	.000	.002	.30	2759	49.6
	1015-1025	.035	.033	.023	.019	.47	2755	48.9
54	2137-2146	.007	.007	.118	.117	.35	2686	43.8
	2385-2394	.012	.012	.108	.105	.53	2672	42.9
	2497-2506	.017	.018	.112	.110	.44	2654	42.3

TABLE 4 (Continued)

<u>Tube S.N.</u>	<u>Tube Rds. Ballistic Data Taken</u>	<u>Wear at Muzzle (in.)</u>		<u>Wear at Commencement of Rifling (in.)*</u>		<u>RPE (%)</u>	<u>Avg.Velo- city (fps)</u>	<u>Avg. Pres- sure (ksi)</u>
		<u>V</u>	<u>H</u>	<u>V</u>	<u>H</u>			
55	242-252	.004	.004	.007	.013	.25	2730	48.1
	493-502	.002	.002	.031	.032	.26	2731	47.7
	1297-1306	.008	.012	.069	.085	.31	2701	44.2
	1497-1506	--	--	--	--	.49	2690	44.7
	1701-1710	.011	.019	.091	.102	.14	2695	45.0
	1903-1912	.011	.021	.098	.112	.23	2695	44.0
	2104-2113	.012	.021	.104	.117	.22	2688	43.9
	2152-2161	.008	.013	.102	.118	.13	--	43.7

*Readings taken 41.6 inches from rear face of tube (nominal commencement of rifling) except those marked "E"; the latter are interpolated from stargage data to 41.6 inches from RFT.

misleadingly high readings), tube S.N.55 will be termed a "low muzzle wear" tube for the purposes of this report.

Tube Ballistic Performance

During the course of the Durability Test, only tubes S.N.51, 52, 53 and 54 were fired until considered "worn out". Tubes S.N.48 and 49 had relatively few rounds fired from them, and S.N.55 was still performing well at the conclusion of the test. For each of the worn out tubes, projectile yaw was the factor upon which condemnation was based.

At various times during each* tube's life, ballistic data was taken. average pressure, average velocity near the muzzle, and range percent error. These parameters have been tabulated in Table 4 and plotted for each tube in Figures 4 thru 8. In figures 9 thru 11, these data are shown as a function of vertical muzzle wear in hopes of finding valid linear relationships:

A. Range Percent Error (RPE) as a Function of Muzzle Wear:

Fig. 9 shows a standard deviation of .1 and correlation coefficient of .469. This means that RPE tends to vary directly with muzzle wear. Statistical analysis shows that the linear relationship between muzzle wear and range percent error shown in Fig. 9 is valid with 95% confidence. However, only 22% of the variation in RPE is determined by muzzle wear.

B. Velocity as a function of Muzzle Wear: Fig. 10 reveals a standard deviation of 30.512 and correlation coefficient of .102. Statistical analysis shows that the linear relationship depicted in Fig. 10 is, for all practical purposes, not valid.

*No ballistic data was gathered for tubes S.N.48 and 49.

