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ANALYSIS OF WEAR DATA FROM 105MM M68 GUN TUBES IN FIELD SERVICE

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Watervliet Arsenal

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This study was performed to determine mean wear profiles of gun tubes in field service. After determining these profiles, a method of interrelating wear at various locations within the gun tube was developed. This will permit a logical reassessment of tube condemnation criteria, if this is found to be necessary in current testing.

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INTRODUCTION

The Cannon, 105MM Gun:M68 has been fielded since 1960 as the primary armament for the M60-series (M60, M60A1, M60A1E3) and, later versions of, the M48-series medium tanks. The United Kingdom fields a similar gun (105MM Tank Gun L7) with a gun tube interchangeable with that of the M68.

A variety of ammunition, classified according to projectile type as APERS-T, APDS-T, HEAT-T, HEP-T, WP-T, and TP-T, is fired in the M68. The M392-series APDS-T cartridge is of the hyper-velocity, armor-piercing type with discarding sabot and is intended for use in defeating armored targets. The M490 TP-T cartridge is used extensively in marksmanship training.[1]

In 1964, efforts to increase the relatively short wear life of the M68 Gun tube culminated in the adoption of several forms and configurations of wear reducing additives included with the cartridge propellant charge.[2,3] Reductions in bore wear rates to as little as

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[1]TM 9-1300-203, Artillery Ammunition, DA, April, 1967
[2]APG Report No. DPS-768, Component Development Test of Laminar Coolant, Barrel-Wear Reducing Additive in Cartridge, 105MM, APDS-T, M392E1, for 105MM Gun, M68, Ammunition Components, January, 1963.
[3]APG Report No. DPS-838, Component Development Test of Swedish Barrel-Wear Reducing Additive for 105MM Gun, M68, Ammunition Components, March, 1963.

1/20 that of non-additive ammunition were documented in test firings.[4] During these test firings, a variation in the monotonically decreasing relationship of diametrical bore wear to distance from origin of rifling, encountered when firing non-additive ammunition, was noted when additive ammunition was fired. Bore wear profiles showed a characteristic second wear maxima slightly forward of the origin of rifling. This second wear maxima, termed secondary wear, was consistently lower in amplitude than the primary wear maxima (at the origin of rifling) and showed negligible effect on gun accuracy.

Early in 1974, erratic flight and poor dispersion with M392A2 APDS-T ammunition were reported during tank and ammunition acceptance tests. These tests were conducted with used (previously fired) gun tubes. Measurements of tube wear showed that secondary wear exceeded primary wear.

At the direction of the CG, ARMCOM, various agencies, including ARMCOM headquarters, TECOM, AMSAA, and Picatinny, Frankford and Watervliet Arsenals, initiated concurrent efforts, relative to their mission functions, to evaluate the erratic performance. This report describes the program undertaken by Watervliet Arsenal to characterize and evaluate the wear characteristics of fielded M68 Gun tubes.

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[4]APG Report No. DPS-1520, Final Report of Product Improvement Test of Ammunition Additive Effect on M41 and M68 Gun Tube Life, December, 1964.

FIELD SAMPLING PLAN

The Product Assurance Directorate at ARMCOM established a sampling plan for inspection of gun tubes in the field. This plan was based on a survey of tubes in use in regular army units and cross referenced to blocks of serial numbers representing manufacturing differences in gun tubes. Though inexact, it was the only approach that could be taken within a reasonable span of time.

The samples obtained are as follows:

Tube S.N.	Samples	Manufacturer	Autofrettage Method	Forging Supplier
1-4299	50	Watervliet	Hydraulic	Cabot
4300 - 5299	12	Wheland	Hydraulic	Cabot
5300 - 7299 & 8800 - 10399	42	Watervliet	Mixed* & Swage	Cabot
7300 - 8799	17	Lockheed	Swage	Cabot
10400 - 11599	27	Watervliet	Swage	Cabot, Nat. Forge
11600 - Higher	5	Watervliet	Swage	Cabot
Total	153			

* Hydraulic or Swage

The samples were obtained from the following locations:

Locations		Samples
Ft. Hood		25
APG & JPG		6
Ft. Lewis		8
Ft. Knox		29
Ft. Riley		9
Ft. Carson		10
	Conus/Total	87
Friedberg, Germany (1 BN. 32 Armor Bde.)		9
Kirchgon, Germany (2 Bn. 32 Armor Bde.)		9
Friedberg, Germany (3 Bn. 32 Armor Bde.)		4
Mannheim, Germany (3 Bn. 68 Armor Bde.)		25
Mannheim, Germany (5 Bn. 68 Armor Bde.)		19
	FRG/Total	66
	Grand Total	153

PRELIMINARY ANALYSIS OF FIELD MEASUREMENTS

Several conventions, to be observed throughout the remainder of this report, have been established to describe M68 Gun tube wear. Land wear at the pull over location (25.25 inches from the rear face of the gun tube) is referred to as primary land wear. This measurement is used as the service condemning criteria for the M68 Gun tube with 100% life expenditure occurring when primary land wear reaches 0.075 inch. Land wear at the secondary maxima is referred to as secondary land wear without reference to its specific location in the tube bore.

The effect of tube groove wear on accuracy has not been established and there is no assigned groove wear limit. Groove wear measurements at the pull over location and secondary groove wear maxima are referred to as primary and secondary groove wear, respectively.

The tubes in the sample were segregated into four quarters of wear life as defined by primary land wear.

Quarter	Wear (in.)	Sample Size
1	0 - .019	28
2	.020 - .037	45
3	.038 - .056	49
4	.057 - .075	28
	.076 & greater	3
	Total	153

The actual wear data was subjected to computer analysis to determine mean wear profiles for each quarter of wear life for both land and groove measurements (Figures 1 - 8). Also, assuming normal distribution of data within wear quarters for each measurement distance, 90% tolerance limits (90% confidence) were placed about the mear profiles to show the extent of variation within each wear quarter. These tolerance limits are shown on Figures 1 - 8. The tube profiles prove conclusively that fielded tubes will exhibit secondary wear exceeding primary wear. Measurements from early tube samples did not include groove data, this is reflected by the smaller number of samples shown in each groove wear quarter.

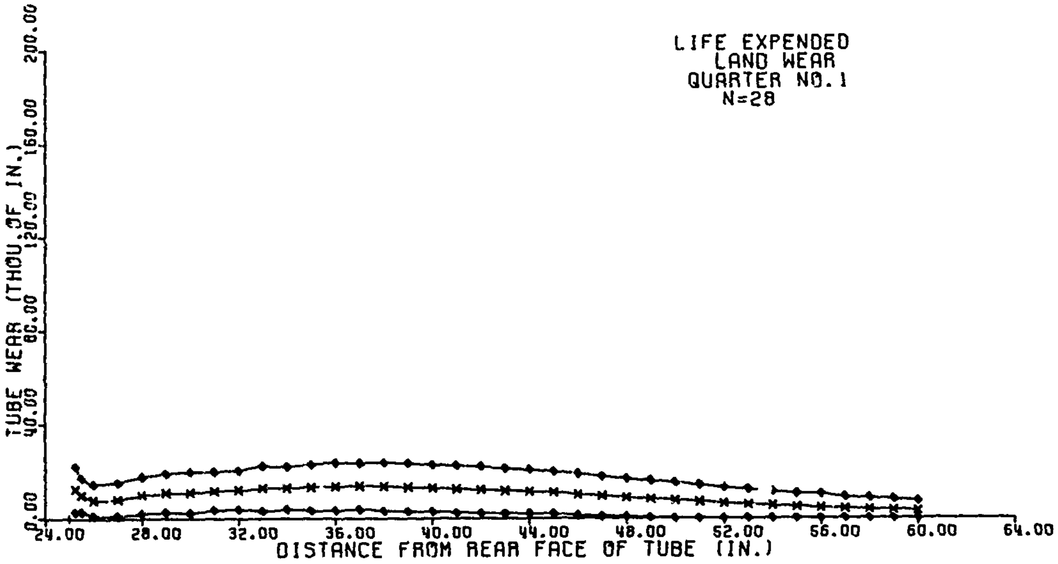


Figure 1. M60 Gun Tube: Mean Land Wear with 90/90 Tolerance Limits - First Wear Quarter