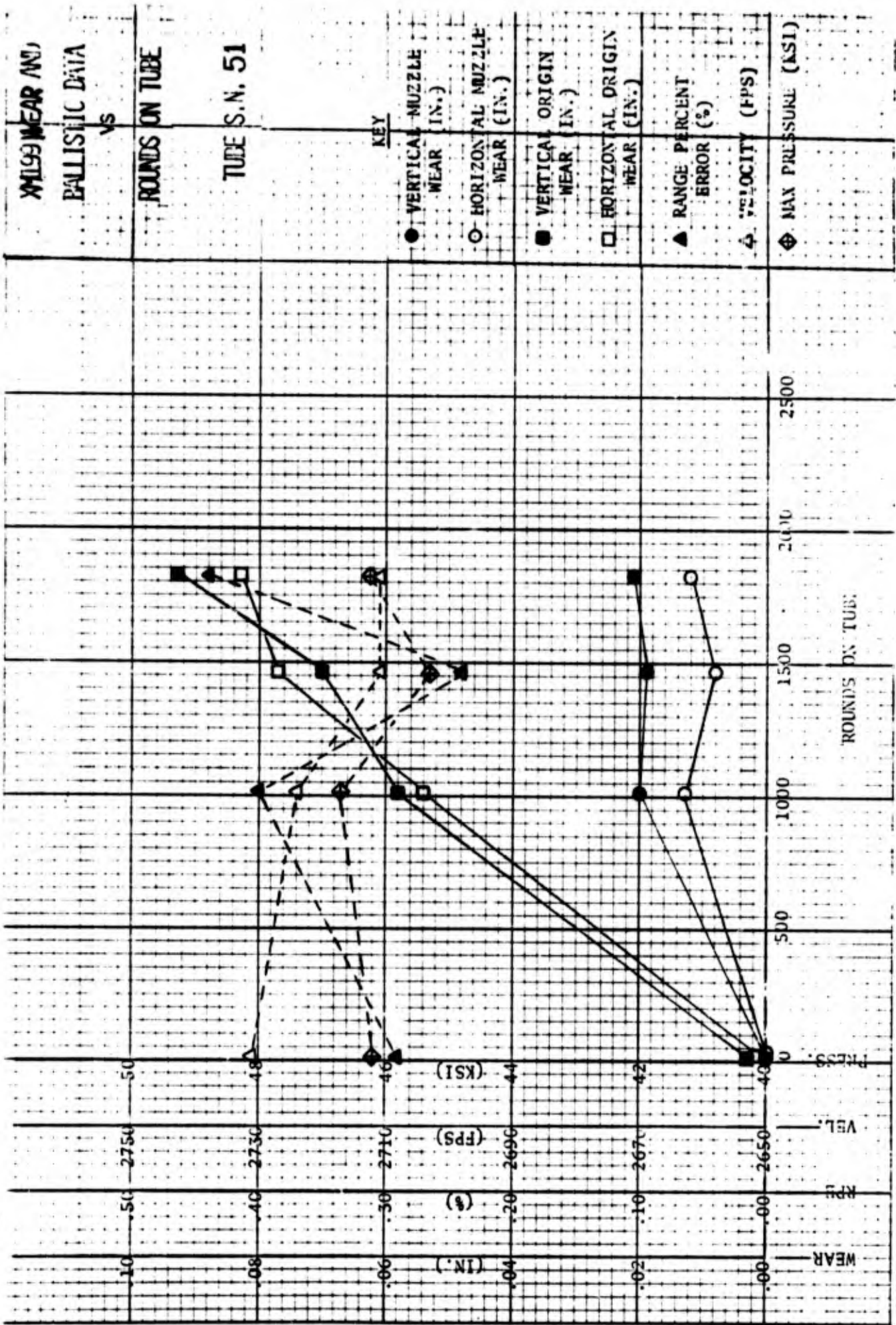


FIGURE 4

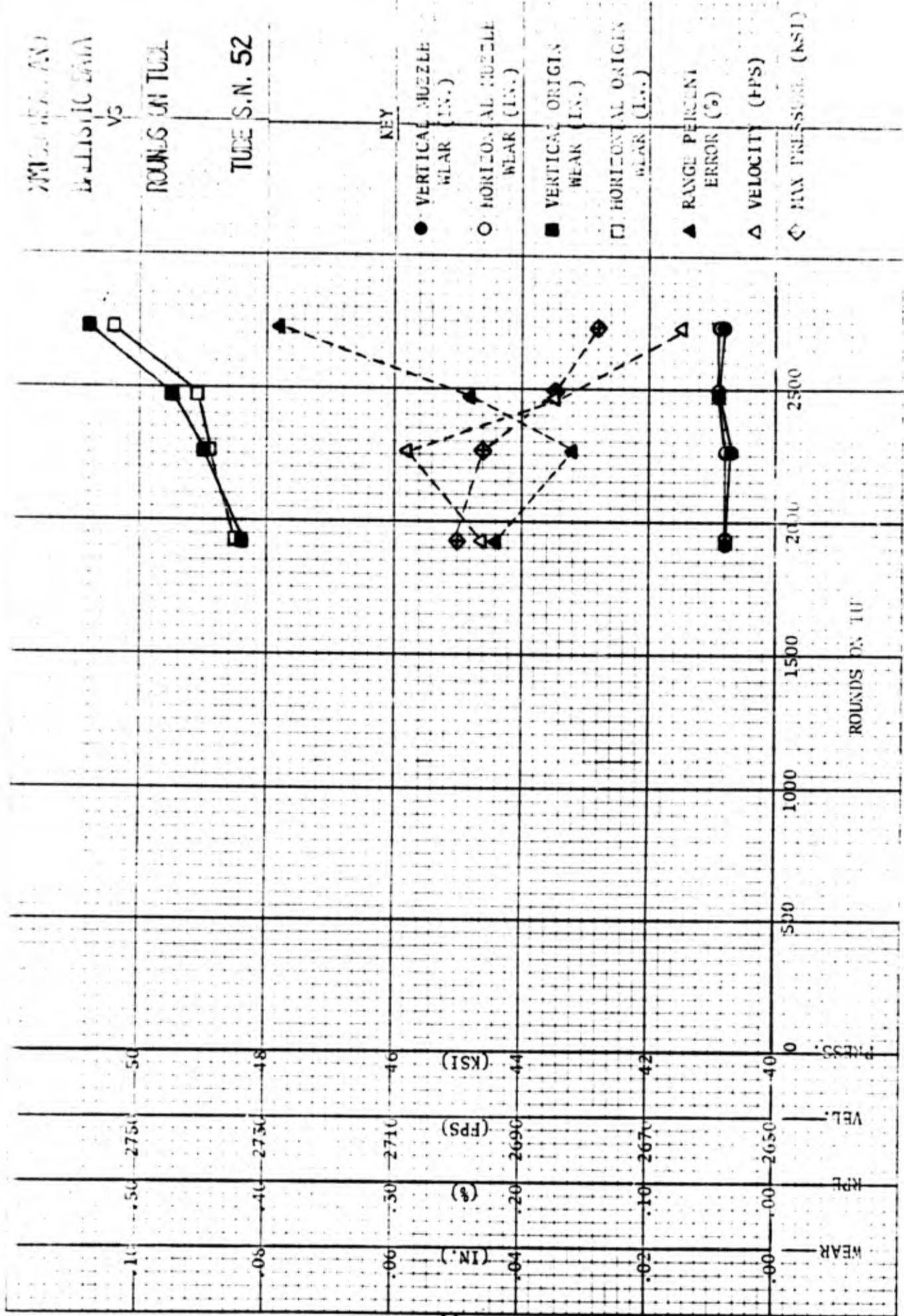


FIGURE 5

M193 WEAR AND BALLISTIC DATA VS ROUNDS ON TUBE

TUBE S.N. 53

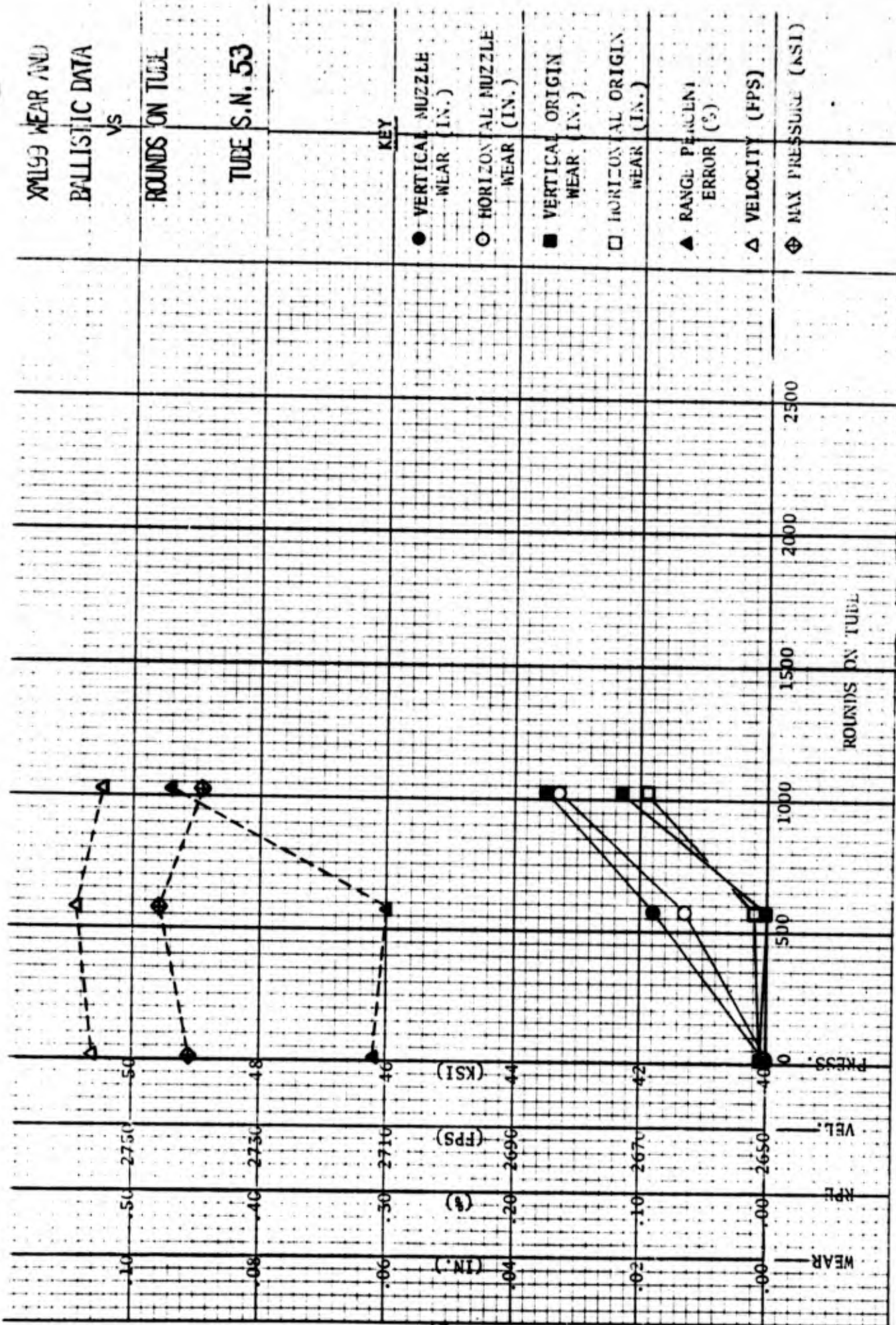


FIGURE 6

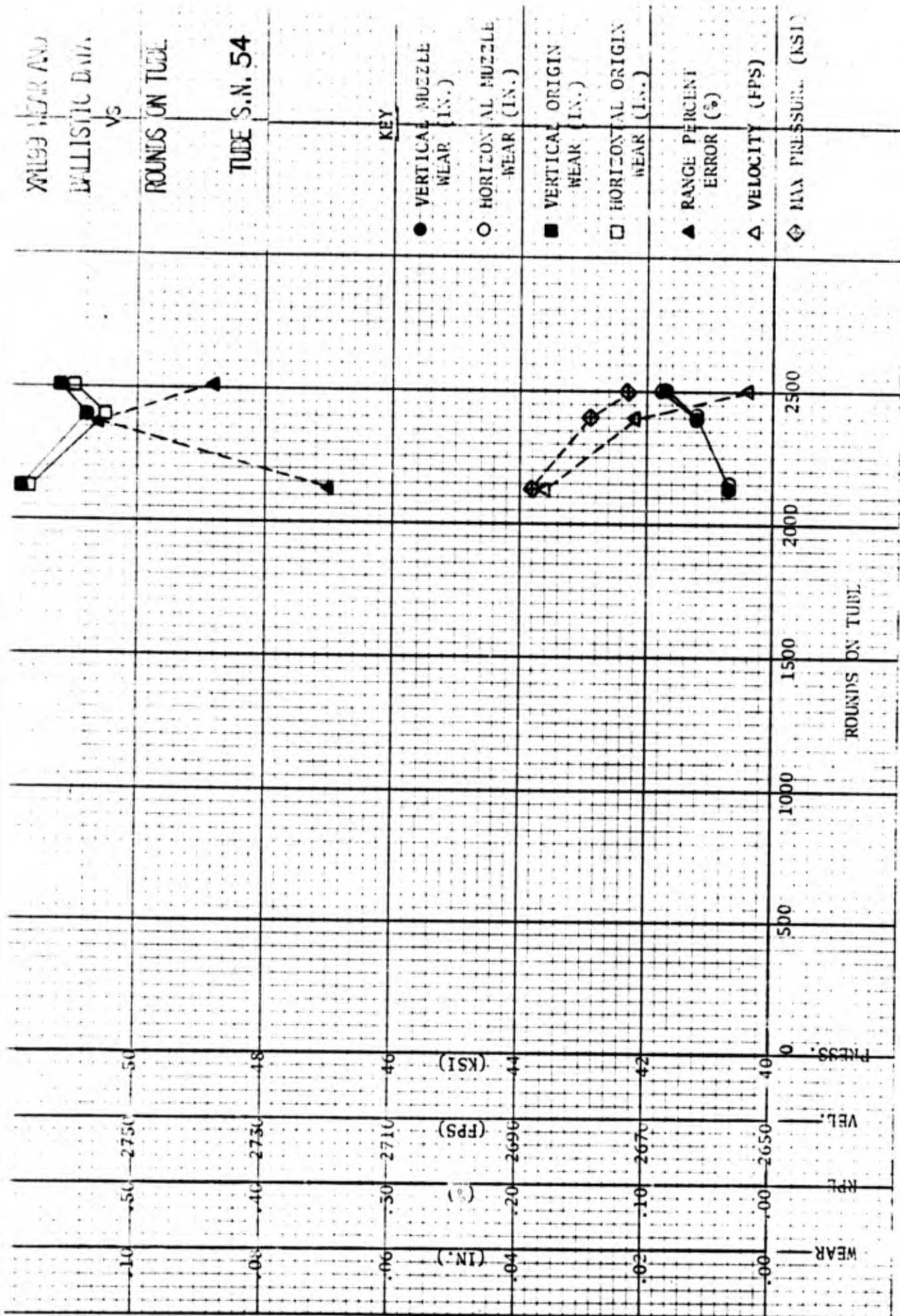


FIGURE 7

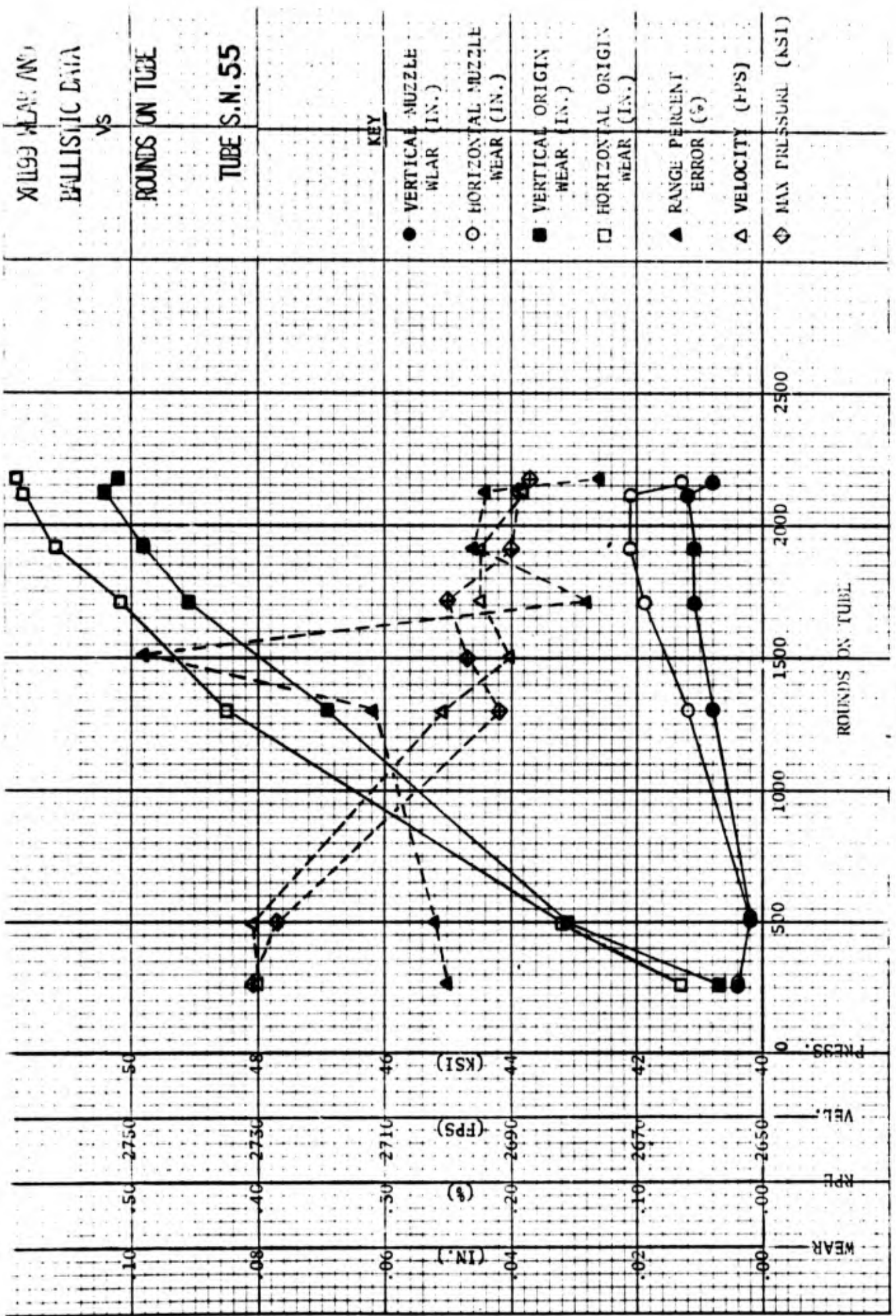


FIGURE 8

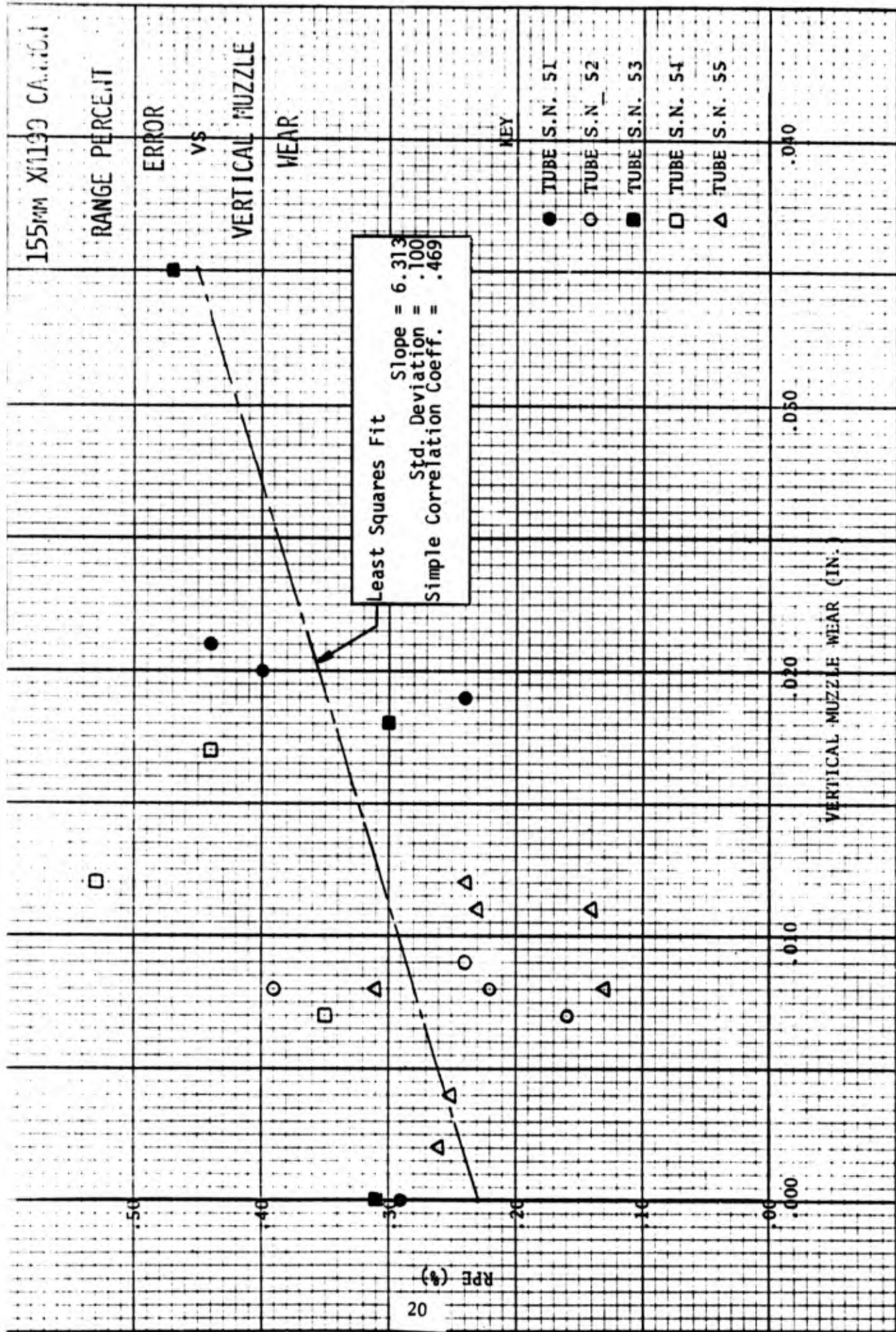


FIGURE 9

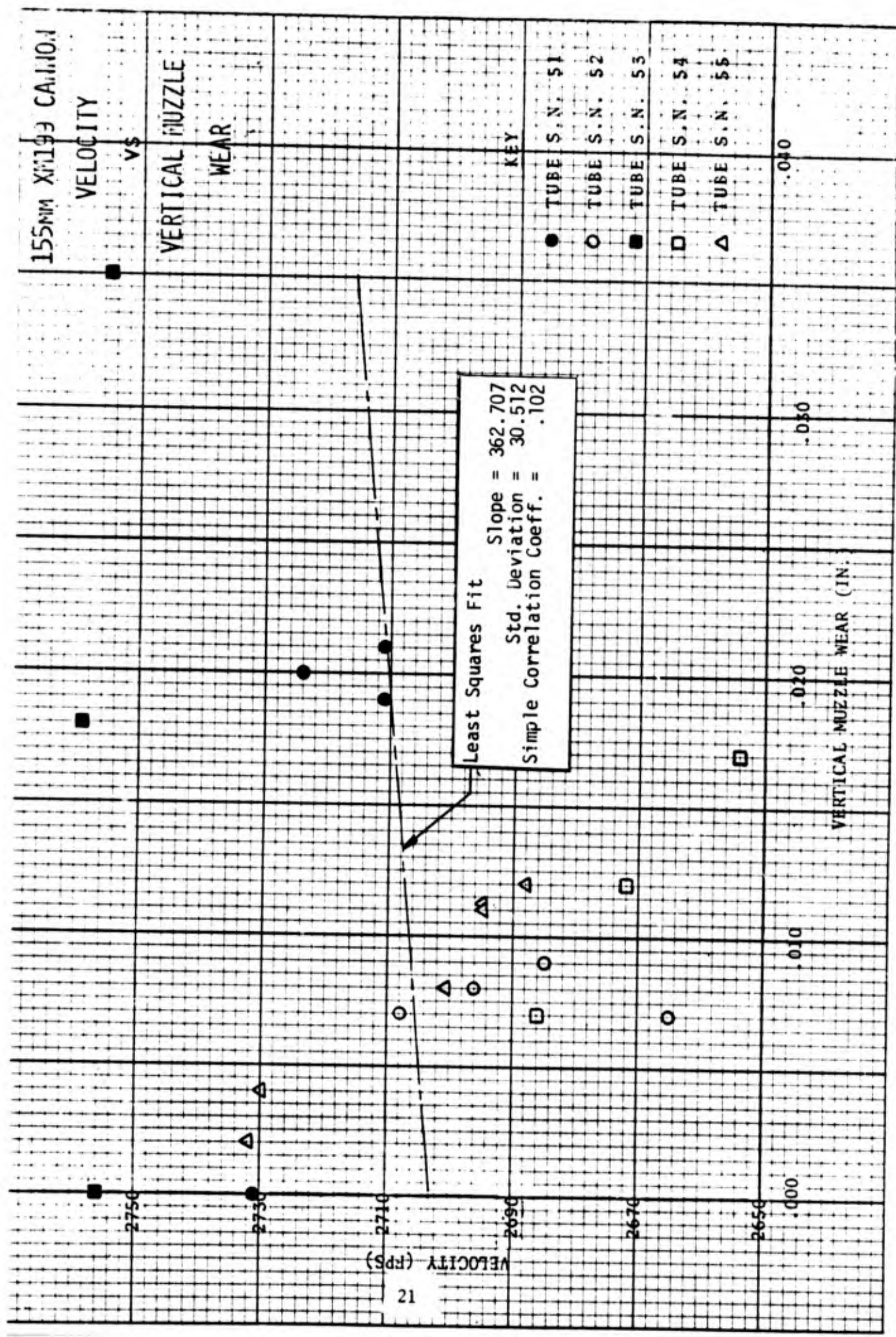


FIGURE 10

C Maximum Pressure as a Function of Muzzle Wear. Fig. 11 reveals a standard deviation of 2.238 and a correlation coefficient of .145. Statistical analysis shows that the linear relationship depicted in Fig. 11 above is, for all practical purposes, not valid.

It can be concluded from the Durability Test data with 95% confidence that a direct linear relationship exists between range percent error and muzzle wear. Attempts to perform regressions of maximum pressure and velocity on muzzle wear did not result in significant linear relationships.

Muzzle Wear as a Function of Wear at the Commencement of Full Rifling.

Vertical stargage data from Table 4 are plotted in Fig. 12. As stated previously, the bore of S.N.53 had been chrome plated .003 inches (nominal) per surface. Fig. 12 shows that its muzzle wear vs. commencement wear pattern differed significantly from the other six tubes. Two regressions of muzzle wear on commencement wear were performed, one including data from S.N.53 and one excluding this data. As can be seen in Fig. 12, both regressions resulted in an approximate 10 to 1 relationship between commencement wear and muzzle wear. Statistical analysis shows that the relationship including data from S.N.53 is valid with only 80 to 90% confidence; however, the regression excluding data from S.N.53 is valid with approximately 98% confidence. Likewise, only 12% of the total variation in muzzle wear can be explained by commencement wear in the first regression whereas, in the second regression, 40% of the total variation in muzzle wear can be explained by commencement wear. Thus, although

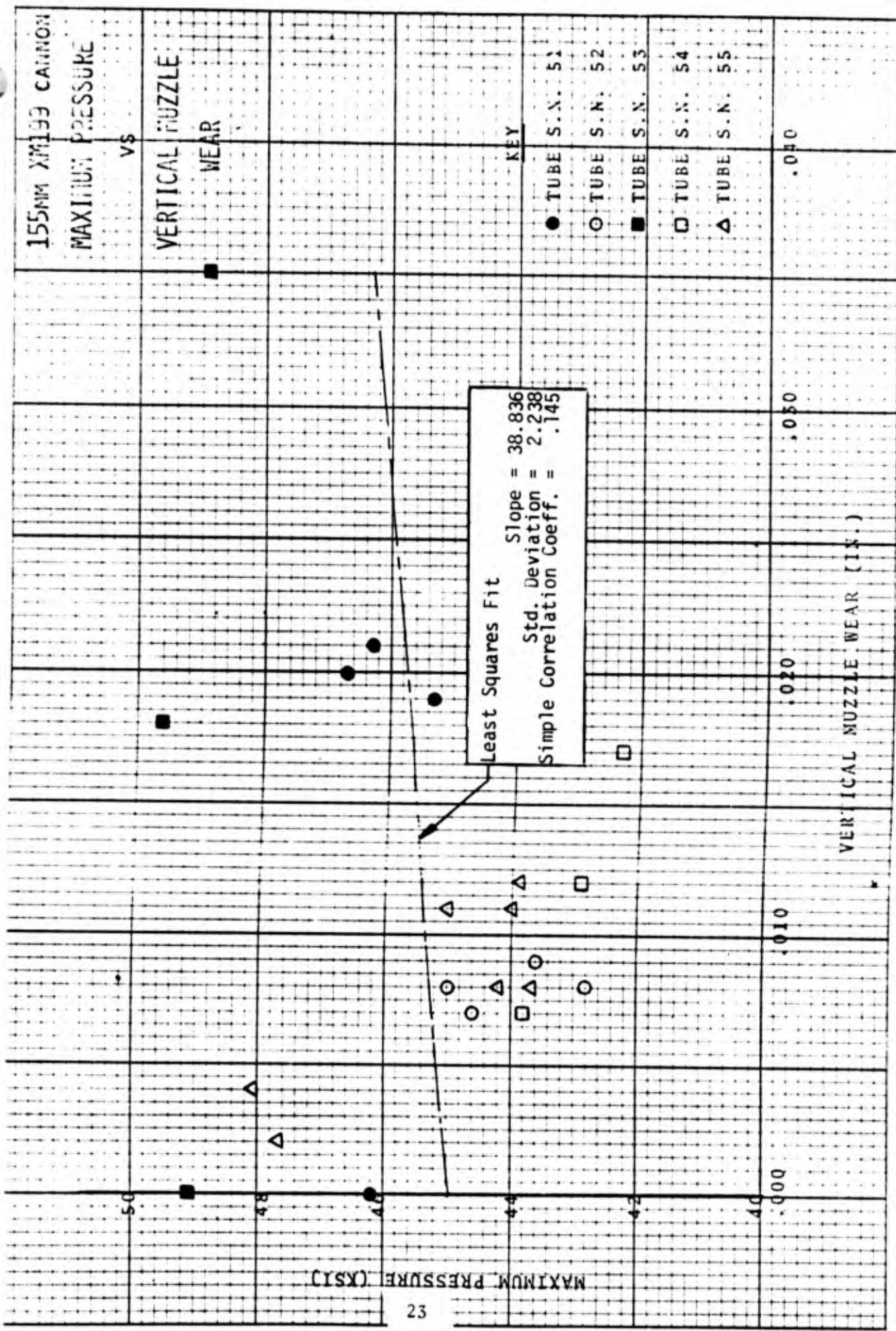


FIGURE 11

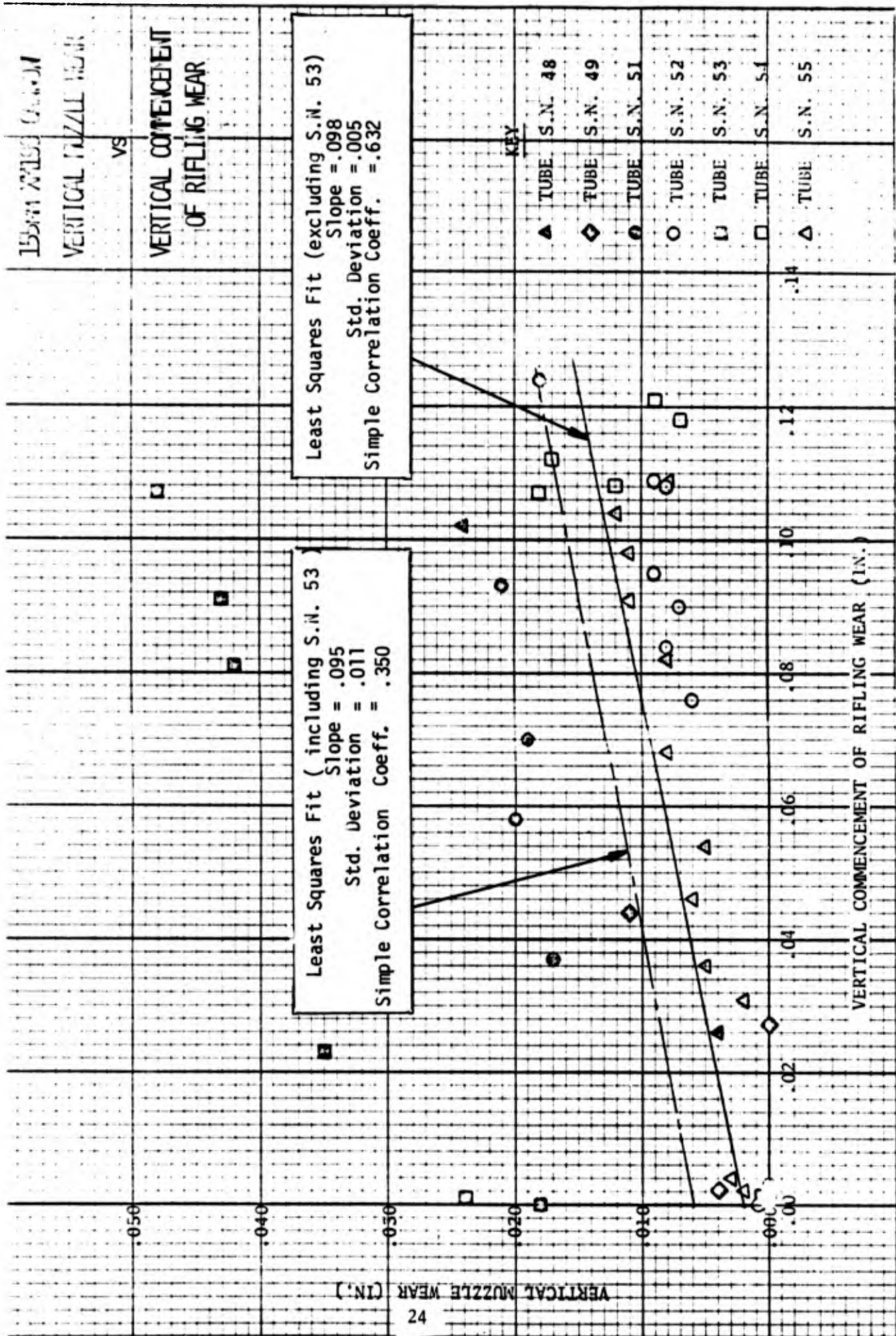


FIGURE 12

vertical wear at the muzzle is dependent in part upon wear at the commencement of rifling, other factors also appear to play a large part in determining the extent of muzzle wear.

Muzzle Wear as a Function of Propelling Charge Lot.

Midway through the Durability Test, it was noted that at least one of the XM123 E2 Zone 8 Propellant Charge Lots (IND-E-114) appeared to have been used during periods of high muzzle wear for four tubes tested to that point. Table 5 has been created to help determine overall muzzle wear rates associated with propelling charge lots used during the entire Durability Test.

Let: A = Number of Rounds (including all Zone 7 and 8 Rounds) fired during a given period.

B = Lot usage factor (number of rounds from specified lot/A).

C = Wear rate ($\times 10^{-3}$ in/rd) during period.

An approximate value of overall muzzle wear rate for a given propelling charge lot can be determined from the following equation:

$$\text{Overall Wear Rate} \Big|_n = \frac{\sum_{i=1}^m A \cdot B \cdot C}{\sum_{i=1}^m A \cdot B} \Big|_n$$

where i = dummy variable
m = number of samples taken for a given prop. charge lot
n = a given prop. charge lot
A, B, C given in Table 5

Results are tabulated in Table 6. It can be seen that lot IND-E-114 was associated with a muzzle wear rate of $.026 \times 10^{-3}$ in/rd. (which extrapolates to .065 inches in 2,500 rounds). The next highest lot wear rate (IND-E-124; $.009 \times 10^{-3}$ in/rd.) was only a third of the above value but still would

TABLE 5

BREAKDOWN OF PROPELLING CHARGE LOTS AND MUZZLE

WEAR RATES FOR EACH TUBE TESTED

<u>Tube S.N.</u>	<u>Ⓐ 1. #Rds.</u>	<u>Zone 8 Prop Charge Lot (s)²</u>	<u>Ⓑ Lot Usage Factor³</u>	<u>Muzzle Wear (in.)⁴</u>	<u>Ⓒ Wear Rate (x10⁻³ in./rd.)</u>
48	1,082	IND-E-124	.99	.018	.017
	326	IND-E-124	.99	.002	.006
49	56	IND-E-115	.98	-.004	-.071
	518	IND-E-124	.99	.011	.021
51		(IND-E-114	.97)		
		(IND-E-123A	<.01)		
	580	-(IND-E-123B	<.01) -	.017	.029
		(IND-E-123C	<.01)		
	420	-(IND-E-114	.40) -	.003	.007
		(IND-E-109B	.59)		
	446	IND-E-115	.99	-.001	-.002
	362	IND-E-115	.98	.002	.006
	669	-(IND-E-115	.21) -	-.003	-.004
		(IND-E-124	.78)		
52	858	PA-E-01-433	.98	.003	.003
	955	PA-E-01-433	.98	.002	.002
	103	IND-E-109A	.95	.002	.019
	333	IND-E-109A	.98	-.001	-.003
	226	IND-E-109A	.98	.002	.009
	257	IND-E-109A	.99	-.001	-.004
	134	IND-E-114	.99	.001	.007
53	560	IND-E-114	.98	.018	.032
	149	IND-E-114	.99	.006	.040
	316	IND-E-114	.98	.011	.035
	803	IND-E-115	.99	.007	.009
	198	IND-E-115	.99	.001	.005
	680	IND-E-115	.99	.005	.007

TABLE 5 (Continued)

BREAKDOWN OF PROPELLING CHARGE LOTS AND MUZZLEWEAR RATES FOR EACH TUBE TESTED

Tube S.N.	(A) 1. #Rds.	Zone 8 Prop Charge lot (s) ²	(B) Lot Usage Factor ³	Muzzle Wear (in.) ⁴	(C) Wear Rate (x10 ⁻³ in./rd.)
54	1,017	PA-E-01-433	.99	.003	.003
	1,025	-(IND-E-82	.44)-	.005	.005
		(IND-E-88	.55)		
	104	IND-E-114	1.00	-.002	-.019
	248	IND-E-114	.99	.005	.020
	112	IND-E-114	.99	.005	.045
	76	IND-E-114	.99	.001	.013
55	188	IND-E-124	.89	.001	.005
	67	IND-E-124	.99	.002	.030
	833	IND-E-124	.99	.004	.005
	1,073	-(IND-E-124	.67)-	.005	.005
		(IND-E-130	.32)		

1. # Rds. - Includes all Zone 7 and 8 rounds fired during a given period.
2. All lots used were XM123E2 Zone 8 Propelling Charge. Zone 7 lots used are not shown.
3. Lot Usage Factor = (#rds. from the specified lot/A).
4. From vertical stargage readings except for SN 55 which are horizontal.

TABLE 6

TABULATION OF OVERALL MUZZLE WEAR RATES
ASSOCIATED WITH PROPELLING CHARGE LOTS

<u>XM123E2-Z8</u> <u>Prop-Charge Lot</u>	<u>No. of</u> <u>Tubes</u>	<u>Rds.</u>	<u>Overall Muzzle</u> <u>Wear Rate</u> <u>(x10⁻³ in./rd.)</u>
IND-E-124	4	4,207	.009
PA-E-01-433	2	2,781	.003
IND-E-115	3	2,658	.004
IND-E-114	4	2,402	.026
IND-E-109A	1	902	.002
IND-E-88	1	561	*
IND-E-82	1	449	*
IND-E-130	1	340	*
IND-E-109B	1	249	*
IND-E-123A	1	5	*
IND-E-123B	1	5	*
IND-E-123C	1	5	*
Total Zone 8 Rds.		14,564	
Zone 7 Rds.		210	
		<u>14,774</u>	
Instrumented Tube SN 46		226	
Total Rds. Durability Test		<u>15,000</u>	

* Insufficient sample/data.

produce .023 inches of wear in 2500 rounds. Three other lots were associated with much lower overall muzzle wear rates which would result in from .005 to .010 inches of muzzle wear in 2500 rounds.

Description of Muzzle Wear.

A. Introductory Comments

1. Tube Dimensional Specifications. All tubes used during this test conformed with the following bore specifications at manufacture:

Land-to-land diameter = $6.100 + .002$ inches

Depth of groove (height of land) = $.050 + .003$ inches

The groove-to-groove diameter of a newly manufactured tube could be as much as 6.208 inches.

2. Stargage Bore Measurements. Periodic bore measurements were made during the life of each tube using a stargage. This instrument indicates the distance between two diametrically opposed lands or grooves at various axial locations. During this test, the stargage was set up either in a vertical (6 and 12 o'clock lands or grooves) or in a horizontal (3 and 9 o'clock lands or grooves) position at the muzzle. Measurements were taken at discrete axial intervals as the gage followed the initial pair of lands or grooves back to the origin of rifling. Stargage data is well suited for plotting the tube's overall wear pattern in the axial direction. Further, the sum of the two (diametrically opposed) land heights can be found easily by subtracting the land-to-land diameter from the adjacent groove-to-groove diameter at a given axial location. However, there is no way of knowing from stargage data whether the land on one side is worn more than its diametrically opposed land.

B. Physical Location

1. Axial Location. The vertical stargage readings were greater than or equal to (within .001 inches) the horizontal readings for every tube except S.N.55 (gain twist rifling). Selected axial wear data are presented in Figures 13 thru 19 for the seven tubes tested. Two types of wear are evident in these figures. The first is origin wear which is greatest in the vicinity of the origin of rifling and decreases downbore. At some axial location, wear again becomes significant and increases all the way to the muzzle. The latter wear phenomena ordinarily is confined to the lands and is termed muzzle wear. Traditionally, origin wear and muzzle wear have been treated as two distinct problems.

Table 7 shows the axial location where muzzle wear began to develop for each tube tested; the last available stargage readings were used. Muzzle wear was evident over the last 44 to 94 inches of projectile travel for the seven tubes tested. On the average, muzzle wear began approximately 175 inches from the rear face of the tube (65 inches from the muzzle) and increased all the way to the muzzle.

It may be noticed that groove wear has not been mentioned. Again, the reason is that muzzle wear primarily affects the lands, not the grooves. After firing, the maximum groove-to-groove diameter encountered in the muzzle wear region was 6.208 inches; as previously stated, this value would be acceptable for a newly manufactured tube.

2. Circumferential Location. Tube circumferential wear patterns cannot be determined from stargage data. Therefore, other methods of locating wear at the muzzle were attempted during this Durability Test.