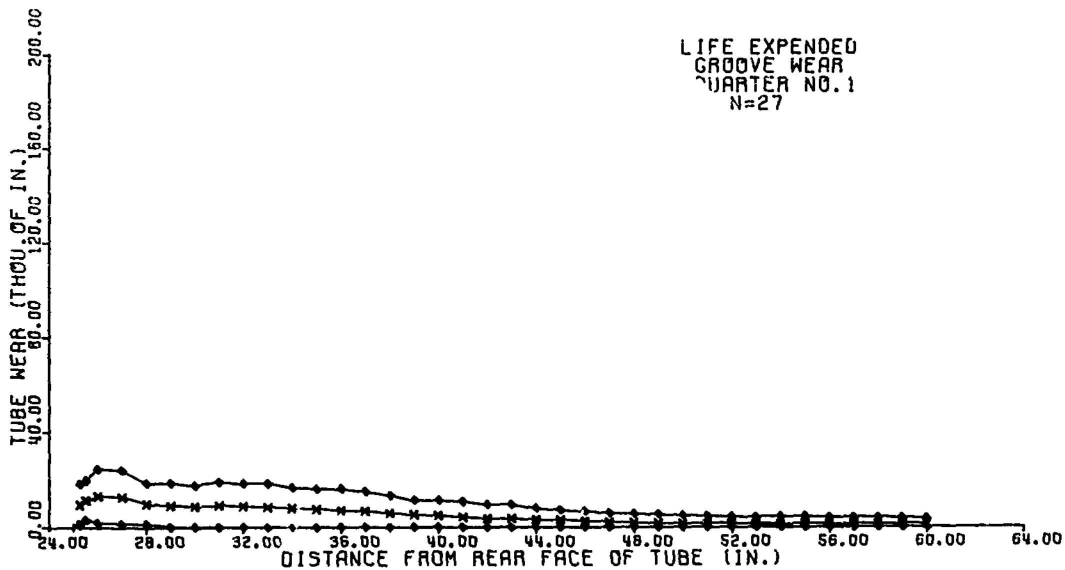


Figure 2. M68 Gun Tube: Mean Groove Wear with 90/90 Tolerance Limits - First Wear Quarter

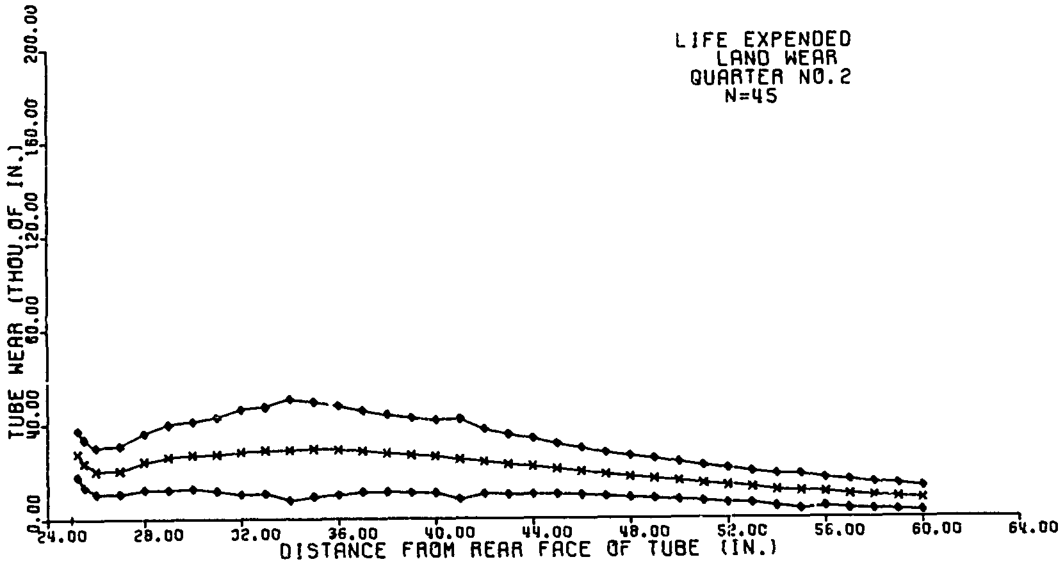


Figure 3. M68 Gun Tube: Mean Land Wear with 90/90 Tolerance Lim ts - Second Wear Quarter

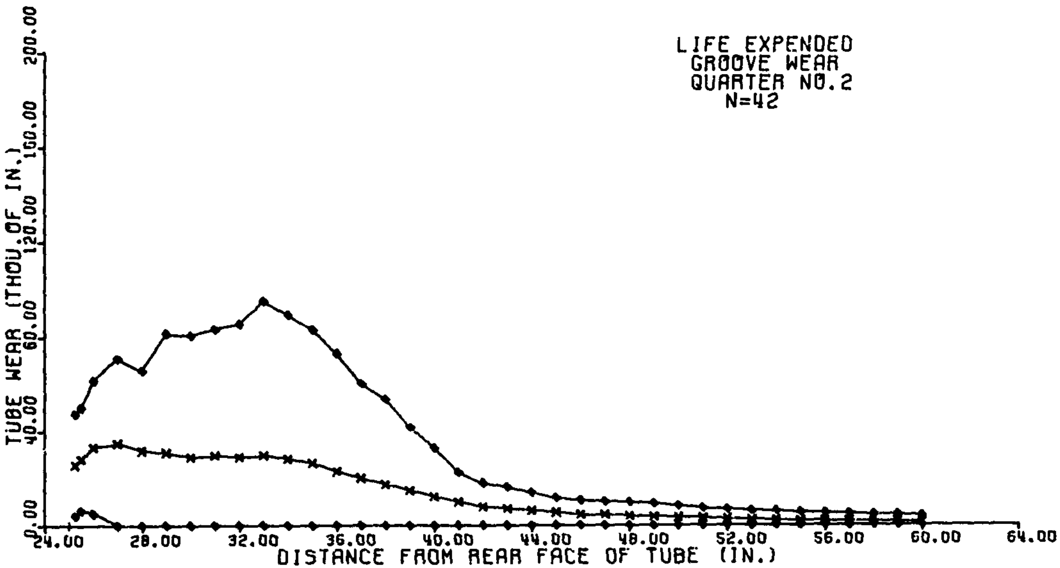


Figure 4. M68 Gun Tube: Mean Groove Wear with 90/90 Tolerance Limits - Second Wear Quarter

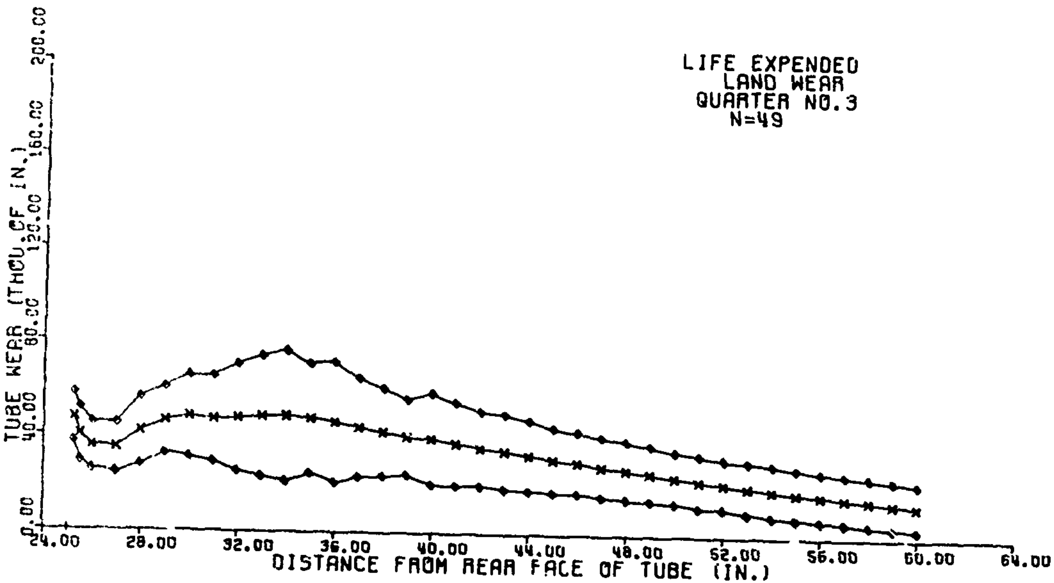


Figure 5. M68 Gun Tube: Mean Land Wear with 90/90 Tolerance Limits - Third Wear Quarter