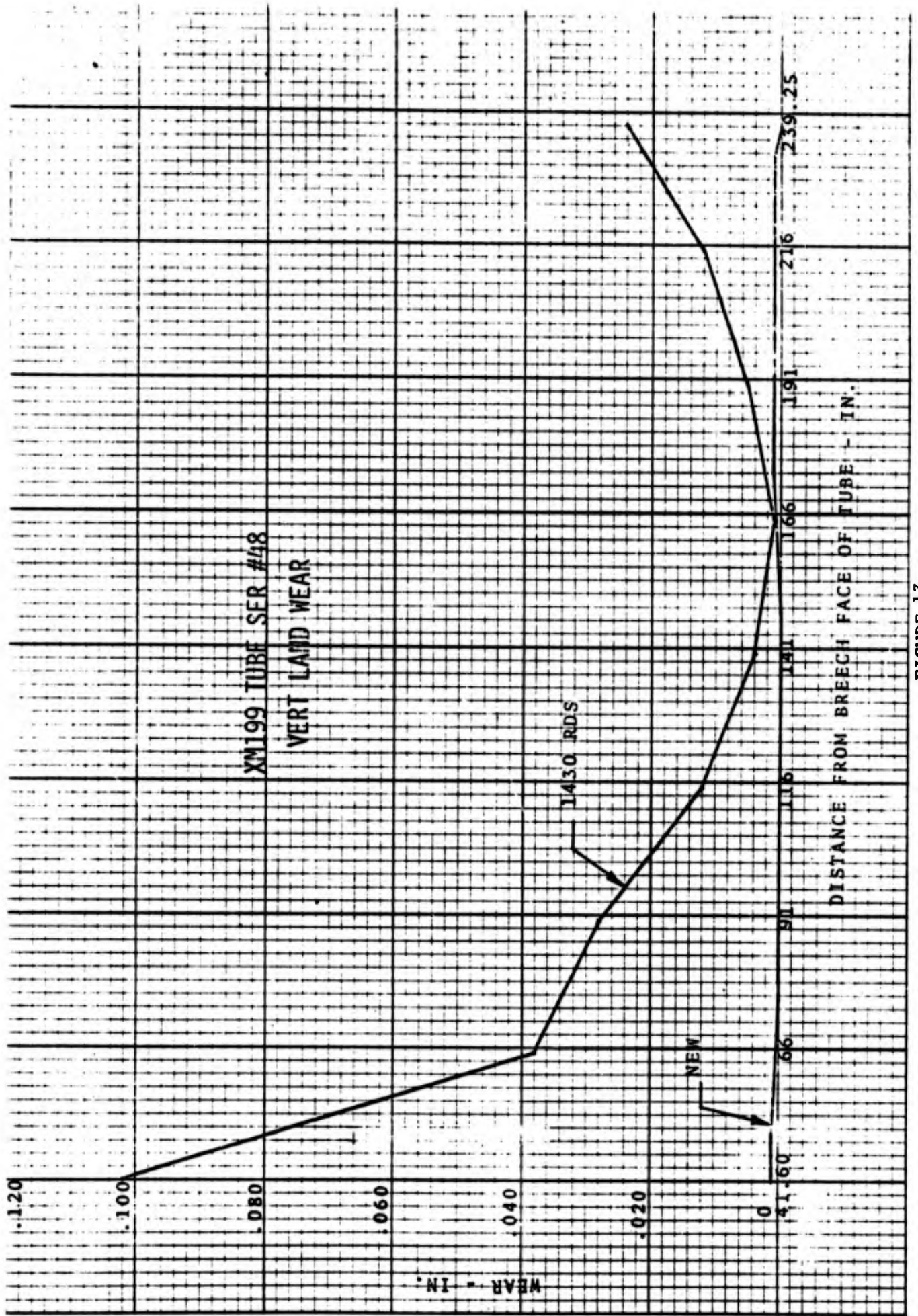


FIGURE 13

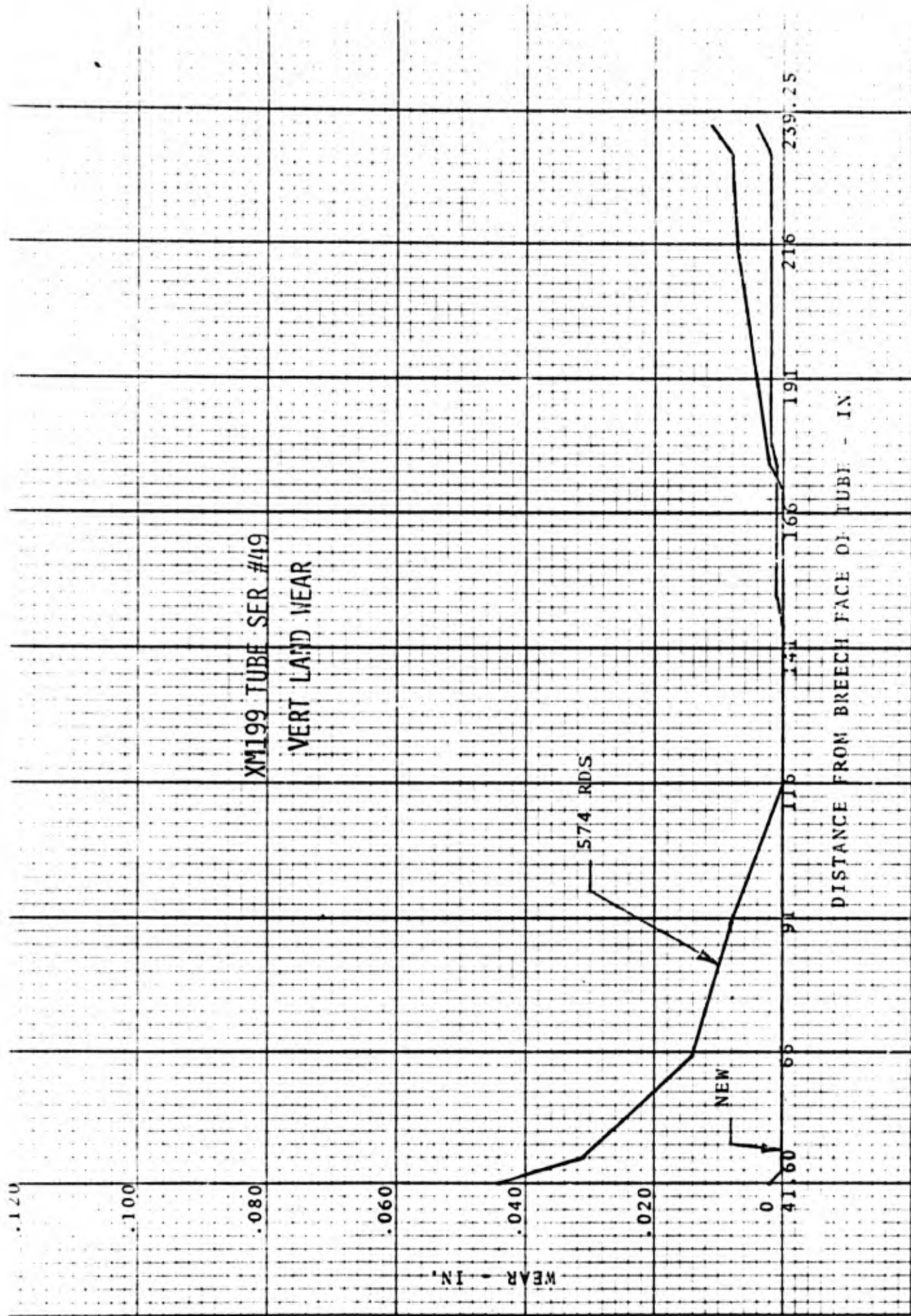


FIGURE 14

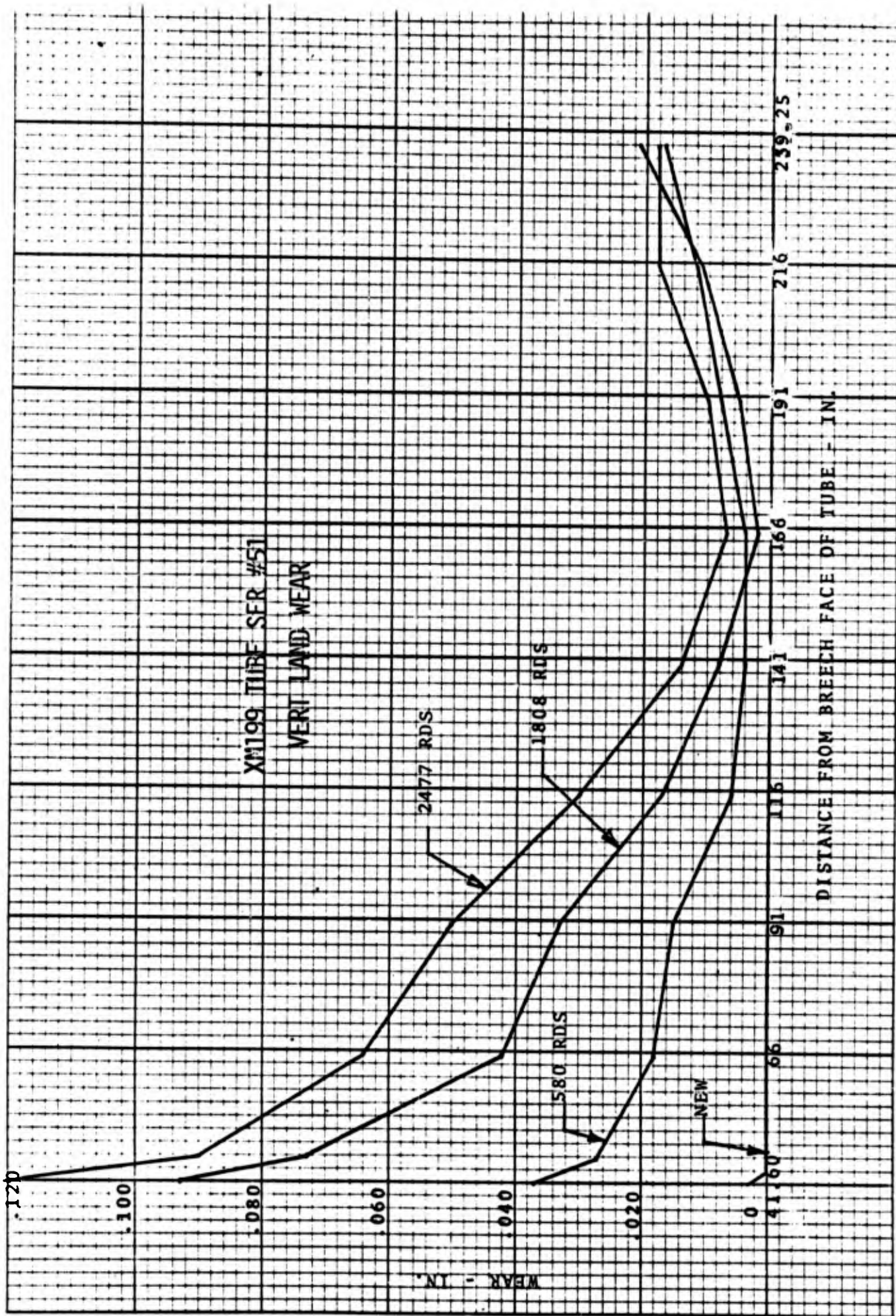


FIGURE 15

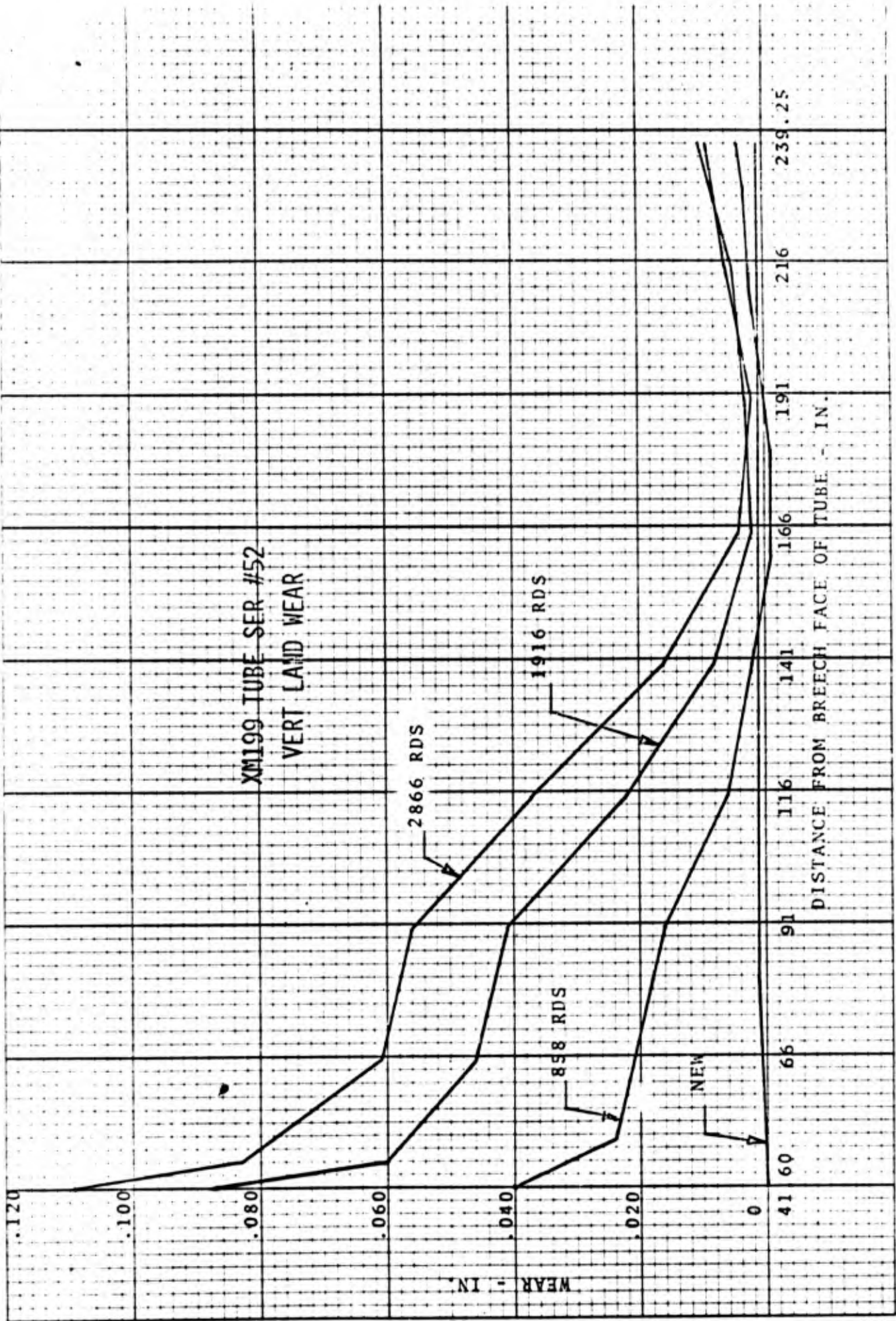


FIGURE 16

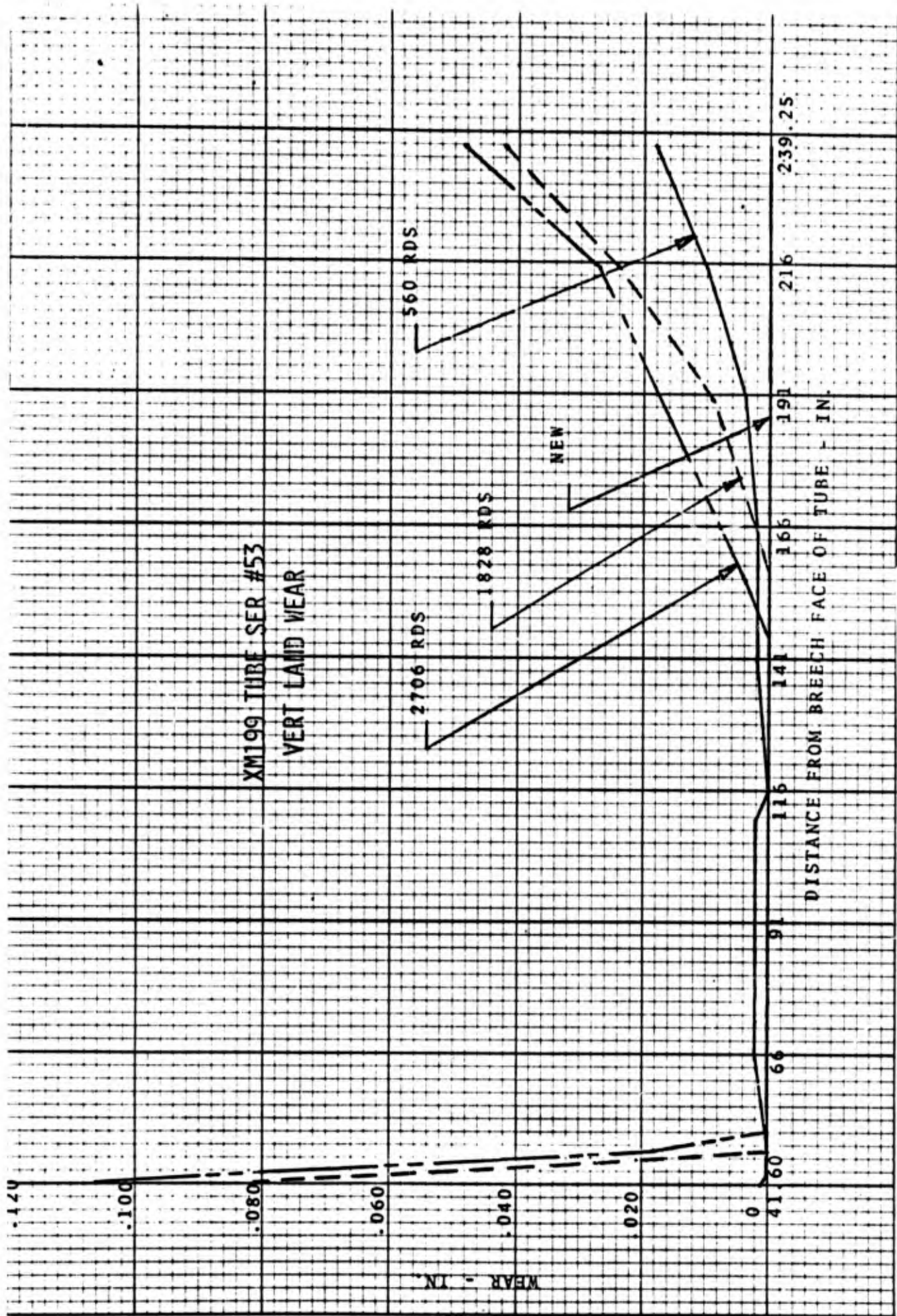


FIGURE 17

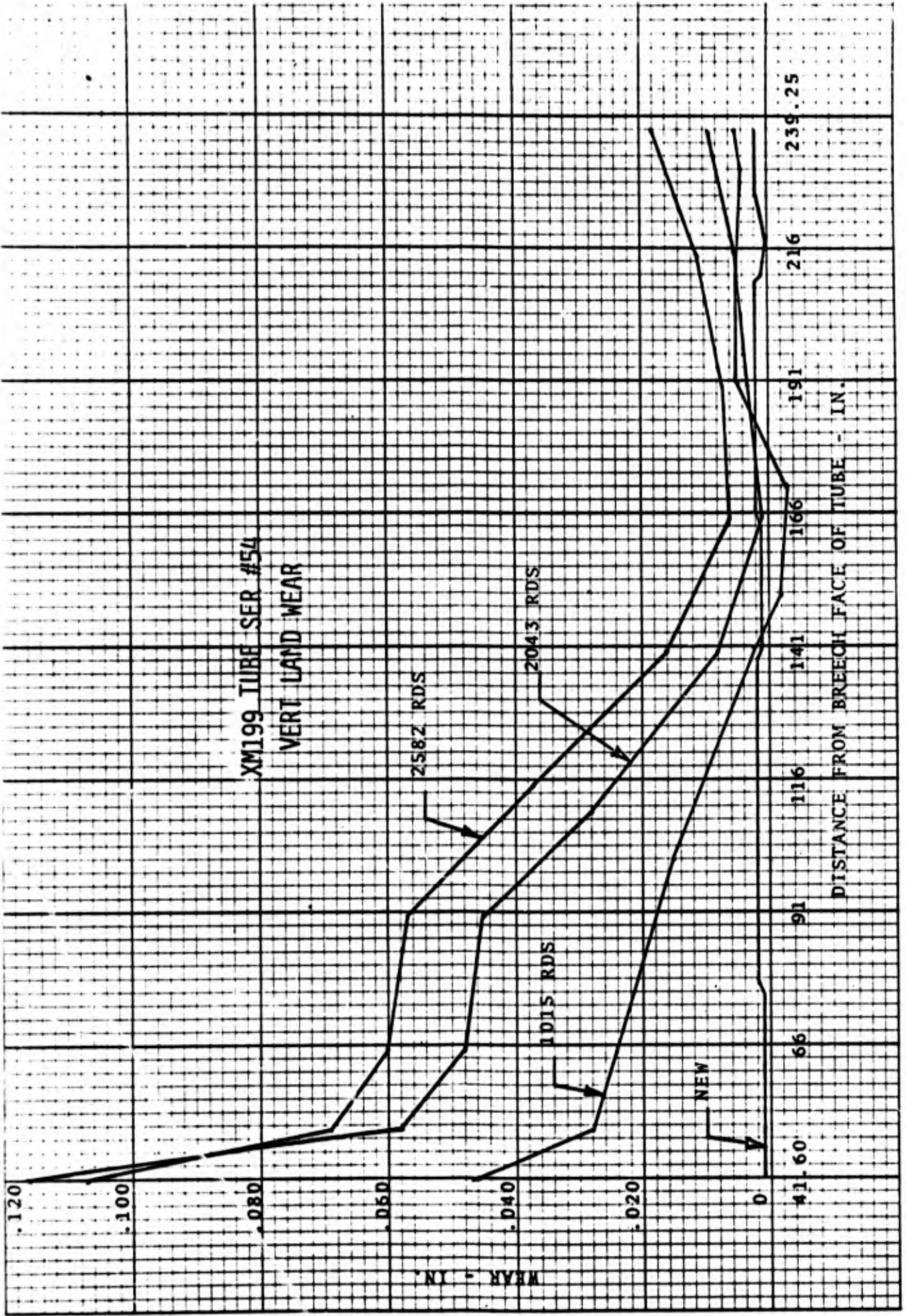


FIGURE 18

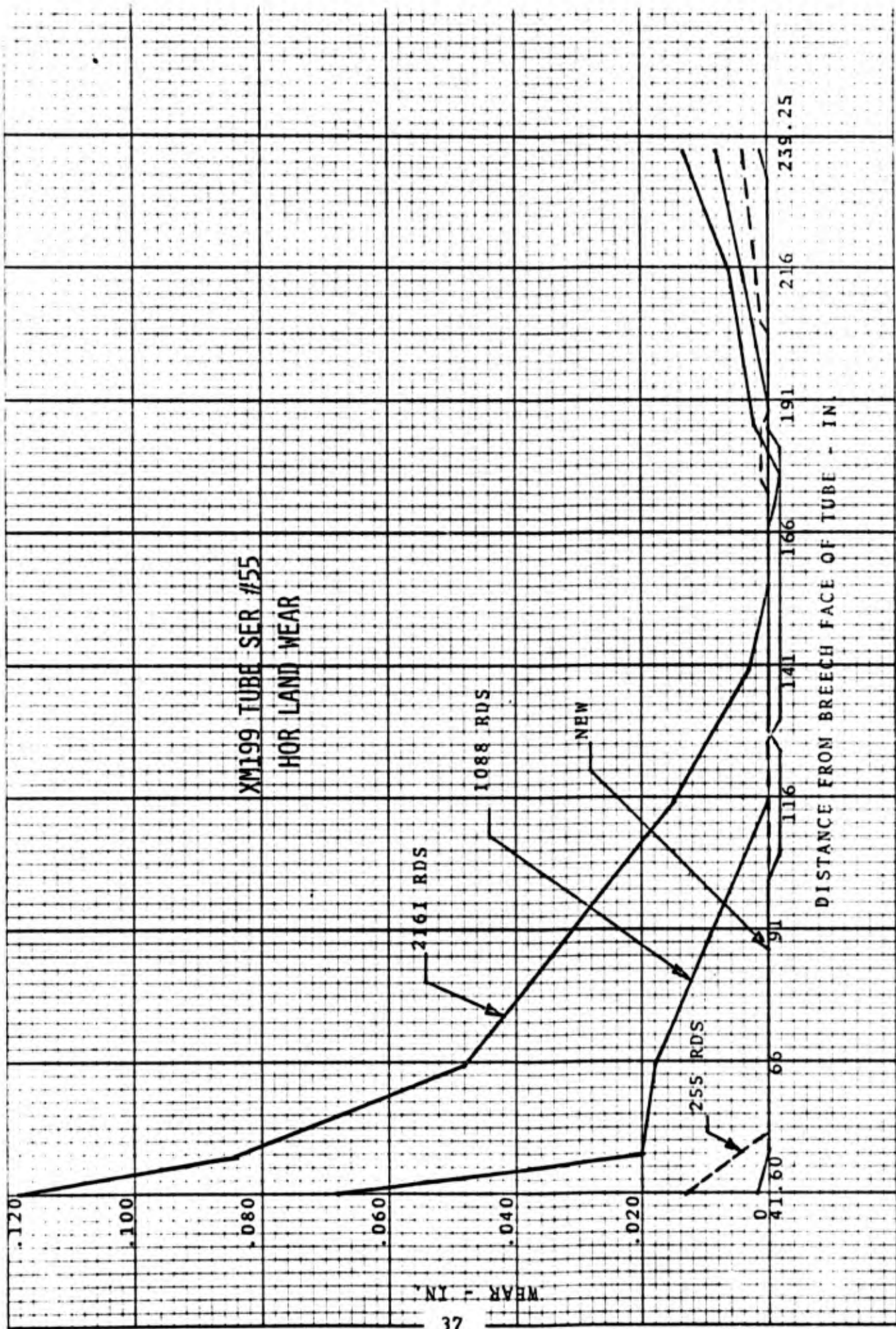


FIGURE 19

TABLE 7

AXIAL LOCATION OF MUZZLE WEAR

<u>Tube S.N.</u>	<u>Rd.</u>	<u>Distance from rear face of tube (in.)</u>	
		<u>from</u>	<u>to</u>
48	1430	170	239.45
49	574	170	239.45
51	2477	160	239.45
52	2866	195	239.45
53	2706	145	239.45
54	2582	185	239.45
55	2161	180	239.45

Average (all tubes): 172 inches increasing to muzzle end.

Average (excluding S.N.53): 177 inches increasing to muzzle end.

A good indication of wear location can be derived from measurements of each land's height at the muzzle. Since the grooves have been found to wear very little, comparative land heights indicate which lands are wearing most heavily. It was found that the best way to obtain land height readings was to take micrometer readings (using spherical heads) between the top of the land and the outside surface of the tube. The average of the micrometer readings between the two grooves on either side of the land and the outside surface of the tube was subtracted from this. Unfortunately, due to the lack of spherical heads required for this method of measurement, many land height readings were taken directly using a depth gage during this test. This latter method gave far less accurate absolute results. However, either method is capable of indicating relative wear at the muzzle and will show the circumferential position of maximum wear. Figures 20 thru 26 show the relative land wear readings for each tube after final use in the Durability Test (except tube S.N.48, measurements taken after round 905). The approximate o'clock positions of maximum and minimum wear are tabulated in Table 8. If all tubes are considered, maximum wear at the muzzle occurs, on the average, at 5:34 o'clock (land #22) while minimum wear occurs on the average at 11:54 o'clock (land #48). These lands are approximately diametrically opposed. If one follows the land of maximum wear clockwise for 1.64 revolutions back to the origin of rifling, the land position would be, on the average, at 12:24 o'clock (viewed from the muzzle).

Tube S.N.48 does not conform well to the above average tube model. Calculations are shown in Table 8 which exclude S.N.48 data; as can be seen, the average values shift by at most three lands.

155MM XM109 CANNON
 RELATIVE WEAR OF
 LANDS AT THE MUZZLE
 TUBE S.N. 48

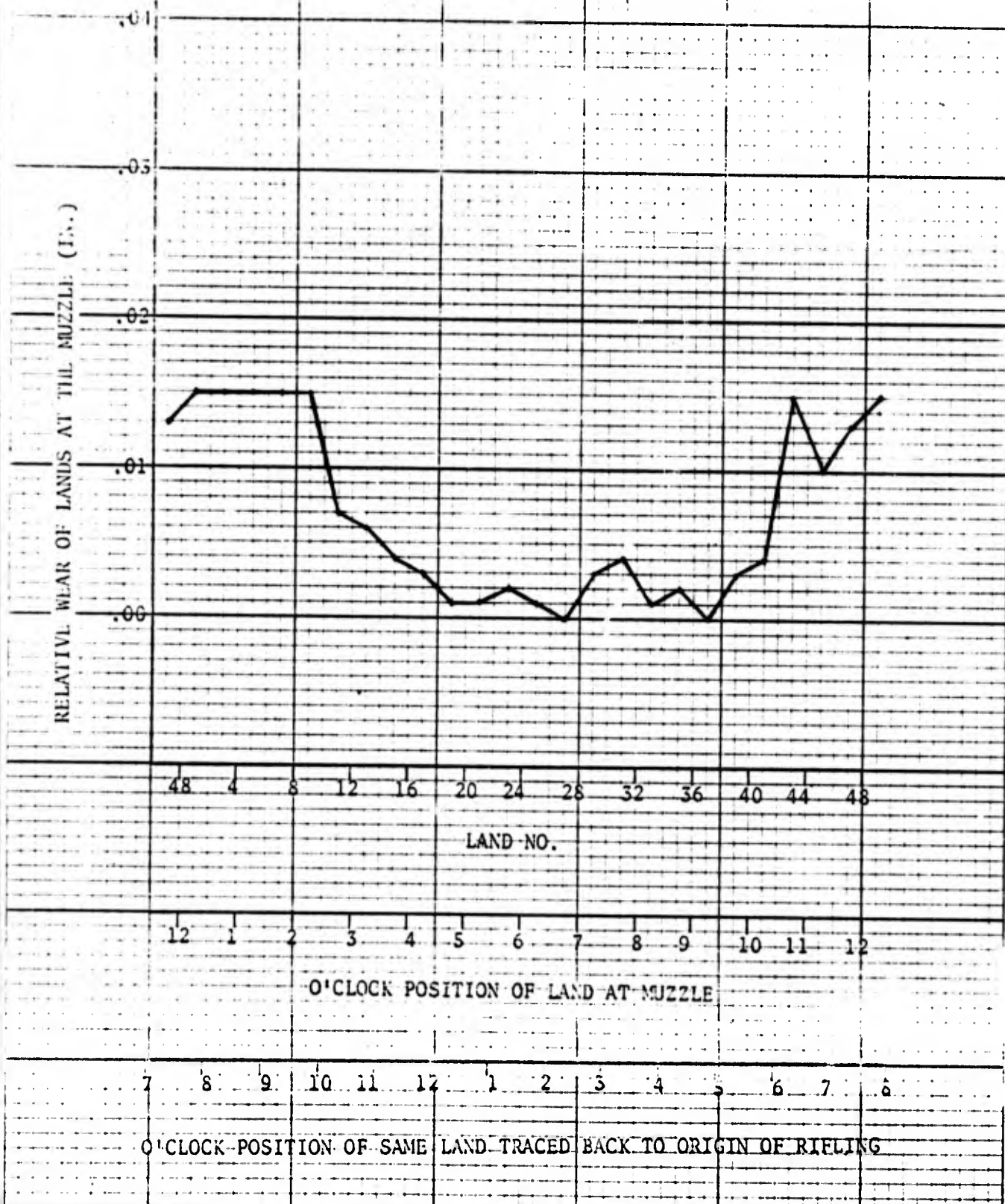


FIGURE 20

155MM XM199 CANNON
 RELATIVE WEAR OF
 LANDS AT THE MUZZLE
 TUBE S.N. 49

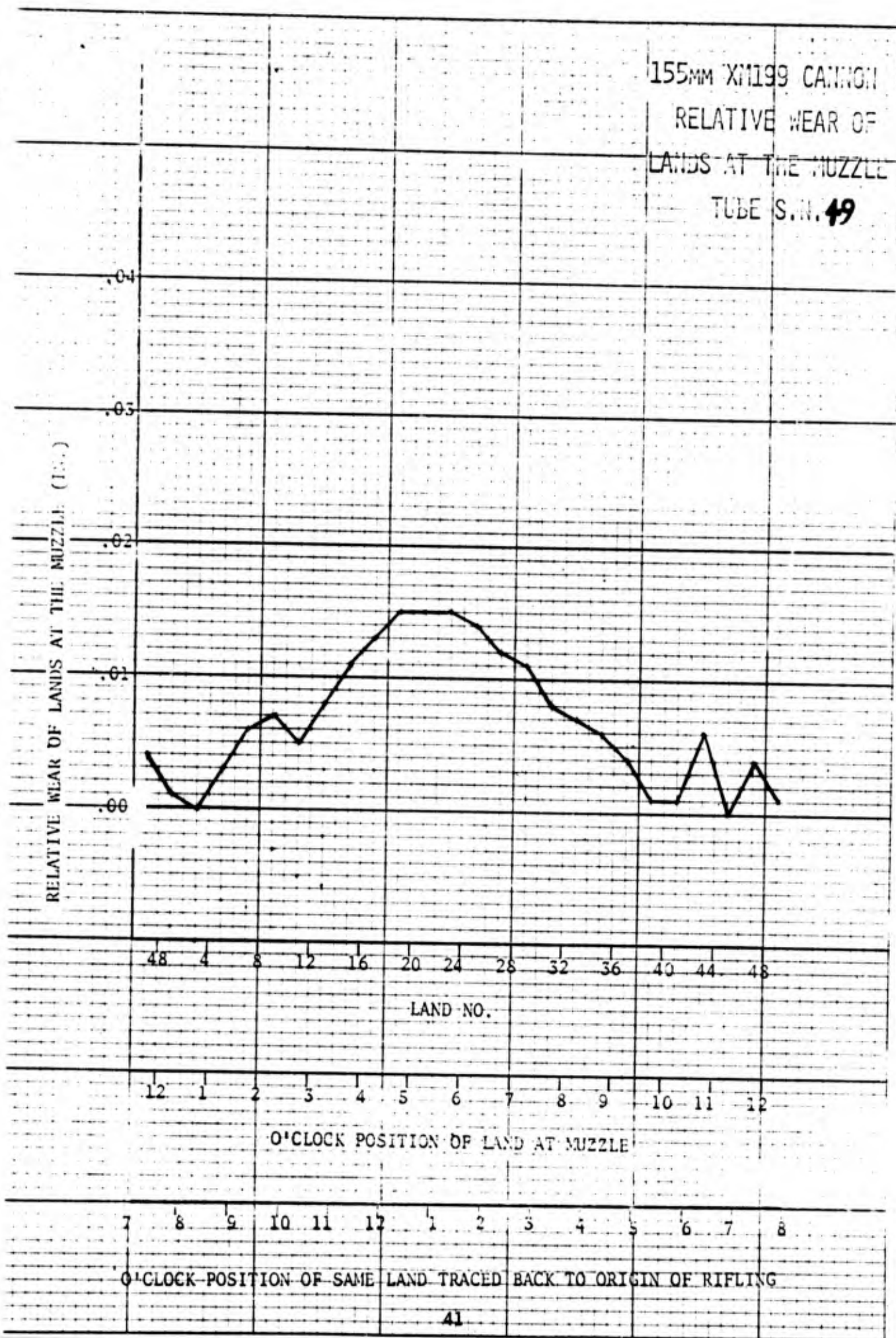


FIGURE 21

155MM XM199 CANNON
 RELATIVE WEAR OF
 LANDS AT THE MUZZLE
 TUBE S.N. 51

RELATIVE WEAR OF LANDS AT THE MUZZLE (IN.)

.04
 .05
 .02
 .01
 .00

48 4 8 12 16 20 24 28 32 36 40 44 48

LAND NO.

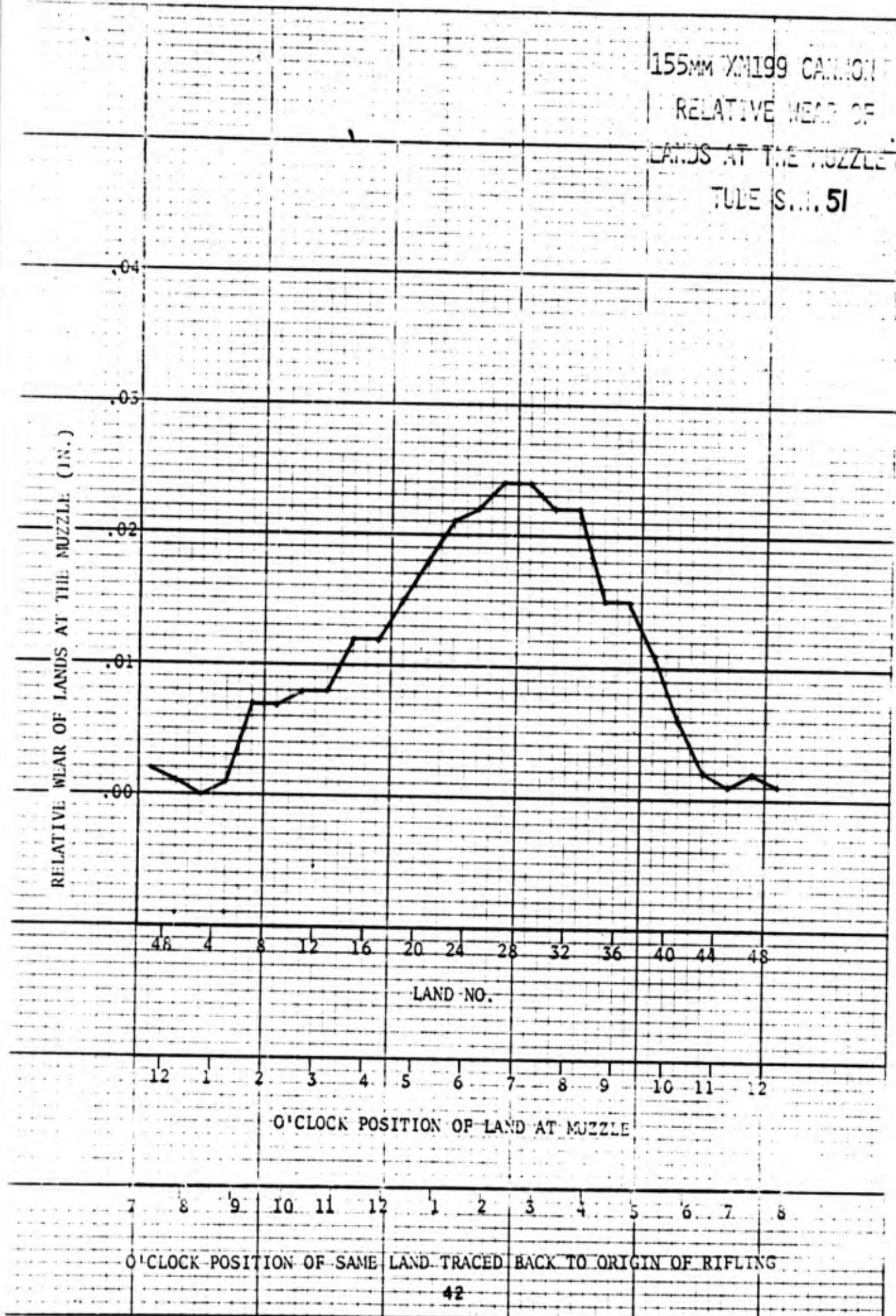
12 1 2 3 4 5 6 7 8 9 10 11 12

O'CLOCK POSITION OF LAND AT MUZZLE

7 8 9 10 11 12 1 2 3 4 5 6 7 8

O'CLOCK POSITION OF SAME LAND TRACED BACK TO ORIGIN OF RIFLING

FIGURE 22



155MM XM199 CANNON
 RELATIVE WEAR OF
 LANDS AT THE MUZZLE
 TUBE S.N. 52

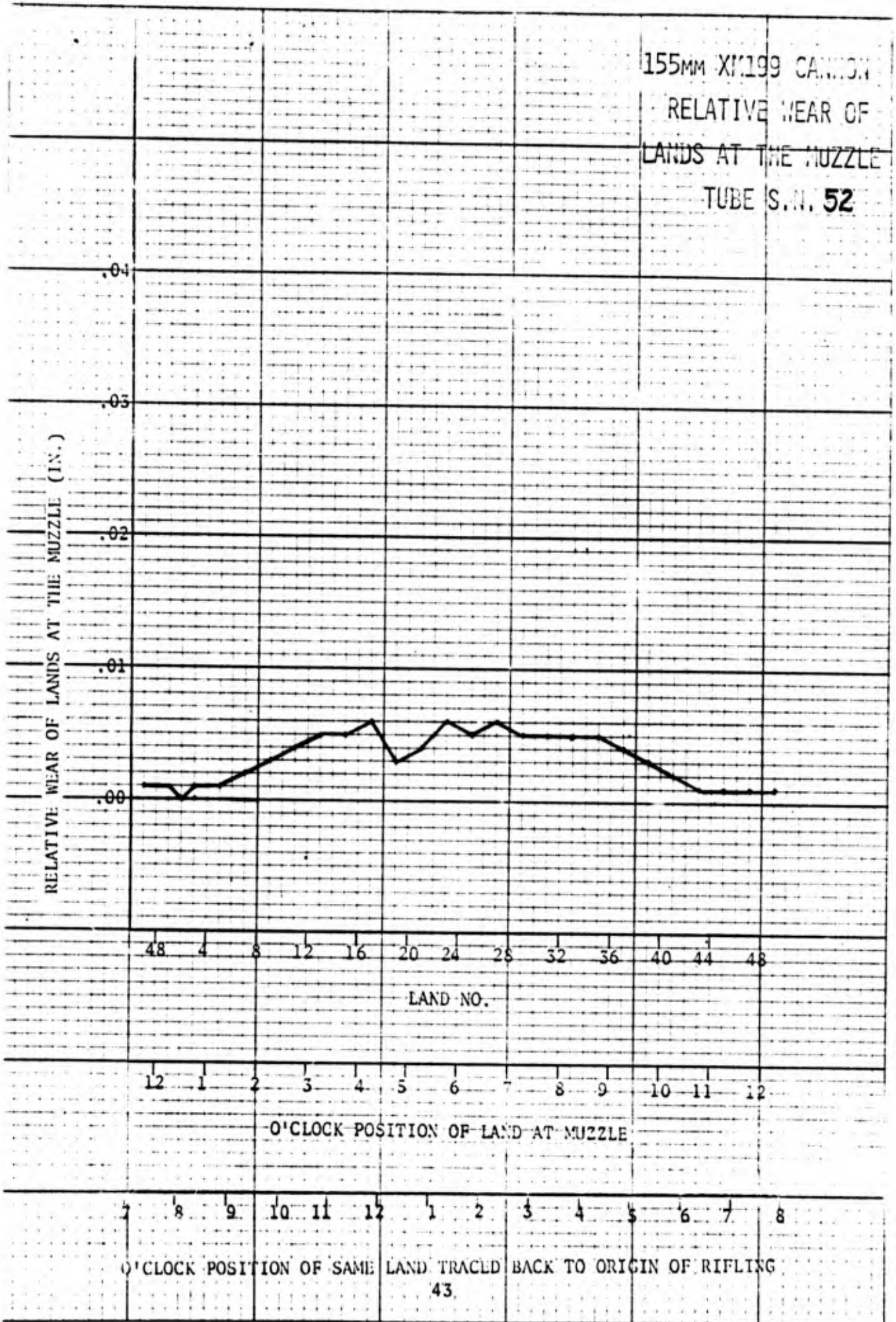


FIGURE 23

155MM XM199 CASE.
 RELATIVE WEAR OF
 LANDS AT THE MUZZLE
 TUBE S.N. 54

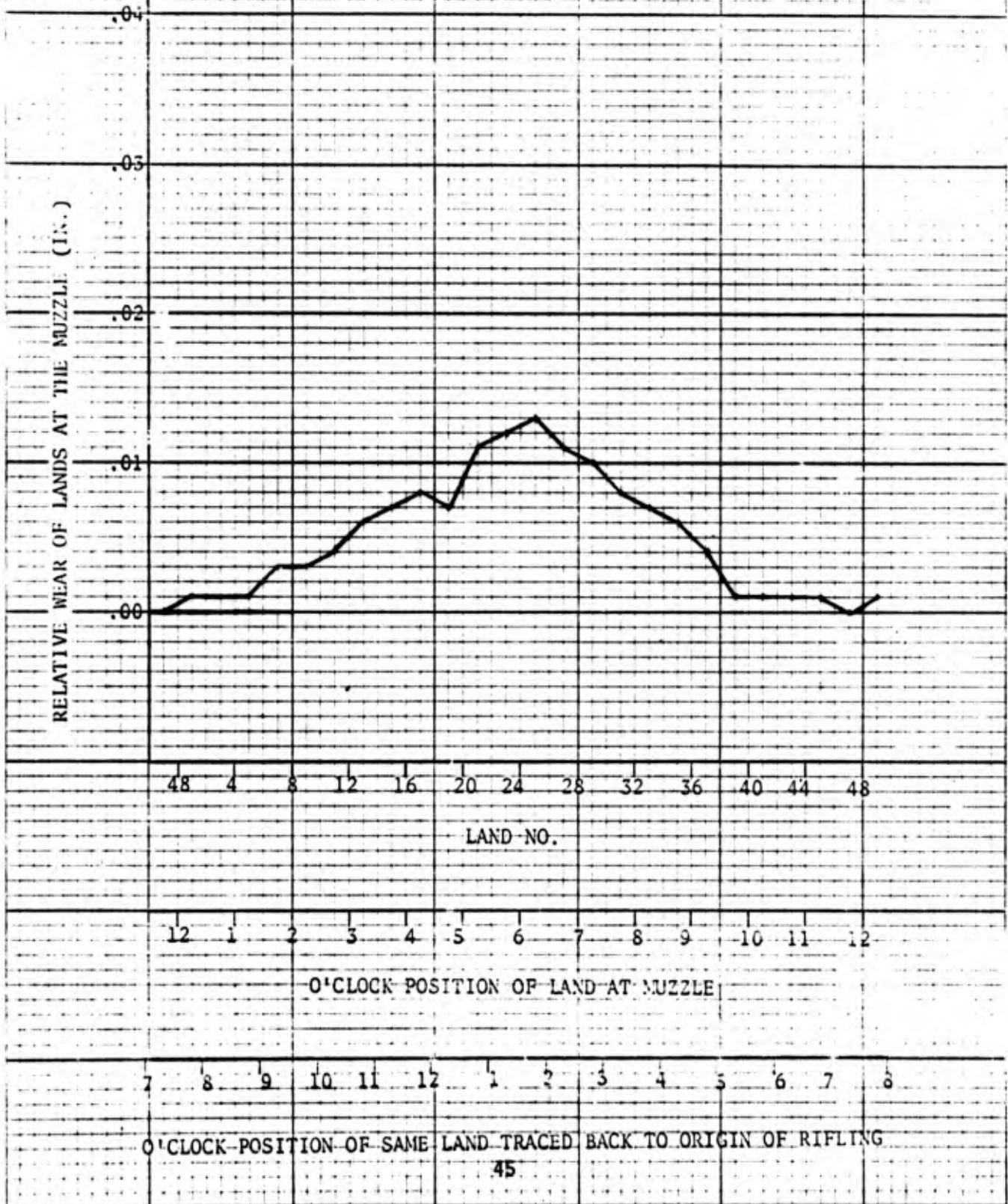


FIGURE 25

155MM XM199 CANNON
 RELATIVE WEAR OF
 LANDS AT THE MUZZLE
 TUBE S...55

RELATIVE WEAR OF LANDS AT THE MUZZLE. (1%)

.04
 .05
 .02
 .01
 .00

48 4 8 12 16 20 24 28 32 36 40 44 48

LAND NO.

12 1 2 3 4 5 6 7 8 9 10 11 12

O'CLOCK POSITION OF LAND AT MUZZLE

2 3 4 5 6 7 8 9 10 11 12 1 2 3

O'CLOCK POSITION OF SAME LAND TRACED BACK TO ORIGIN OF RIFLING

FIGURE 26

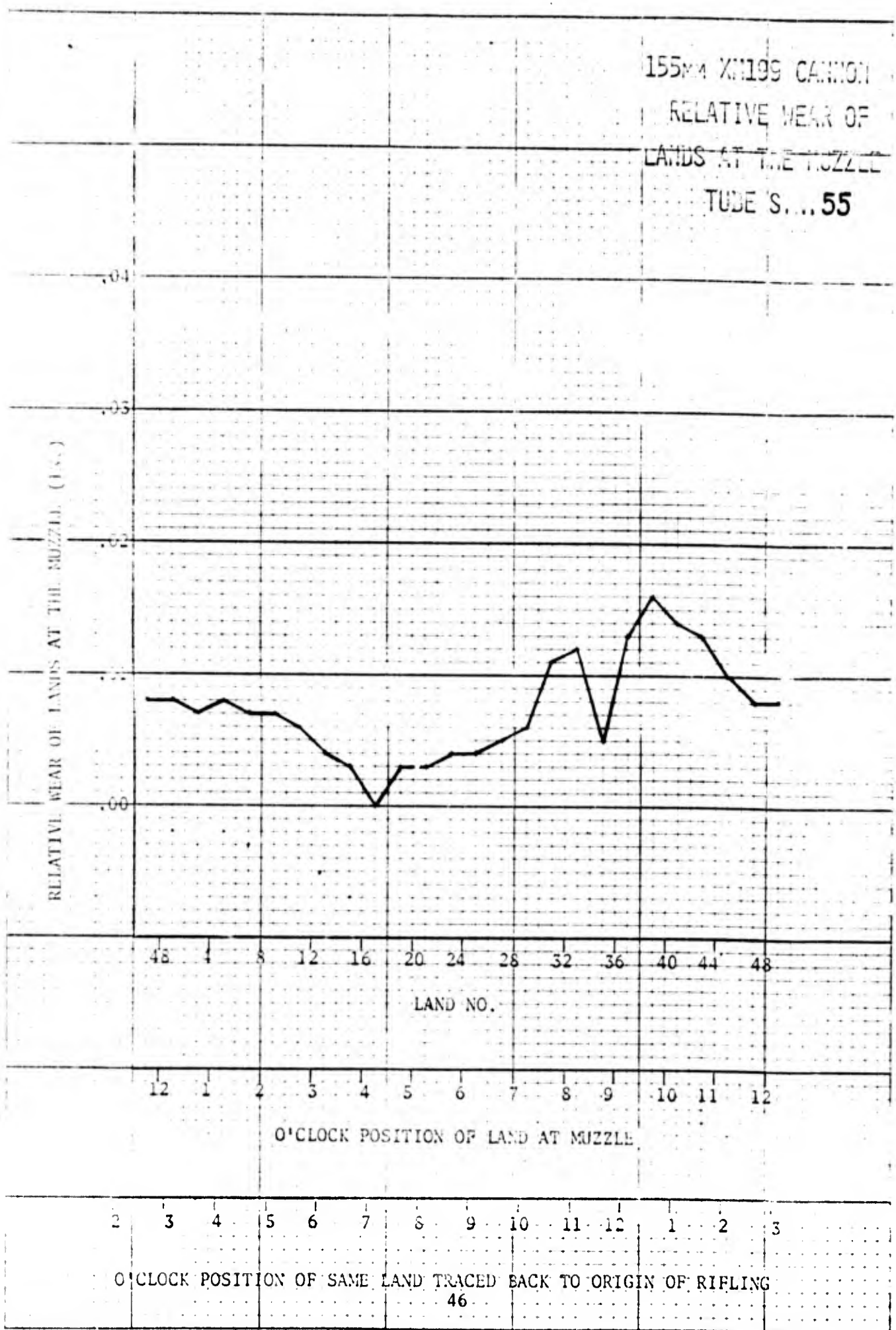


TABLE 8

RELATIVE MAXIMUM AND MINIMUM LAND WEAR AT THE MUZZLE

<u>Tube S.N.</u>	<u>Approx.Max. Wear (o'clock)*</u>	<u>Approx.Min. Wear (o'clock)*</u>	<u>Difference (Degrees)</u>	<u>Max. Wear Land Position @ Origin of Rifling (o'clock)*</u>
48	1:15	8:00	158	8:45
49	5:15	12:00	158	12:45
51	7:00	12:45	172	2:30
52	5:30	12:30	150	1:00
53	4:00	10:00	180	11:30
54	6:15	11:45	165	1:45
55	9:45	4:15	165	12:30
Average:	5:34	11:54	164	12:24
Average Excl. S.N. 55	4:52	11:10	164	12:23
Average Excl. S.N. 48	6:17	12:32	165	1:00

* O'clock readings read facing the muzzle.