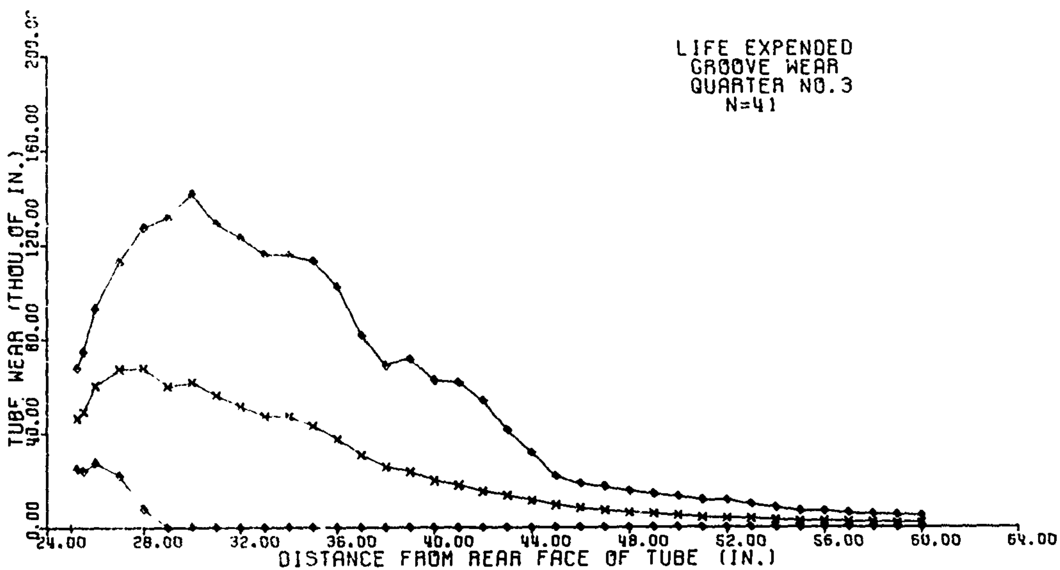


Figure 6. M68 Gun Tube: Mean Groove Wear with 90/90 Tolerance Limits - Third Wear Quarter

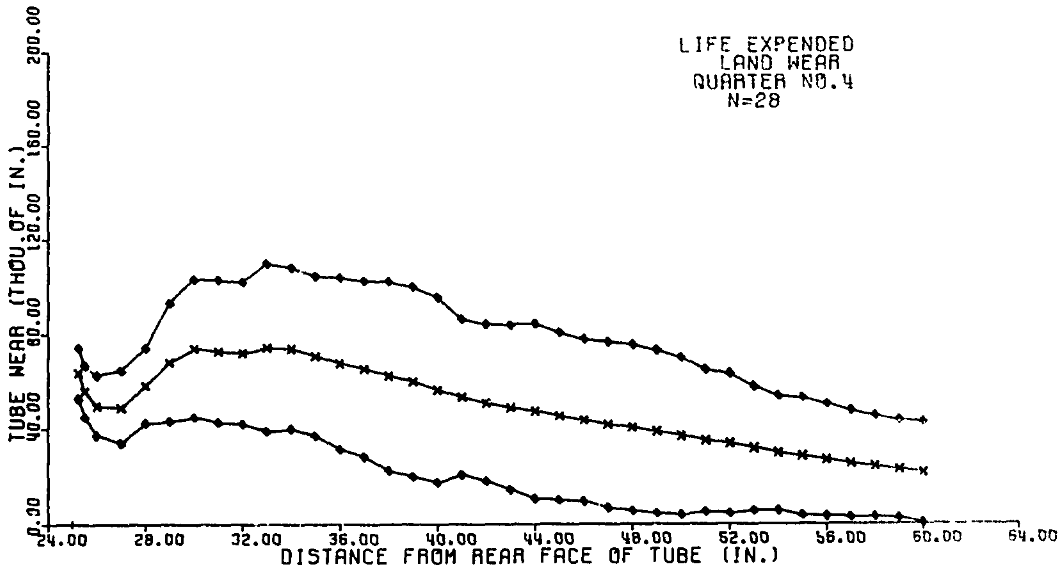


Figure 7. M68 Gun Tube: Mean Land Wear with 90/90 Tolerance Limits - Fourth Wear Quarter

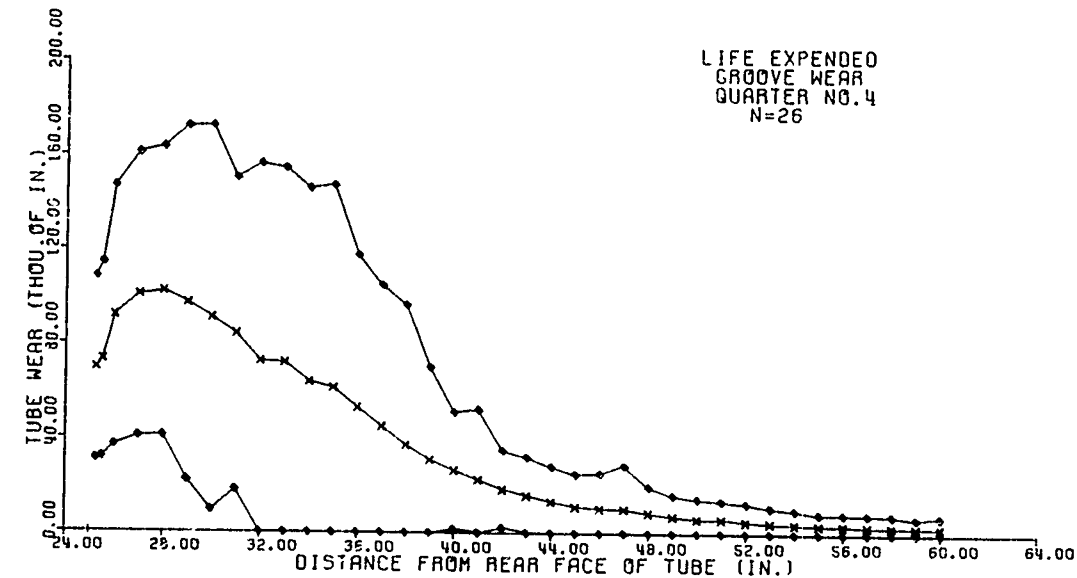


Figure 8. M68 Gun Tube: Mean Groove Wear with 90/90 Tolerance Limits - Fourth Wear Quarter

SELECTION OF REPRESENTATIVE TUBES FOR TEST FIRING

All tubes in each wear quarter were ranked against the respective mean profile and a tube as representative as possible was selected and forwarded to Aberdeen Proving Grounds for test firings conducted under the supervision of Picatinny Arsenal. The tubes selected as most representative are listed below; their wear profiles are shown in Figures 9 - 16. Since no tube exactly represents the mean profile, selected tube profiles shown in Figures 9 - 16 are bounded by lines representing one sample standard deviation corresponding to the respective sample mean to show the relationship to the assumed population distribution. An explanation of the selection procedure is given in Appendix A; the predominant factor in selection was groove wear.