Tube S.N.55 also appears at first glance not to conform with the average tube model above. However, it must be remembered that this tube was manufactured with gain twist rifling while all others had constant twist rifling. Although the locations of maximum and minimum wear at the muzzle are different than the average tube model, the land of maximum wear traces back to the same location at the origin of rifling: approximately 12:30 o'clock. This would tend to substantiate previous findings which correlate muzzle wear with commencement wear.

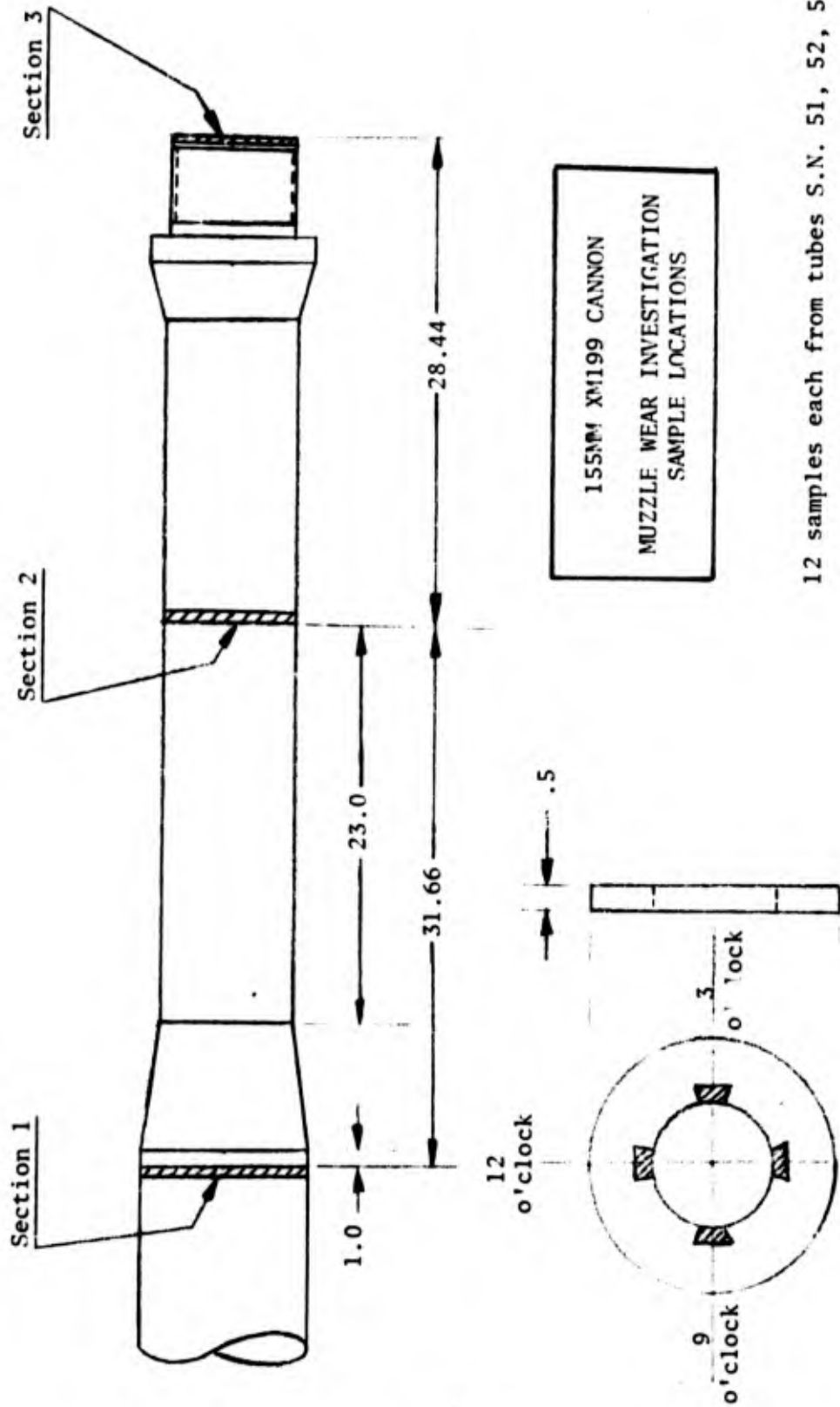
C. Condition of Bore

Four tubes were fired to the end of their useful lives during this Durability Test (S.N.51, 52, 53 and 54). These tubes were cut up, and twelve bore samples were machined from each as shown in Fig.27. Each specimen was mounted so that the lands could be observed in cross-section using a high power microscope.

Macroscopically, the chamfer of the driving edge of the lands was generally rounded and cracked whereas the non-driving edge's chamfer was generally intact and crack-free. (See Fig. 28). The base metal of all tubes was well-structured tempered martinsite, homogeneous and free of impurities. Hardness was uniform and generally in the Rc 40 - 43 range for all tubes.*

*As a matter of information, hardness checks on random projectile used during this test gave the following results:

M101 HE Projectile	Bourettelet Rc	33 - 34
	Boattail Rc	19 - 25
XM549 RAP Projectile	Bourettelet Rc	39 - 40
	Boattail Rc	19 - 20



49

12 samples each from tubes S.N. 51, 52, 53, 54

3 axial sections

4 samples each section

Section Sample Location:

(Times Looking At Muzzle End)

FIGURE 27

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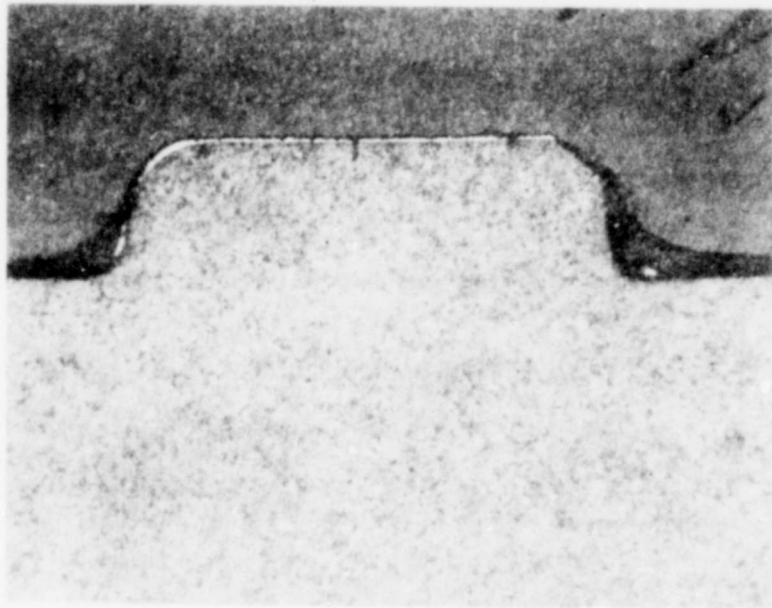


Fig. 28 Bore sample showing cross sectional geometry of a worn land.
Tube S.N.52; Section 1; 3 o'clock position: (15 X)

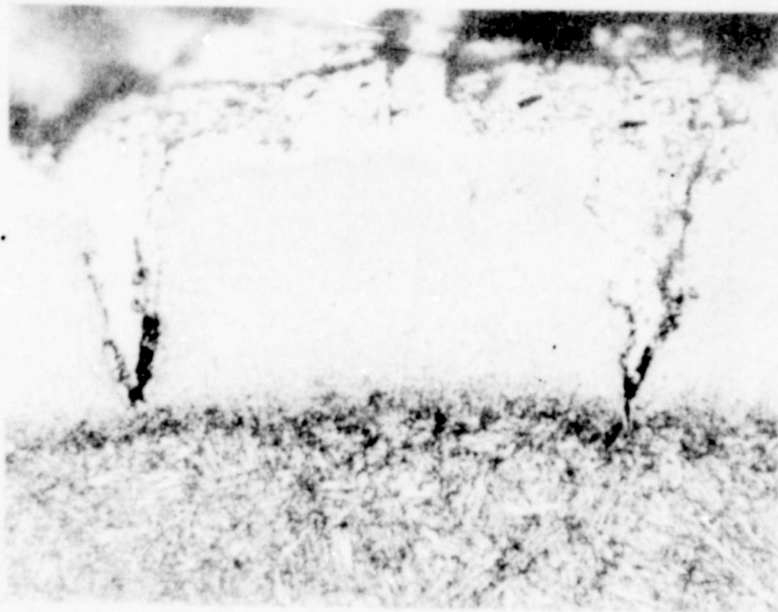


Fig. 29 Bore sample showing thermally altered layers on driving
edge of land.
Tube S.N.52; Section 1; 3 o'clock position (750 X)

Observations on a microscopic scale revealed the presence of thermally altered layers (also called "heat affected zones", HAZ) in certain areas near the bore (see Fig. 29). Two distinct types of HAZ were noted: a gray zone which had a much finer grain structure than the base metal; and a white zone which appeared to have an even finer structure. Microhardness readings indicate that the gray layer was substantially harder than the base metal; the white layer was too thin and close to the surface to measure hardnesses (see Fig. 30). These HAZ are not located uniformly on the bore's rifled surface but rather tend to form in certain areas. The non-driving edge of the land (including its chamfer and radius) and the half of the groove towards the non-driving edge show, in nearly all cases, no evidence of a HAZ. The groove surfaces towards the driving edge of the land sometimes had a HAZ, although these were normally quite thin. On the other hand, the driving edge of the land (including its chamfer and radius) normally showed an extensive HAZ. A HAZ was also noted on top of the land, and it tended to be only slightly thinner than that on the driving edge.

Whenever a HAZ was present, V-shaped cracks were noted which generally extended through the HAZ. Most cracks appeared to be arrested by the base metal, although some were able to penetrate through into the less hard metal. Whenever the HAZ was not present, the surface was generally good, i.e., somewhat rough, but noticeably free of cracks (compare Fig. 31 and Fig. 32).

Bright yellow coppering was easily distinguishable in certain areas. Generally, it was present only in samples from Section 1; Sections 2 and 3 showed little distinguishable copper. The copper appeared to be

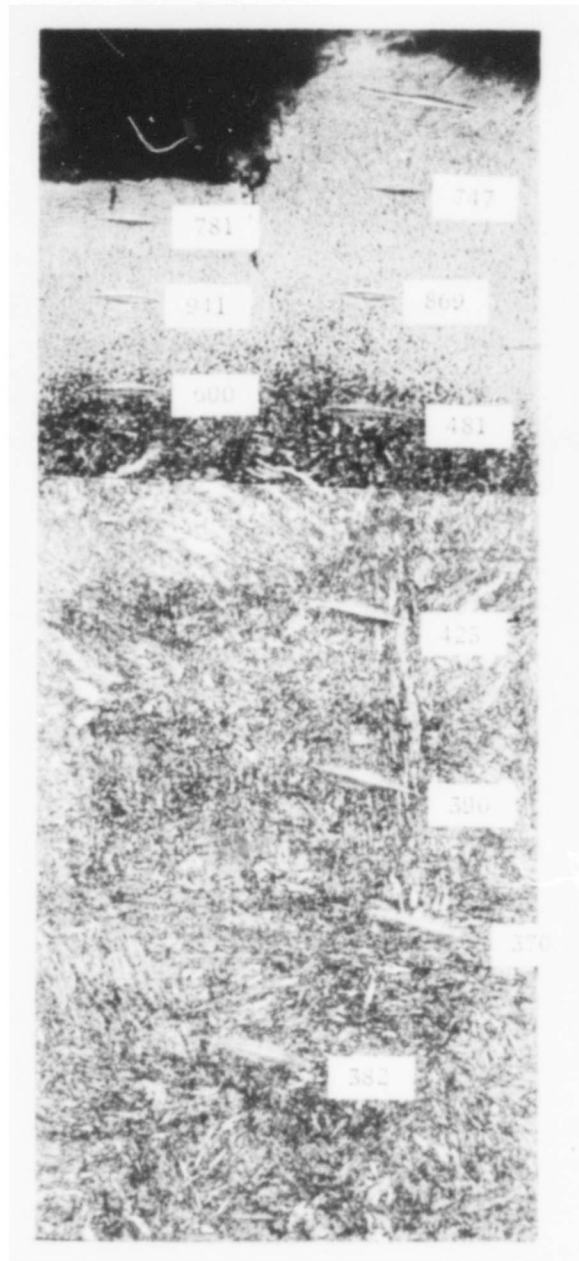


Fig. 30 Typical microhardness readings in the area of a thermally altered layer. Readings obtained using a Knoop Hardness Tester, 10 gram load. (750 X)

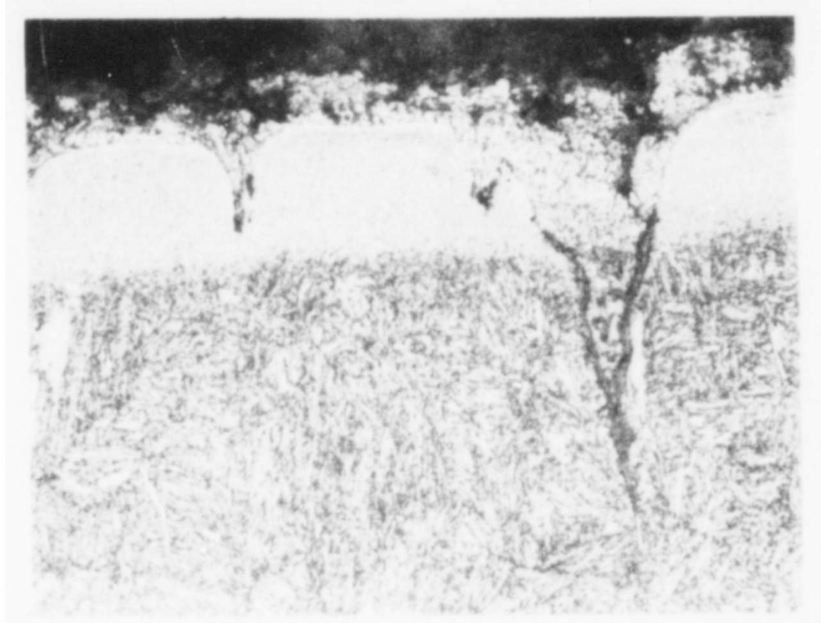


Fig. 31 Bore sample showing cracks in HAZ, with some penetration into base metal (750 X).

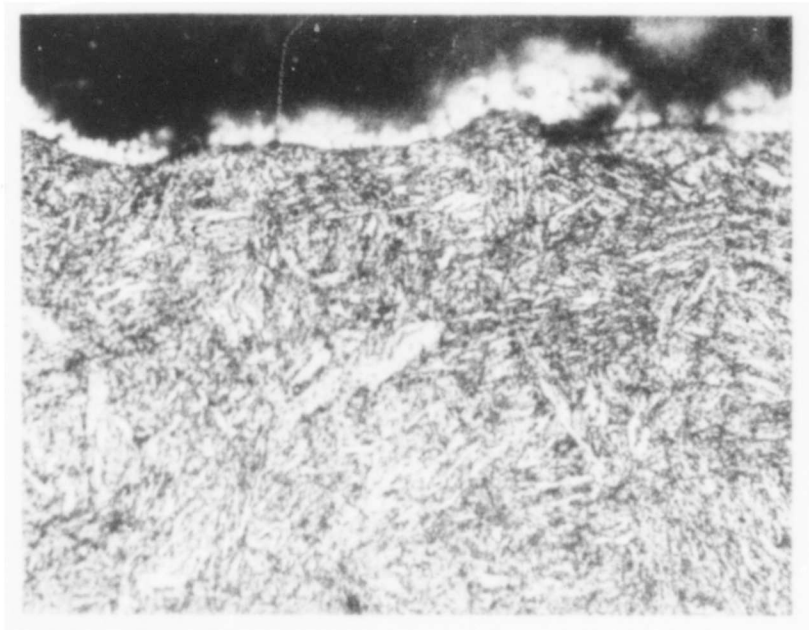


Fig. 32 Bore sample showing area free of HAZ and associated surface cracks. (750 X).

present only in areas associated with the HAZ (i.e. driving surface and top of land) and was able to work itself into the V-shaped cracks associated with the HAZ.

Tube S.N.53 was manufactured with a chrome plate bore. Wherever the chrome was intact, no HAZ was observed beneath the chrome; however, if the chrome was worn or flaked away, the HAZ was present.

Earlier in this report it was stated that the lands do not all wear at the same rate. Rather, maximum and minimum wear are found on diametrically opposite sides of the tube. Previous reports on this subject ² have stated that muzzle wear tends to follow the twist of rifling. Photographs of tube S.N.53 show graphically that maximum muzzle wear does in fact follow a specific set of lands. Fig. 27 shows that the three sections taken from the tube are located approximately 30 inches apart. Since the twist of rifling is one turn in 20 calibers (122 inches) the rifling turns through approximately one-fourth of a revolution every 30 inches. Figures 33 and 34 show that the most worn land for S.N.53, Section 1 is located at 9 o'clock and the least worn land at 3 o'clock. As expected, the most worn land is located at 6 o'clock for section 2 (see Fig. 35 and 36) and 3 o'clock for Section 3 (see Fig. 37 and 38). Note that the lands in Figures 35 and 37 are worn down almost to the depth of the groove. The chrome in the grooves and, to a lesser extent, on the side walls is largely intact. (Fig. 33 thru 38).

2. Lloyd E. Line, Jr., "The Erosion of Guns at the Muzzle",
NDRC Report No. A-357, OSRD Report No. 6322 (1945)

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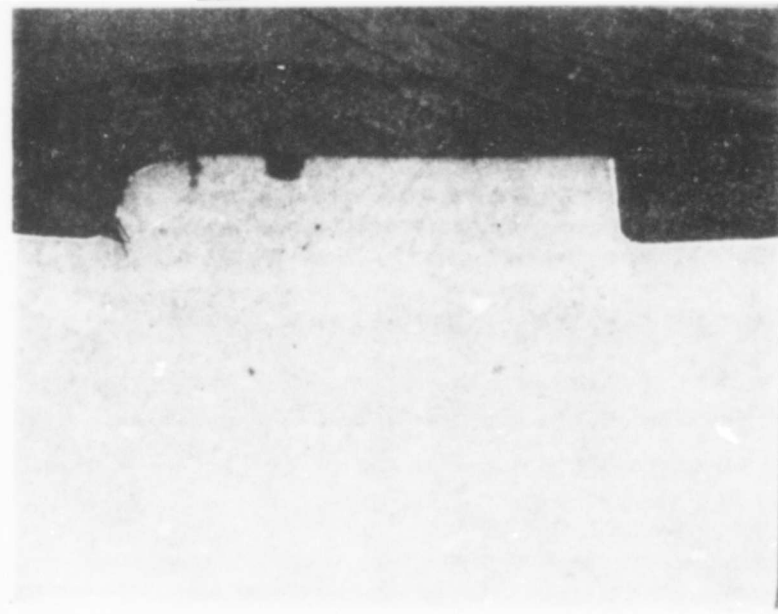


Fig. 33 Tube S.N.53; Section 1; 9 o'clock.
Position of maximum wear (15 X).

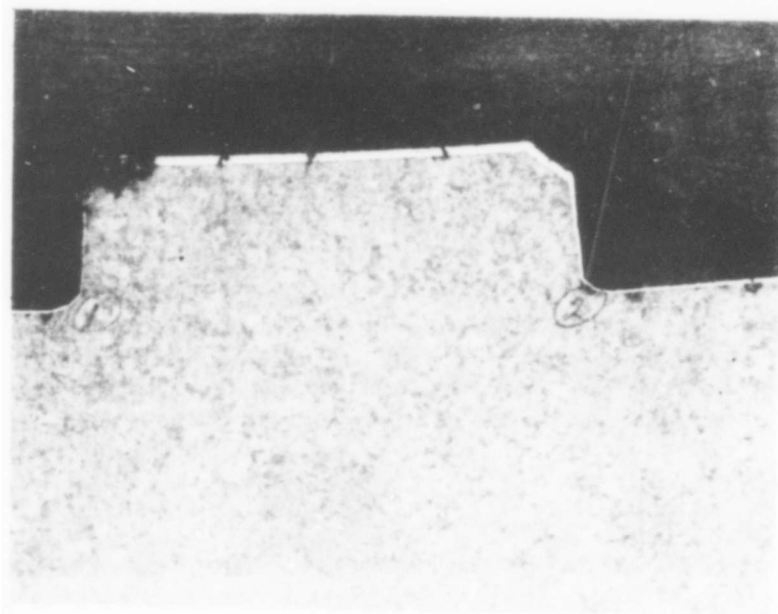


Fig. 34 Tube S.N.53; Section 1; 3 o'clock.
Position of minimum wear (15 X).

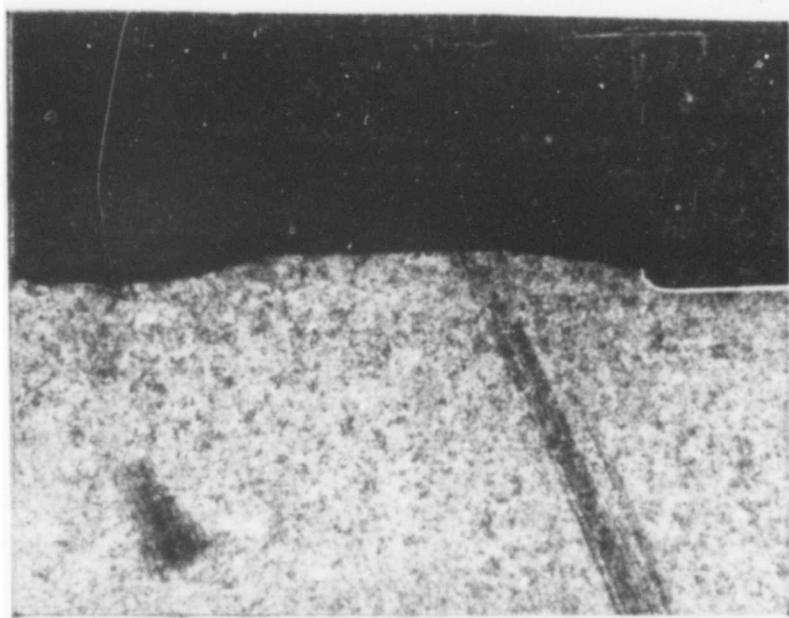


Fig. 35 Tube S.N.53; Section 2; 6 o'clock.
Position of maximum wear. (15 X)

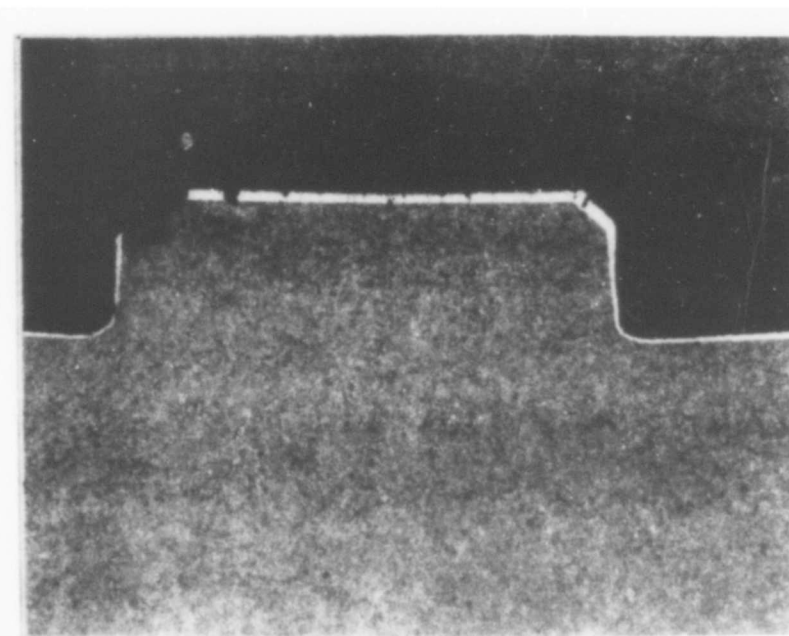


Fig. 36 Tube S.N.53; Section 2; 12 o'clock.
Position of minimum wear. (15 X).

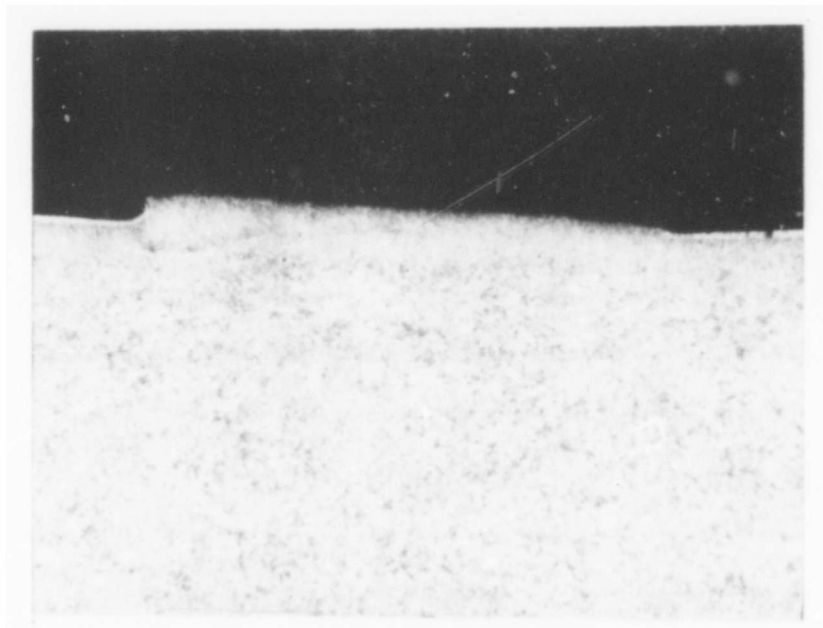


Fig. 37 Tube S.N.53; Section 3; 3 o'clock.
Position of maximum wear (15 X).



Fig. 38 Tube S.N.53; Section 3; 9 o'clock.
Position of minimum wear (15 X).

A new theory concerning the mechanism of muzzle wear, based in part on the above data, has been developed by Dr. Robert S. Montgomery of Watervliet Arsenal³.

D. Conclusions

During the Durability Test, muzzle wear was encountered in the bore beginning, on the average, 175 inches from the rear face of the tube; it increased from that point all the way to the muzzle. The wear was restricted almost entirely to the lands and followed the spiral of rifling. Looking at the tube from the muzzle, the lands which emerged in the 5 o'clock region (on the average) tended to wear the most. This particular set of lands can be traced back to approximately 12 to 1 o'clock at the origin of rifling.

A thermally altered layer which was substantially harder than the base metal was found to exist on the driving edge (including radius and chamfer) and the top of the lands. On the other hand, no thermally altered layer was found to exist on the non-driving edge of the land or in the groove. The physical location of the altered layer would indicate that the source of the heat which transforms the base metal (tempered martensite) is physical abrasion rather than hot propellant gases. It is not known whether tube contact with the shell body or the copper rotating band or both is generating this heat; however, the presence of copper deposits was noticed, especially in cracks in the HAZ and in samples from Section 1.

3. Robert S. Montgomery, "Muzzle Erosion of Cannon", Watervliet Arsenal Report WTV TR 74050 (1974)

The thermally altered layer invariably showed V-shaped surface cracks which were, in most cases, arrested by the softer base metal.

The hardness of the HAZ and presence of cracks make the altered layers especially susceptible to flaking, chipping, etc. by the projectile.

One might speculate that, as the projectile wipes away all or part of an existing altered layer, a new one is formed; this layer, in turn, is worn away during subsequent rounds.

TABLE 9
FORGING YIELD STRENGTH

<u>Tube 48</u>	<u>Yield Strength (ksi)</u>				<u>Avg.</u>	<u>Spread</u>
Breech End:	173.0	173.5	174.0	173.5	173.5	1.0
Muzzle End:	170.2	169.8	170.0	169.8	170.0	.4
 <u>Tube 49</u>						
Breech End:	176.2	175.5	175.0	176.0	175.7	1.2
Muzzle End	166.5	168.2	169.0	168.0	167.9	2.5
 <u>Tube 51</u>						
Breech End:	174.5	173.0	173.8	175.5	174.2	2.5
Muzzle End:	167.0	168.0	167.0	166.5	167.1	1.5
 <u>Tube 52</u>						
Breech End:	168.5	168.0	167.5	168.0	168.0	1.0
Muzzle End:	167.0	164.0	165.5	164.5	165.3	3.0
 <u>Tube 53</u>						
Breech End:	165.5	166.0	171.0	165.0	166.9	6.0
Muzzle End:	163.5	162.5	163.5	161.6	162.8	1.9

TABLE 9 (Continued)

<u>Tube 54</u>	<u>Yield Strength (ksi)</u>				<u>Avg.</u>	<u>Spread</u>
Breech End:	167.0	166.5	165.0	163.5	165.5	3.5
Muzzle End:	165.0	164.5	166.5	163.5	164.9	3.0
 <u>Tube 55</u>						
Breech End:	167.5	169.5	167.5	167.5	168.0	2.0
Muzzle End	163.0	167.5	165.0	165.0	165.1	4.5

Tube Forging and Manufacturing Histories

A. Forging Data

1. Yield Strength The required yield strength of the forging material specified on the forging drawing (WTV-F20994) was 160 - 180 ksi. In addition, MIL-S-46119 specifies that the spread in yield strength in any test disc shall not exceed 6 ksi. Actual data are shown in Table 9; it can be seen that all forgings were within specifications. It is evident that the yield strength was invariably lower at the muzzle end than at the breech end. If S.N.53 is treated as a special case, the tubes which were considered to have low muzzle wear (S.N.52, 54 and 55) had a generally lower average yield strength and a greater circumferential variation in yield strength than tubes which were considered to have high muzzle wear.

2. Reduction of Area MIL-S-46119 specifies that the minimum allowable % R.A. for 160 - 180 ksi yield strength material is 25% (transverse direction). Actual data are shown in Table 10; it can be seen that all forgings were above the minimum value. If S.N.53 is treated as a special case, the tubes which were considered to have low muzzle wear (S.N.52, 54 and 55) had a generally lower average % R.A. than tubes which were considered to have high muzzle wear.

3. Charpy V-Notch Impact Resistance MIL-S-46119 specifies that the minimum value for this parameter for 160 - 180 ksi yield strength material is 15 ft. lbs (transverse direction) at -40°F. Actual data are shown in Table 11; it can be seen that all forgings were above the

TABLE 10

FORGING REDUCTION OF AREA

<u>Tube S.N.</u>	<u>RA (%)</u>				<u>Avg.</u>
<u>Tube S.N.48</u>					
Breech End:	46.5	41.1	47.4	45.7	45.2
Muzzle End:	47.0	47.0	50.2	47.4	47.9
<u>Tube S.N.49</u>					
Breech End:	41.9	41.1	46.5	44.9	43.6
Muzzle End:	42.8	40.7	42.4	43.2	42.3
<u>Tube S.N.51</u>					
Breech End:	36.3	40.2	38.5	39.8	38.7
Muzzle End:	39.4	39.4	38.5	41.9	39.8
<u>Tube S.N.52</u>					
Breech End:	36.6	31.5	32.8	30.8	32.9
Muzzle End:	35.0	31.5	36.3	33.4	34.1
<u>Tube S.N.53</u>					
Breech End:	38.2	34.4	35.7	34.1	35.6
Muzzle End:	31.2	30.8	35.4	32.2	32.4
<u>Tube S.N.54</u>					
Breech End:	27.5	31.5	32.5	30.2	30.4
Muzzle End:	34.1	30.5	36.0	33.4	33.5
<u>Tube S.N.55</u>					
Breech End:	--	38.8	37.9	39.4	38.7
Muzzle End:	37.5	36.0	37.3	37.6	37.1

TABLE 11

FORGING CHARPY V-NOTCH IMPACT RESISTANCE

<u>Tube S.N.48</u>	<u>Charpy Values (Ft.-Lb.)</u>				<u>Avg.</u>
Breech End:	24.0	23.0	23.0	--	23.3
Muzzle End:	20.5	17.0	20.0	20.5	19.5
 <u>Tube S.N.49</u>					
Breech End:	21.0	21.0	21.0	--	21.0
Muzzle End:	19.0	20.3	18.0	20.0	19.3
 <u>Tube S.N.51</u>					
Breech End:	18.5	19.0	20.0	21.0	19.6
Muzzle End:	18.5	18.5	19.0	22.5	19.6
 <u>Tube S.N.52</u>					
Breech End:	21.0	20.0	20.5	20.0	20.4
Muzzle End:	17.5	17.0	18.0	17.5	17.5
 <u>Tube S.N.53</u>					
Breech End:	18.0	17.0	16.5	17.0	17.1
Muzzle End:	18.0	16.0	17.0	16.5	16.9
 <u>Tube S.N.54</u>					
Breech End:	17.5	18.5	18.0	19.0	18.3
Muzzle End:	16.5	18.0	17.0	16.5	17.0
 <u>Tube S.N.55</u>					
Breech End:	19.5	18.0	18.0	18.0	18.4
Muzzle End:	18.0	19.5	19.5	20.5	19.4

minimum value. If S.N.53 is treated as a special case, the tubes which were considered to have low muzzle wear (S.N.52, 54 and 55) had a generally lower average Charpy value than tubes which were considered to have high muzzle wear.

4. Ultimate Tensile Stress. No material requirement is made in MIL-S-46119 or on the forging drawing concerning this parameter. Actual data are shown in Table 12 for the purpose of comparison. If S.N.53 is treated as a special case, the tubes which were considered to have low muzzle wear (S.N.52, 54 and 55) had a generally lower average UTS than tubes which were considered to have high muzzle wear.

5. Elongation. No material requirement is made in MIL-S-46119 or on the forging drawing concerning this parameter. Actual data are shown in Table 13 for the purpose of comparison. No pattern emerges which relates high and low muzzle wear tubes.

6. Forging Supplier/Heat. Again, S.N.53 is treated as a special case. Forgings which resulted in high muzzle wear tubes (S.N.48, 49 and 51) were all supplied by Cabot Corp.; those which resulted in low muzzle wear tubes (S.N.52, 54 and 55) were all supplied by National Forge Co. The forging for tube S.N.53 was also supplied by National Forge Co. Of the seven forgings, only S.N.52 and 55 came from the same heat. The quench and temper processes used by Cabot and National differed and were as follows:

Cabot: Quench - 1550°F; 12 hrs.; water.

Temper - 1045°F (Breech) except S.N.48 which was 1050°F;
16 hrs.; water.

1035°F (Muzzle); 16 hrs.; water.

National: Quench - 1550°F; 6 hrs.; water.

Temper - 1080°F except S.N.54 which was 1090°F;
6 hrs.; water.

TABLE 12

FORGING ULTIMATE TENSILE STRENGTH

<u>Tube S.N.</u>	<u>UTS (ksi)</u>				<u>Avg.</u>
<u>Tube S.N.48</u>					
Breech End:	191.0	190.8	191.0	190.8	190.9
Muzzle End:	192.0	191.4	192.2	191.4	191.8
<u>Tube S.N.49</u>					
Breech End:	192.4	192.2	192.8	192.4	192.5
Muzzle End:	187.2	188.8	189.6	188.2	188.5
<u>Tube S.N.51</u>					
Breech End:	193.6	192.6	193.0	193.2	193.1
Muzzle End:	188.0	190.0	188.2	186.2	188.1
<u>Tube S.N.52</u>					
Breech End:	183.2	183.5	183.2	183.5	183.4
Muzzle End:	183.0	181.5	182.0	182.0	182.1
<u>Tube S.N.53</u>					
Breech End:	181.5	182.2	180.7	181.5	181.5
Muzzle End:	180.5	179.5	180.5	178.8	179.8
<u>Tube S.N.54</u>					
Breech End:	181.0	180.7	180.5	179.5	180.4
Muzzle End:	180.0	179.5	182.0	178.2	179.9
<u>Tube S.N.55</u>					
Breech End:	184.5	184.0	183.5	184.0	184.0
Muzzle End:	181.5	183.2	181.0	181.2	181.7

TABLE 13

FORGING ELONGATION

<u>Tube S.N.</u>	<u>Elongation</u>				<u>Avg.</u>
<u>Tube S.N.48</u>					
Breech End:	13.6	12.1	13.6	12.9	13.1
Muzzle End:	13.6	13.6	--	--	13.6
<u>Tube S.N.49</u>					
Breech End:	12.1	12.1	12.9	12.9	12.5
Muzzle End:	12.1	12.1	--	--	12.1
<u>Tube S.N.51</u>					
Breech End:	11.4	12.1	11.4	12.1	11.8
Muzzle End:	11.4	11.4	11.4	12.1	11.6
<u>Tube S.N.52</u>					
Breech End:	12.0	12.5	12.0	12.0	12.1
Muzzle End	12.5	12.0	12.0	12.5	12.3
<u>Tube S.N.53</u>					
Breech End:	13.0	12.5	12.5	12.5	12.6
Muzzle End	12.0	11.5	12.5	12.0	12.0
<u>Tube S.N.54</u>					
Breech End:	10.0	11.5	12.0	11.0	11.1
Muzzle End:	12.0	11.5	12.5	12.0	12.0
<u>Tube S.N.55</u>					
Breech End:	13.5	14.0	14.0	14.0	13.9
Muzzle End:	10.0	12.0	12.5	13.0	11.9

B. Summary of Forging Data.

All material properties of the seven tube forgings fell within specifications. No striking variations in material properties were evident from tube to tube. It was noted, however, that (if tube S.N.53 is treated as a special case) the tubes which were considered to have low muzzle wear (S.N. 52, 54 and 55) demonstrated a slightly lower average yield strength, ultimate tensile strength, reduction of area, and Charpy V-notch impact resistance than those tubes which were considered to have high muzzle wear (S.N.48, 49 and 51). That is, the tubes which had poorer physical properties fared better with respect to muzzle wear. The forgings which resulted in low muzzle wear tubes were supplied by National Forge Co. while those which resulted in high muzzle wear tubes were supplied by Cabot Corp.; the two suppliers used differing quench and tempering processes as noted above.