Wear Quarter	Candidate Tube
1	7366
2	7500
3	7465
4	7503

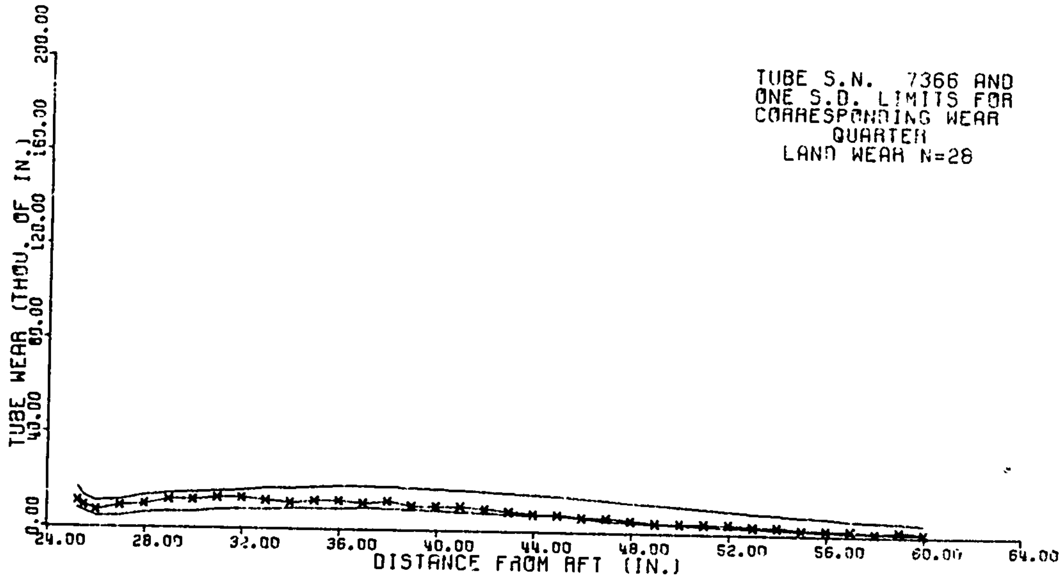


Figure 9. Tube Number 7366 - Land Wear with one S. D. Limits for Corresponding Wear Quarter

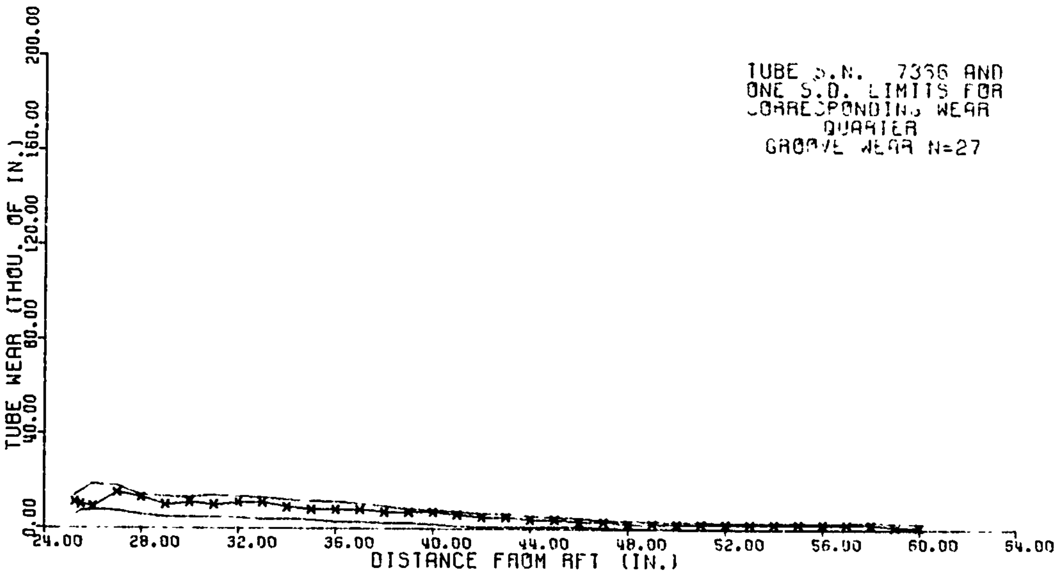


Figure 10. Tube Number 7366 - Groove Wear with One S. D. Limits for Corresponding Wear Quarter

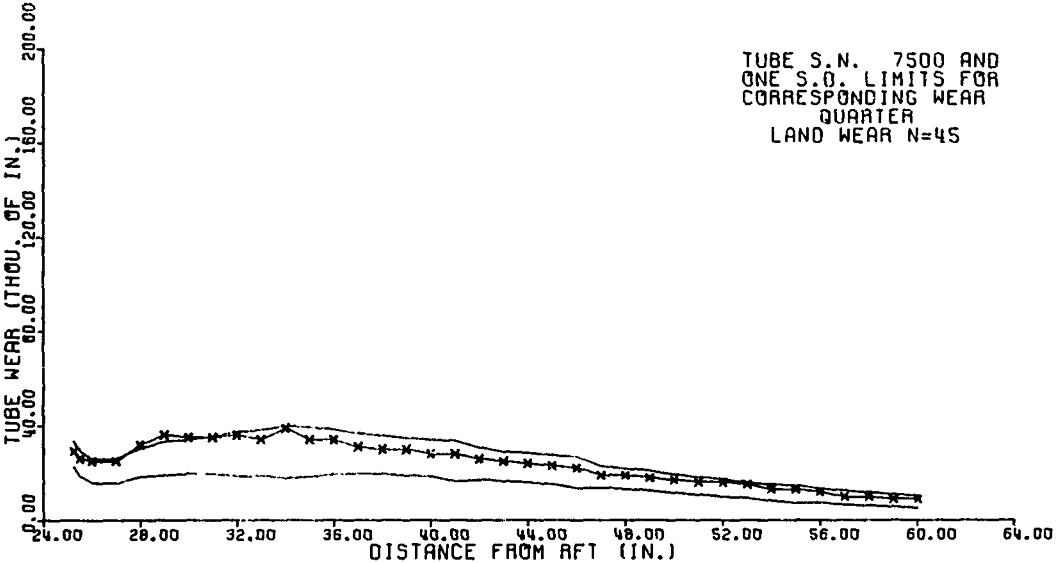


Figure 11. Tube Number 7500 - Land Wear with One S. D. Limits for Corresponding Wear Quarter

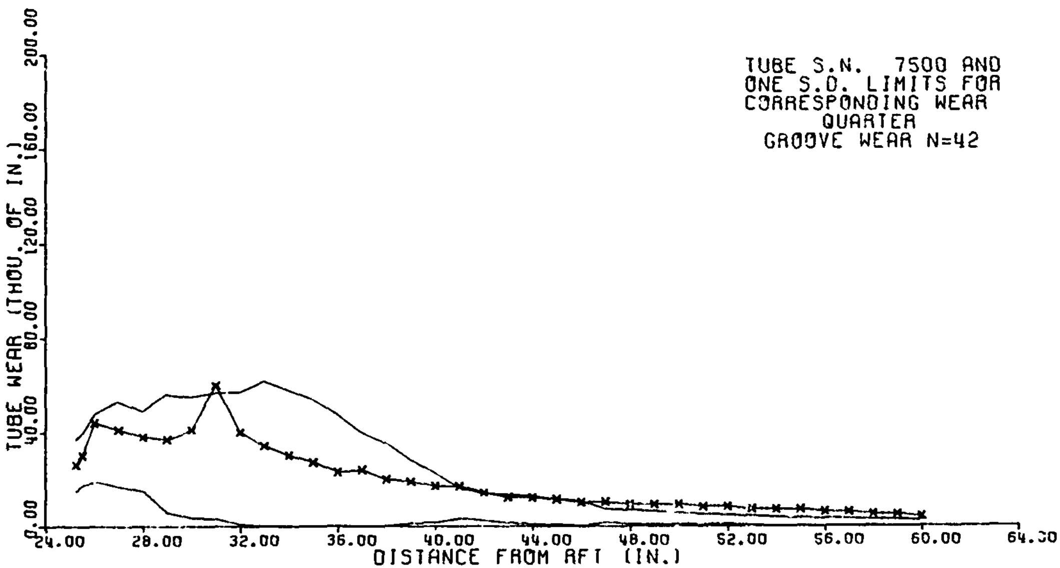


Figure 12. Tube Number 7500 - Groove Wear with One S. D. Limits for Corresponding Wear Quarter

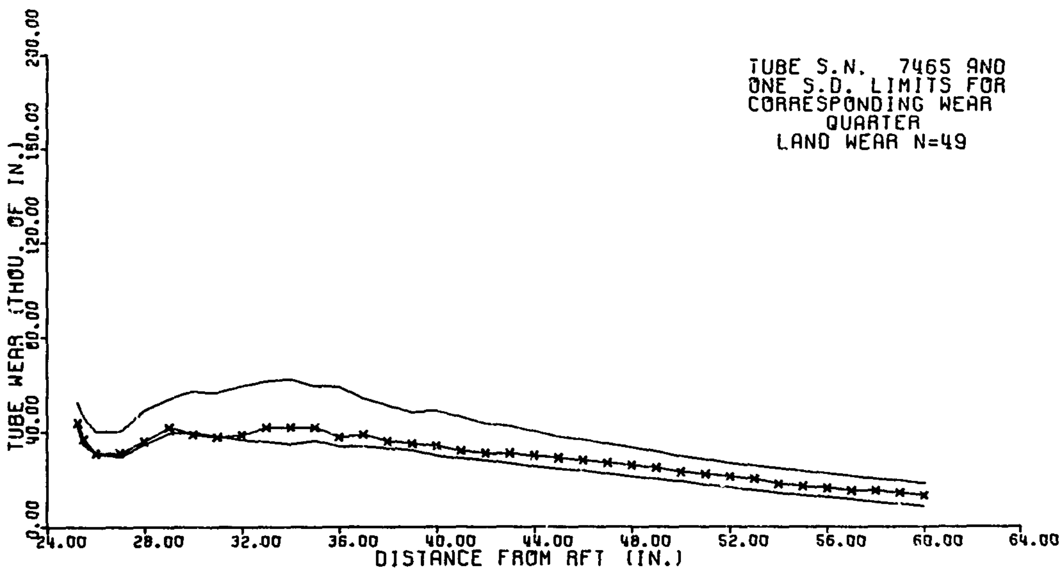


Figure 13. Tube Number 7465 - Land Wear with One S. D. Limits for Corresponding Wear Quarter

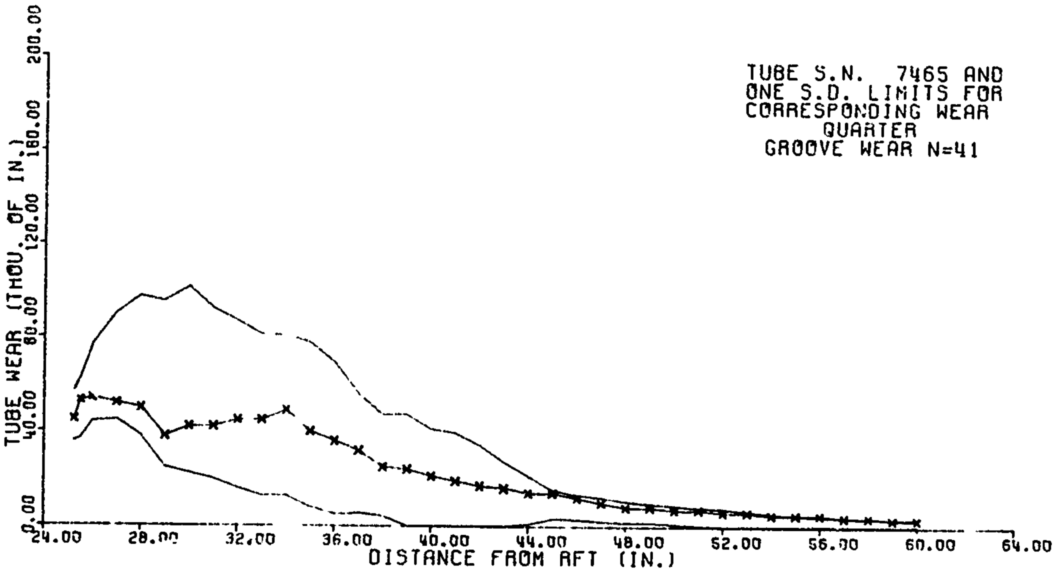


Figure 14. Tube Number 7465 - Groove Wear with One S. D. Limits for Corresponding Wear Quarter

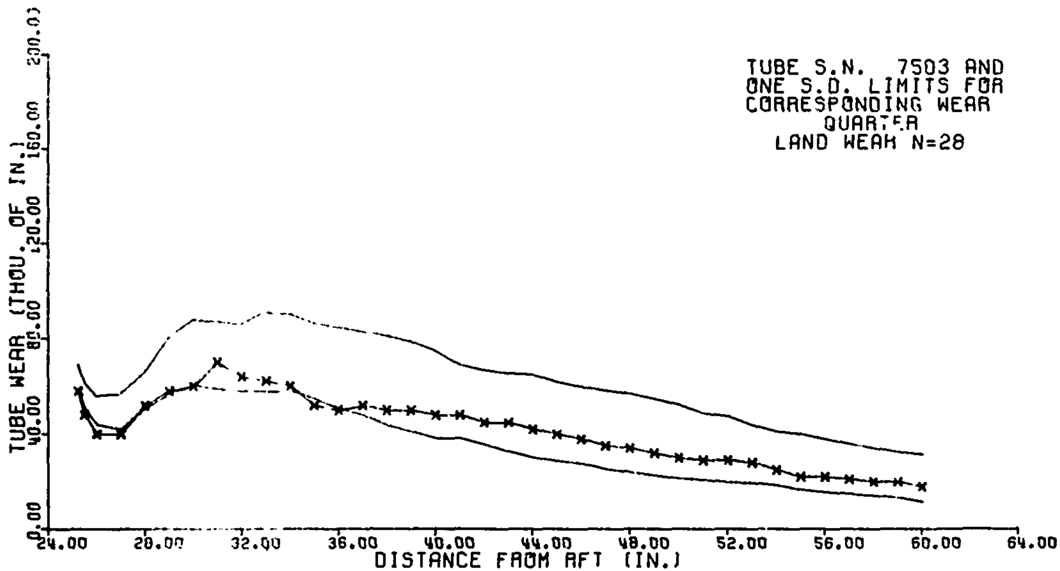


Figure 15. Tube Number 7503 - Land Wear with One S. D. Limits for Corresponding Wear Quarter

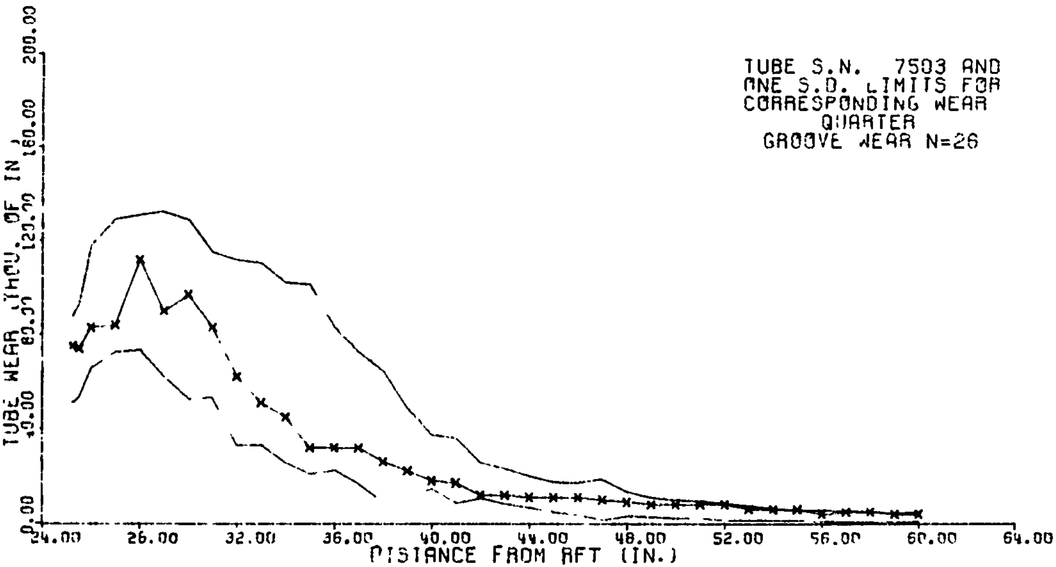


Figure 16. Tube Number 7503 - Groove Wear with One S. D. Limits for Corresponding Wear Quarter

ANALYSIS OF DATA

The available data was evaluated for several purposes using regression analysis (See Appendix B).