C. Manufacturing Data.

1. Manufacturing Deviations:

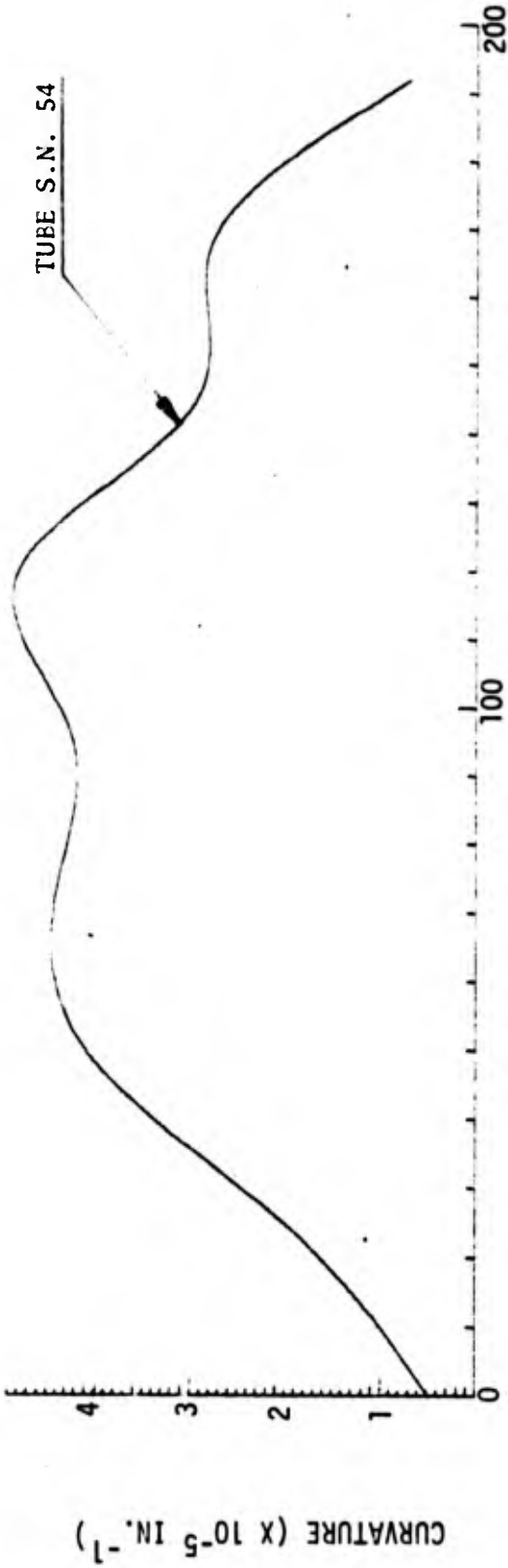
- a. S.N.48: Gain pilot undersized by .001 inches max.; forward breeching bearing surface .001 to .006 inches undersized.
- b. S.N.49; Slightly oversized chamber (approximately 1%).
- c. S.N.51: Length of O.D. taper (12" to 10.25" diameter) .75 inches too short. Breech end gain pilot .007 to .008 inches undersized.
- d. S.N.52: None
- e. S.N.53: Chrome undersized .0004 inches approximately 100 inches from rear face of tube.

f. S.N.54: None

g. S.N.55: Final borescoping revealed a slight step in the bottom of every other groove approximately .001 inches deep, but within drawing tolerances.

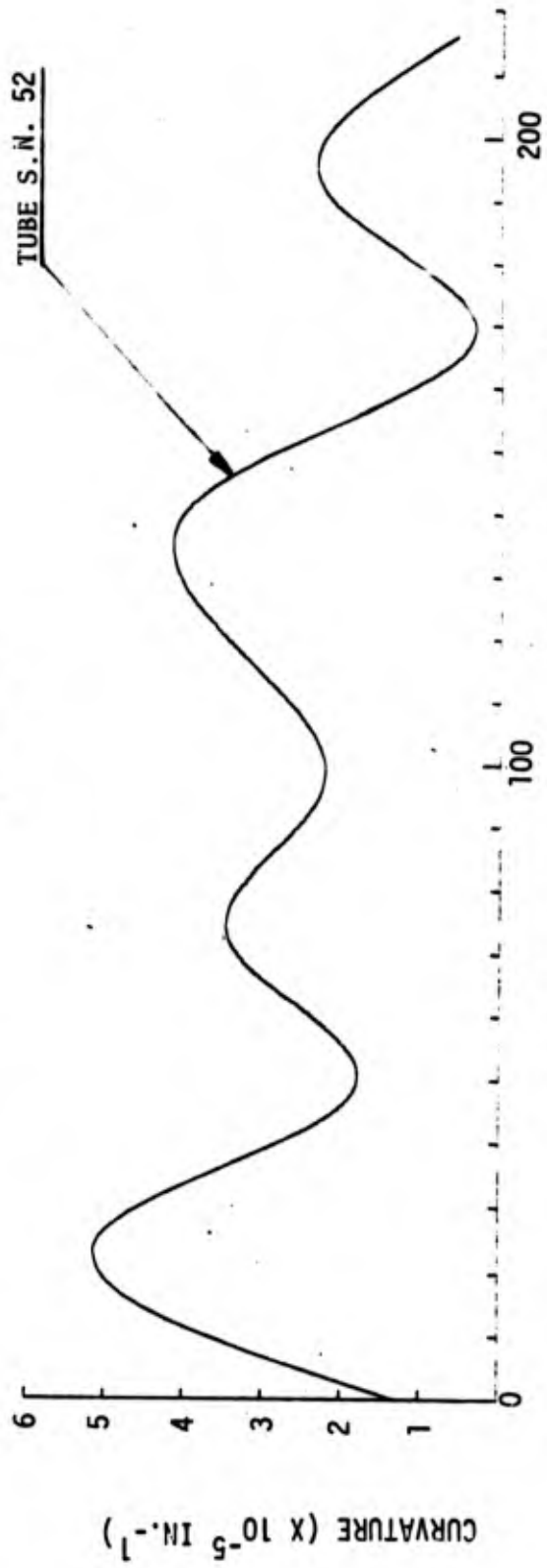
2. Wall Thickness Variation. All tubes fell within drawing specifications. No pattern emerges relating this parameter to muzzle wear.

3. Bore Straightness. (excluding droop) According to drawing specifications, the bend (excluding droop) in the rifled portion of the tube shall not exceed .020 inches in any 24 inch interval nor cumulate to more than .060 inches in the entire rifled length. Measurements were taken optically in two directions normal to the axis of the tube, and all proved to be within specifications. From these data, Mr. David Finlayson (Reliability and Maintainability Engineering Office, Watervliet Arsenal) and Mr. Royce Soanes (Computer Science Office, Watervliet Arsenal) have calculated the three-dimensional curavature for each point in the rifled portion of four tubes. Calculations were performed for two low muzzle wear tubes (S.N.52 and 54) and two high muzzle wear tubes (S.N.49 and 51). These data are shown in Fig. 39thru 42. As can be seen, the greatest curvature computed is approximately 9×10^{-5} in.⁻¹ for tube S.N.49. That is, the smallest radius of curvature encountered was 11,111 inches (roughly 1/6 mile). A simple calculation indicates that the resulting acceleration normal to the path of the projectile would be on the order of 200 g's (maximum encountered). For the same tube at the same point, the acceleration tangent to the path of the projectile would be on the order of 20 times greater. In spite of



DISTANCE FROM COMMENCEMENT OF FULL RIFLING (IN.)

FIGURE 39



DISTANCE FROM COMMENCEMENT OF FULL RIFLING (IN.)

FIGURE 40

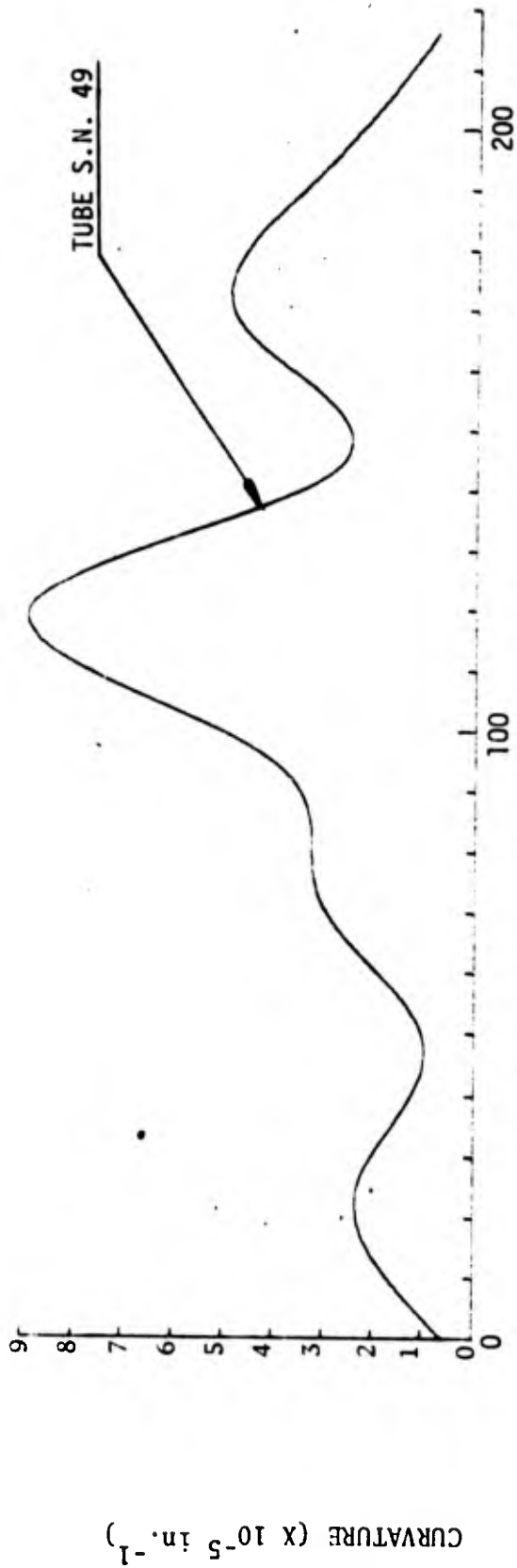


FIGURE 41

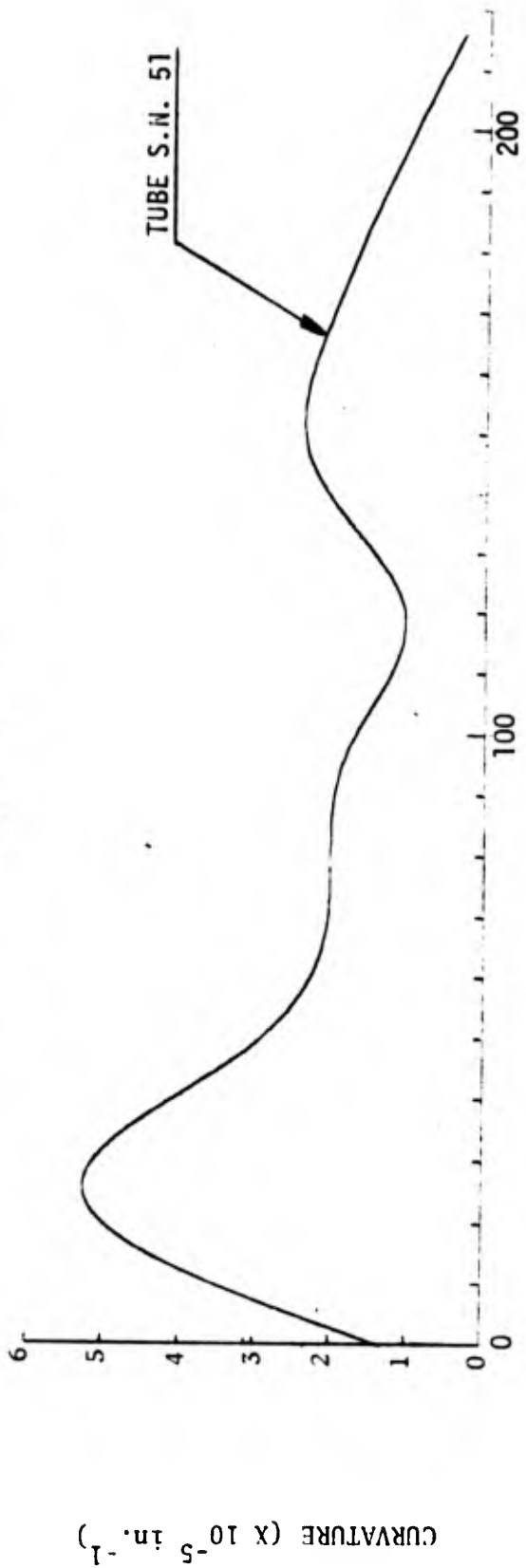


FIGURE 42

this however, Figures 39 thru 42 reveal no obvious pattern relating radius of curvature and the extent or location of muzzle wear. A report in-process by Mr. Finlayson⁴ will deal analytically with bore straightness as well as projectile imbalance and misalignment.

4. Bore Diameter as Manufactured. All tubes fell within tolerances (land-land: 6.100 to 6.102 inches; groove-groove: 6.200 to 6.208 inches). No relationship was apparent relating this parameter to tube muzzle wear.

D. Summary of Manufacturing Data.

All manufacturing requirements for these tubes fell within specifications except for the deviations noted in Section C. 1. above. No pattern was evident relating muzzle wear with tube thickness variation, initial bore diameter, or bore straightness (excluding droop).

4. David F. Finlayson, "Forces of Constraint on Projectiles with Spiral Motion In-Bore", report in process, Watervliet Arsenal (1975).

VIII. Borescope Reports

The tube bores were visually inspected at various times during the tubes' lives using a borescope. Generally, an inspector looks for cracks, deposits, condition of the lands and grooves, changes in surface appearance, and other bore defects. The data derived from these inspections are subjective but can be quite informative. The following is a recap of borescope inspections for five of the tubes tested.

A. Tube S.N.51

1. 0 Rounds: An unspecified material buildup was found at the origin of rifling (O. of R.) on the lands and grooves between 6 and 9 o'clock (breach time).

2. 1115 Rounds: Light coppering found on the edge of lands (side not specified) from O. of R. to 114" from the rear face of the tube(RFT).

3. 2477 Rounds: Copper buildup starting 80" from RFT in grooves. Build-up increases up to 130" from RFT where it becomes "heavy" and stays this way to 160" from RFT. Coppering decreases from 160" to 180" to muzzle, very light copper buildup.

B. Tube S.N.52

1. 858 Rounds: One land slightly flattened 114" from RFT (1.25" long x .005 deep). O. of R. shows some coppering and heat checking. Grooves appeared rounded from origin to 40-50" forward.

2. 2866 Rounds: A cut-off 166" Section (incl. muzzle end) showed heavy copper buildup up to 180" from RFT, lesser copper from 180-190", and light to medium copper from 190" to the muzzle.

C. Tube S.N.53

1. 1616 Rounds: Chrome was stripping at 4 o'clock (breach time) 228" from RFT. Lands were chipped at 4 o'clock at 217" from RFT. Chrome was stripped from edge of land at 12:10 at 198" from RFT.

2. 2706 Rounds: Lands were completely worn at origin of rifling; condition continues but decreases for 5 inches. From 45-50" from RFT both sides of lands are chipped from 3 - 6 o'clock (breach time). Lands are chipped on

the driving side at 6 o'clock at 50" from RFT; the condition continues counterclockwise to 11 o'clock 100" from RFT where condition disappears. Three positions have the driving side and edge of one land chipped away from 1/4": 1 o'clock @ 101", 11 o'clock @ 109", and 2 o'clock @ 110". Starting @ 170" from RFT, the driving side and edge of some lands get progressively more worn as the muzzle is approached. At the muzzle, the driving edge is at groove height.

D. Tube S.N.54

1. 1016 Rounds: Slight erosion at 12 o'clock area of forcing cone. Slight heat checking at O. of R.; lands rounded continuing out to 100" from RFT. Tears on lands and slight wear on top of lands (3 - 6 o'clock) from 115" - 155" from RFT.

2. 2042 Rounds: Heat checking and early development of longitudinal cracks at O. of R. light copper and firing debris buildup in grooves.

3. 2582 Rounds: A cut-off 100" Section (incl. muzzle end) showed heavy coppering up to 185" from RFT. Up to 180" from RFT, copper deposits were fused in the grooves at 7 and 3 o'clock (muzzle time) position.

E. Tube S.N.55

1. 255 Rounds: A noticeable buildup of copper starts 122" from RFT at 2 o'clock (breech Time) position. Heaviest deposits are on the driving side of the lands and in the groove, close to the same land edge. These extend intermittently almost to the muzzle end of the tube. Over the last couple of feet, the buildup is much lighter and more scattered. In most cases, the center of the groove is free of buildup so that stargaging would probably not pick it up.

To summarize, it appears that except for tube S.N.53 (chrome bore), the inspector was concerned primarily with copper deposits. This is of special interest in this investigation since previous tests have indicated a relationship between bore coppering and muzzle wear⁵. Table 14 indicates that heavy copper deposits generally were noted up to the point where muzzle wear begins to appear. Conversely, lighter coppering was noted in the region of the tube associated with higher muzzle wear. The inspector made no note of coppering for tube S.N.53; here he was concerned with the chipping of chrome and extreme wearing of the lands.

5. R. G. Hasenbein, "Analysis of Muzzle Wear Data for the 155mm Howitzer XM198", Watervliet Arsenal Report (1973)

TABLE 14

LOCATION OF COPPER DEPOSITS

<u>Tube S.N.</u>	<u>Rounds</u>	<u>Extent of Coppering*</u> <u>(in. from RFT)</u>	<u>Start of Upswing</u> <u>of Muzzle Wear Curve</u> <u>(in. from RFT)</u>
48	1104	--	170
49	574	--	170
51	2477	Heavy: 130 - 160" Decreases: 160 - 180" Very Light: 180" - muzzle	160
52	2866	Heavy: to 180" Less Heavy: 180 - 190" Light to Medium: 190" muzzle	195
53	2706	No comment on copper	145
54	2582	Heavy: to 185"	185
55	255	Noticeable copper Buildup: 122 - 215" Buildup lighter and more scattered: 215 - 240"	205

*Based on qualitative borescope inspections.

Summary of Observations and Conclusions.

- A. Muzzle wear rate can vary substantially during the life of a tube, apparently without regard to how many rounds have been fired.
- B. Tube muzzle wear performance is best judged by knowing the rate of wear at various times during the tube's life. Naturally, tubes with high wear rates at the end of their lives are considered superior to tubes exhibiting high wear rates early in their lives.
- C. From the Durability Test data, it can be stated with 95% confidence that a direct linear relationship exists between range percent error and (vertical) wear at the muzzle.
- D. From the Durability Test data, it can be stated with 98% confidence that a direct linear relationship exists between (vertical) wear at the muzzle and corresponding wear of the same land at the commencement of rifling.
- E. One XM123E2 Z-8 propelling charge lot used during the Durability Test, IND-E-114, was associated with high muzzle wear rates. Another lot, IND-E-124, had similar tendencies, but at a rate one-third of IND-E-114. Other lots used were associated with lower muzzle wear rates.
- F. Muzzle wear began on the average, 175 inches from the rear face of the tube and increased all the way to the muzzle.
- G. Muzzle wear was largely limited to a particular set of lands and followed the spiral of rifling.

- H. On the average, the lands emerging at the muzzle at approximately 5 o'clock (viewed from the muzzle) tended to wear the most. This set of lands can be traced back to 12 - 1 o'clock at the origin of rifling.
- I. A thermally altered layer was found on the driving edge and top of the lands. This layer was much harder than the tube's base metal and contained many V-shaped cracks. Probable cause of the layer is abrasion between the tube and projectile.
- J. Tubes considered to have higher muzzle wear were found to have better strength and ductility than the tubes considered to have lower muzzle wear.
- K. The tubes used during the Durability Test met all significant manufacturing specifications.
- L. Heavy copper deposits generally were noted up to the axial location where muzzle wear begins; conversely, lighter coppering was noted in the region of the tube associated with higher muzzle wear.

Acknowledgement

The author wishes to acknowledge the constructive comments and suggestions given by Dr. Robert Montgomery and Messrs. Raymond Betner, William Lewis and David Finlayson. The metallography was done by Mrs. Theresa Brassard.

Special thanks to Mrs. Mary Clinton, Rita Hannigan, and Frances Gormley for their help in typing and preparing the text.

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1. Analysis of Muzzle Wear Data for the 155mm Howitzer XM198; Hasenbein, R. G., Watervliet Arsenal, 1973; Technical Report WVT-TR-75024
2. The Erosion of Guns at the Muzzle; Line, L.E.; National Defense Research Committee of the Office of Scientific Research and Development, 1945; NDRC Report No. A-357; OSRD Report No. 6322.
3. Muzzle Erosion of Cannon; Montgomery, R.S.; Watervliet Arsenal, 1974; Technical Report WVT-TR-74050.
4. Forces of Constraint on Projectiles with Spiral Motion In-Bore; Finlayson, D. F.; Watervliet Arsenal, 1975; report in process. Reliability and Maintainability Engineering Office, Benet Laboratory, Watervliet Arsenal, N. Y.