Secondary Wear

First, all the data was utilized to project the relationship between primary and secondary wear for both the lands and grooves. The results of this analysis (Figure 17) indicate that mean secondary land wear of .075 inches occurs when primary land wear is only .061 inches. In the case of the grooves (Figure 18), mean secondary groove wear of .075 inches occurs when primary groove wear is only .041 inches. The relationship of secondary groove wear to primary land wear is shown in Figure 19. In this instance, mean secondary groove wear of .075 inches corresponds to primary land wear of .0425 inches.

If consideration is restricted to secondary land and groove wear in the fourth wear quarter sample, as depicted in Figures 7 and 8, mean land wear of 0.075 inch can be seen to coincide with 0.100 inch groove wear. While inconclusive, it is noted that the United Kingdom condemns gun tubes for reaching their wear accuracy limit at 0.100 inch land wear and that the United Kingdom does not fire M490 or M456-series cartridges.

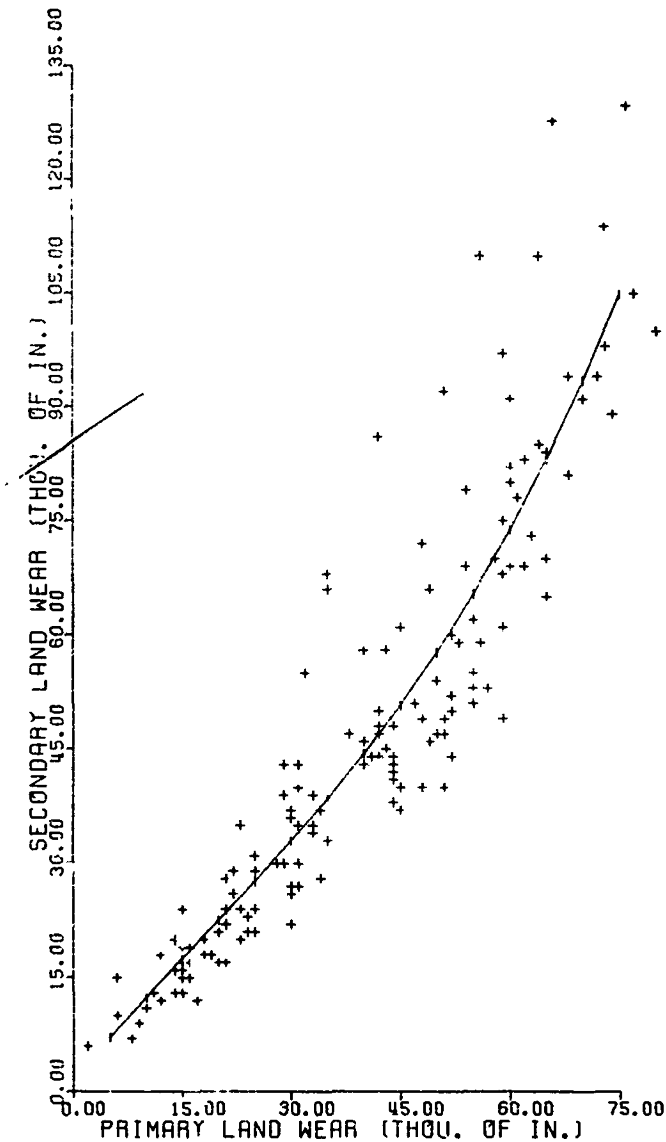


Figure 17. Primary vs. Secondary Land Wear With Regression Line

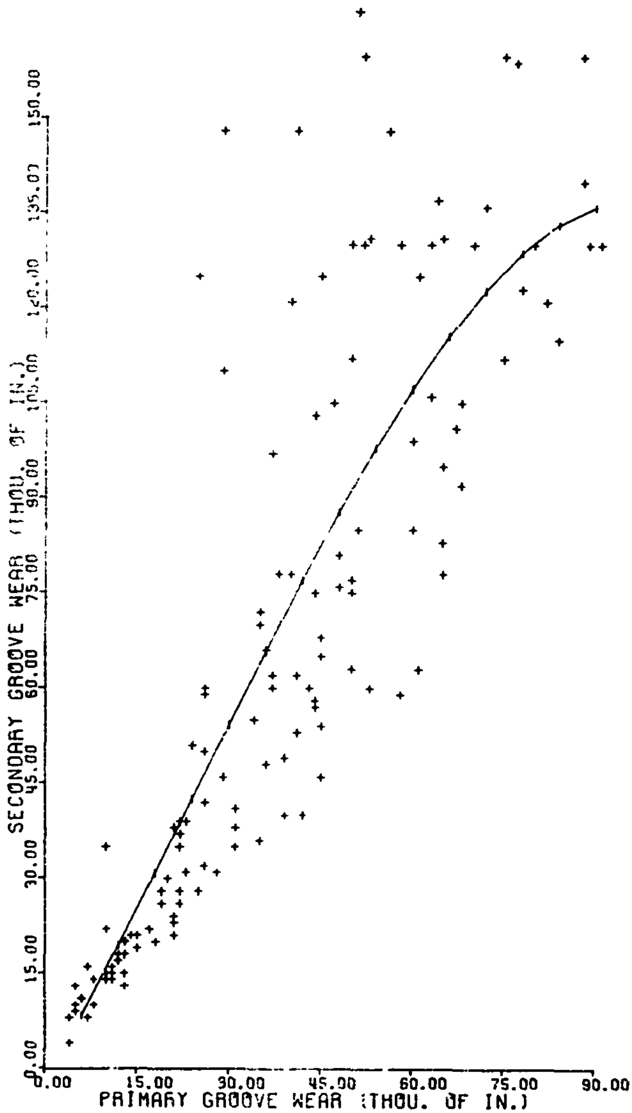


Figure 18. Primary vs. Secondary Groove Wear with Regression Line

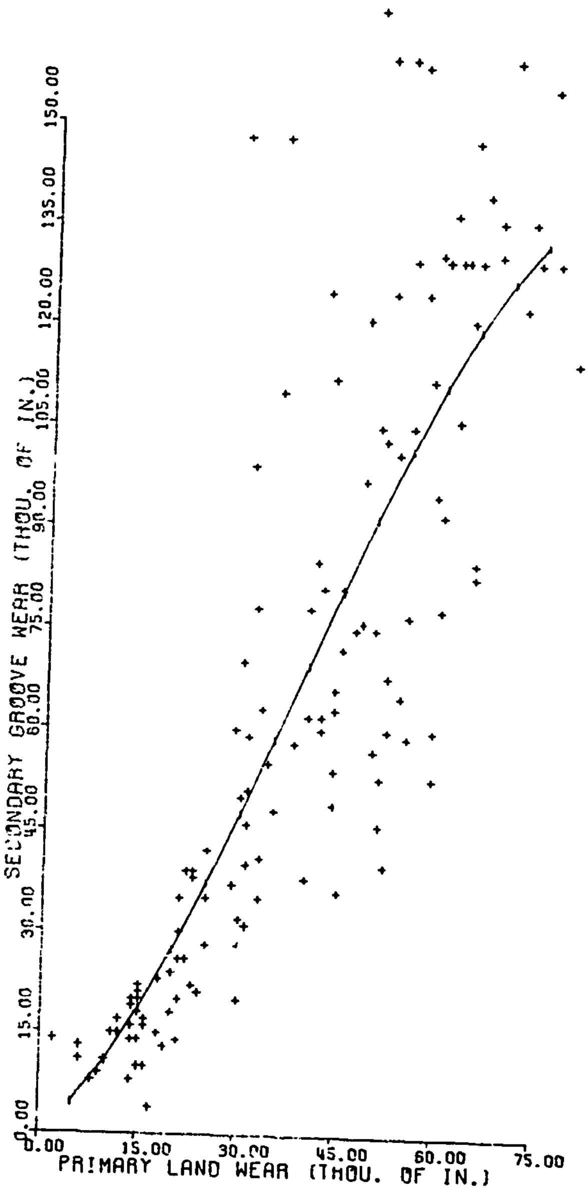


Figure 19. Primary Land vs. Secondary Groove Wear with Regression Line

Relative Land And Groove Wear

Secondary land and groove wear has been shown to exceed corresponding primary wear. Figure 20 shows the amount (as percent) by which the expected values of secondary land and groove wear exceed primary land wear, as tube wear life progresses, and depicts the predominance of excess secondary groove wear. This predominance is further demonstrated when it is noted that secondary groove wear exceeded primary groove wear in all but three of the 153 gun tubes sampled.

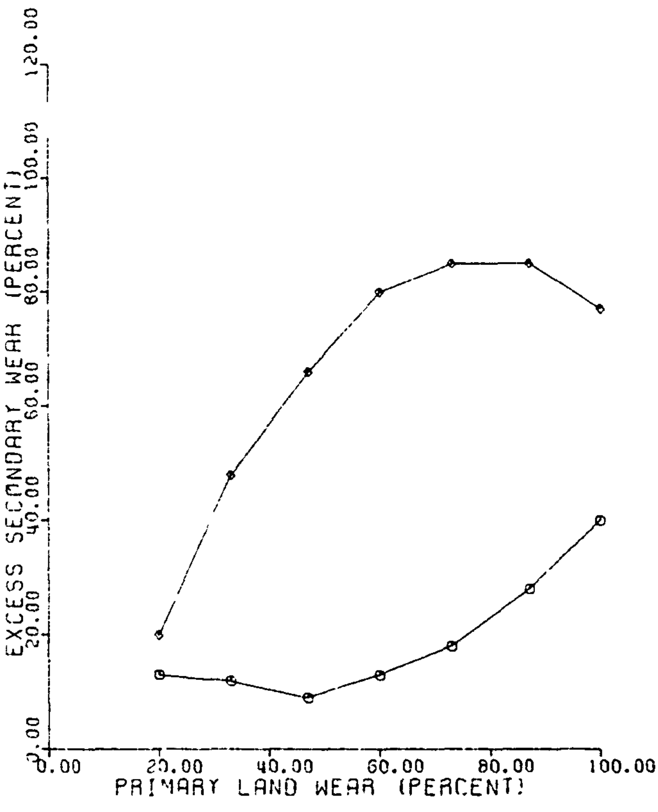


Figure 20. Secondary Land and Groove vs. Primary Land Wear

Effect Of Tube Sample Segregations

The model used to project the relationship between primary and secondary land wear has been applied to measurements segregated into the various sample groups specified in the field sampling plan described earlier. Several contributing factors must be considered in drawing conclusions from these group comparisons.

The evolution of an M68 gun tube wear profile is governed to some degree by the types of ammunition fired, especially in situations where combinations of additive and non-additive (e.g. T382, M392, M456) ammunition have been fired. Figure 21 shows the evolution of bore wear in an M68 gun tube firing ammunition without bore wear reducing additive. Gun tubes in the sample dating from production and proofing in the early 1960's were fielded with high (.007 - .012 inch) initial wear with profiles similar to those shown in Figure 21. As indicated in Appendix C, the majority of tubes in the FRG sample exhibit this condition.

Figure 22 shows the relationship between primary and secondary land wear for the CONUS and FRG tube samples. With consideration given to the high initial primary wear in the FRG tubes, this relationship is effectively the same for both sample groups. Similar results are obtained from various other sample groupings and are described in Appendix C.

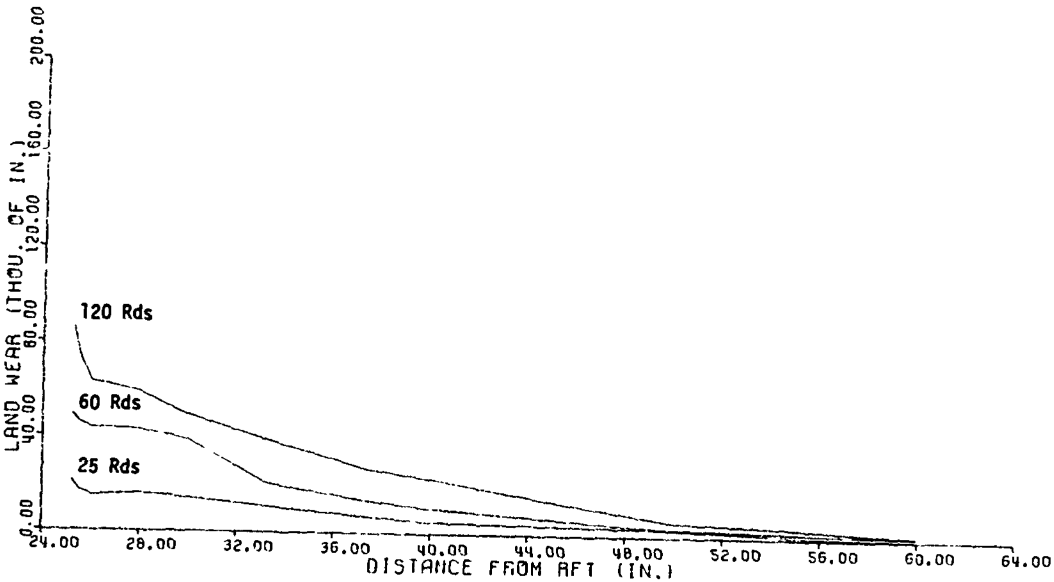


Figure 21. M68 Gun Tube Land Wear with Non-Additive Ammunition

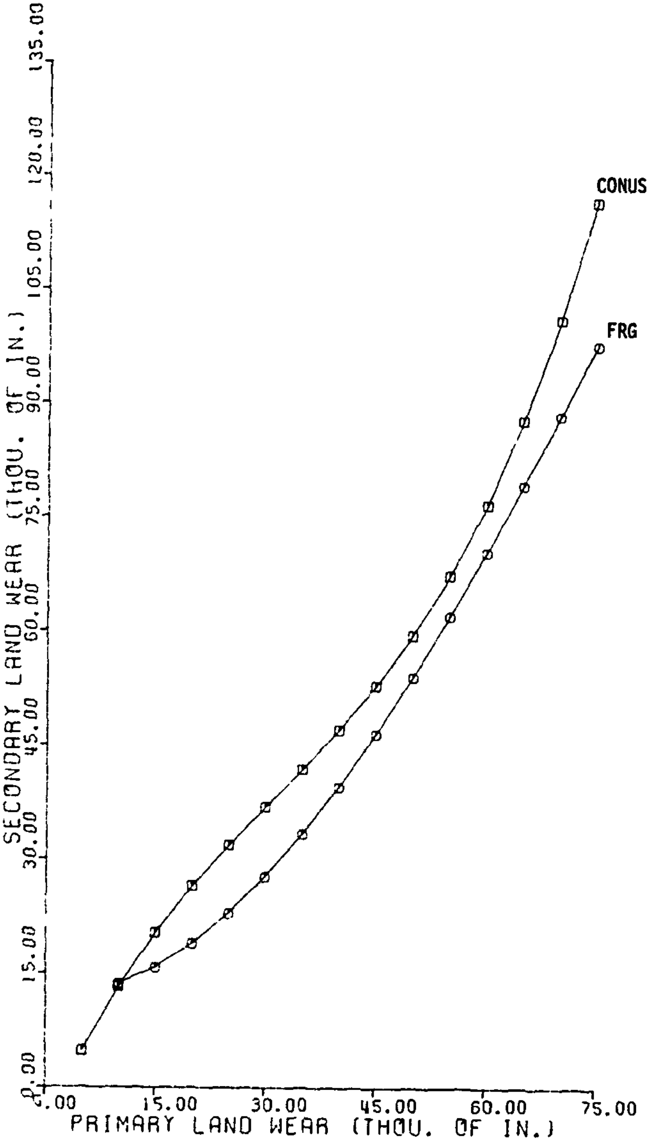


Figure 22. Primary vs. Secondary Land Wear - Regression Lines for CONUS and FRG Samples

Effect Of Reducing Primary Land Wear Requirement

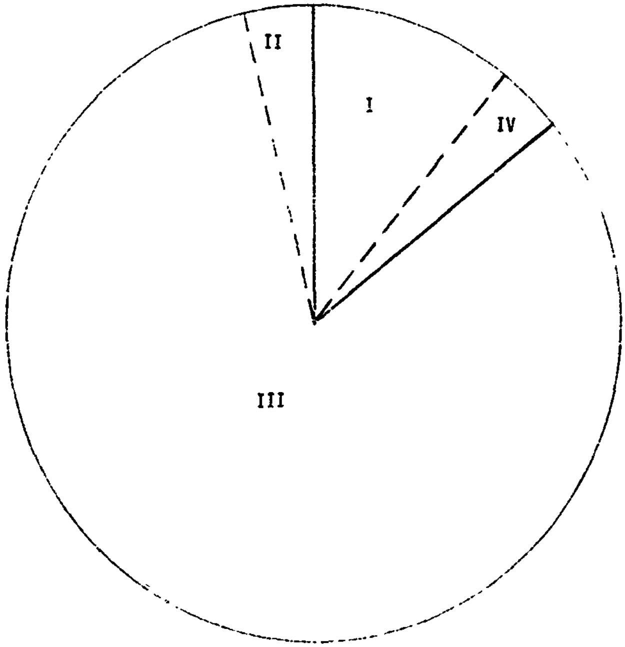
If it is established that it is necessary to revise or amend the existing tube wear life criteria, it will be advantageous to predict the impact of such a criteria on the present gun tube population. For example, if it is found that secondary land wear in excess of 0.075 inch produces unacceptable performance, and the condemnation criteria is to be based on primary land wear, a reduction in the allowed primary land wear will not only condemn tubes with excess secondary land wear, but will also condemn tubes with acceptable (in this hypothetical situation) secondary land wear (cf. Figure 17). In addition, unless the reduction in the primary land wear limit is extreme, a number of tubes with excess secondary land wear will survive under the revised criteria.

A trade-off analysis, described in Appendix D, has been conducted, assuming the field wear survey data as representative of the total gun tube population wear life distribution. Examples of the results of this analysis for specific condemnation situations are shown in Figures 23 - 25.

Figure 23 shows the disposition of the current field population after a 20% (0.075 to 0.060 inch) reduction in the primary land wear condemning criteria. As indicated in the figure, 3.4% of the tubes acceptable under the present criteria would be condemned with secondary land wear less than 0.075 inch and 3.4% of the tubes accepted under the revised criteria would have secondary land wear exceeding 0.075 inch.

Figure 24 shows the disposition of the current field population after a 20% reduction of the maximum groove wear in the field sample. This modification would cause none of the tubes to be rejected, should a criteria of this form be established, with secondary groove wear less than 0.100 inches and allow 25% of the tubes accepted under this criteria to have secondary groove wear exceeding 0.100 inch.

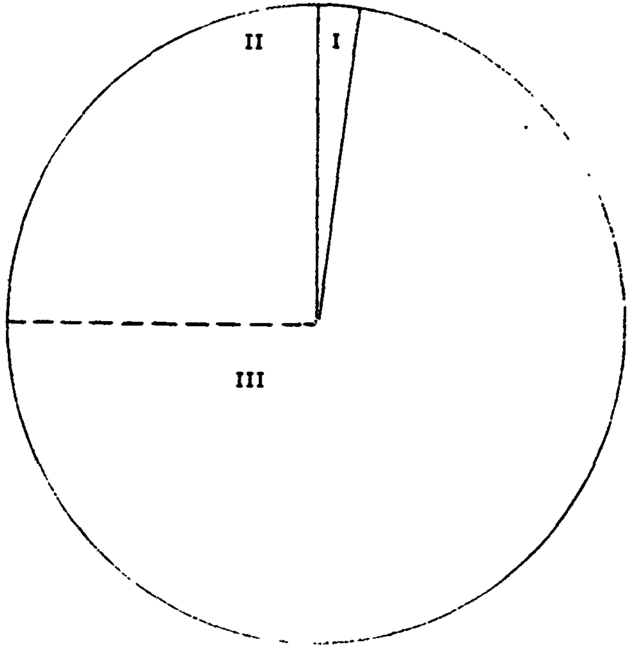
Figure 25 shows the disposition of the current field population in a situation where the primary land wear limit is reduced 20% and secondary groove wear of 0.100 inch is an accuracy defining factor.



II: 3.4% accepted w/excessive secondary land wear
III: 82.4% accepted w/o excessive secondary land wear
85.8% total accepted

I: 10.8% rejected w/excessive secondary land wear
IV: 3.4% rejected w/o excessive secondary land wear
14.2% total rejected

Figure 23. Gun Tube Population Disposition after a 20% Reduction in Primary Land Wear

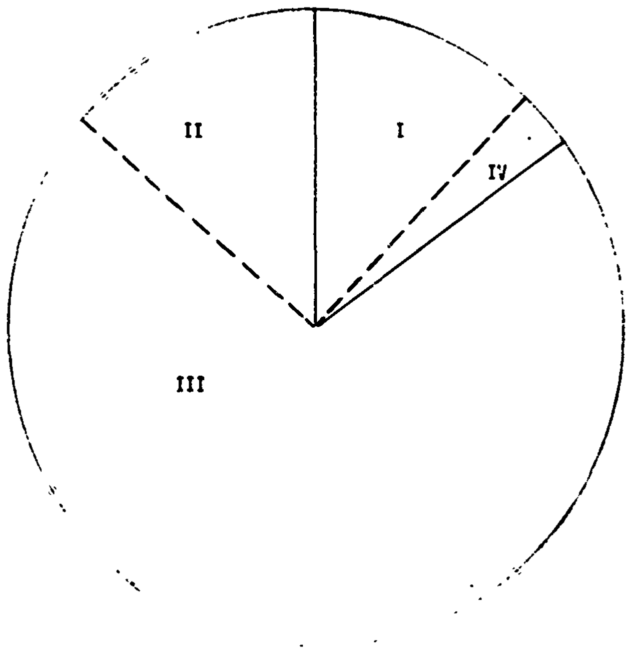


II: 25% accepted w/secondary groove wear greater than 0.100"

III: 74% accepted w/o excessive secondary groove wear
99% total accepted

I: 1% rejected w/secondary groove wear greater than 0.100"
(0% rejected w/o excessive secondary wear)
1% total rejected

Figure 24. Gun Tube Population Disposition after a 20% Reduction in Primary Groove Wear



II: 14% accepted w/secondary groove wear greater than 0.100"
III: 71% accepted w/o excessive secondary groove wear
85% total accepted

I: 12% rejected w/secondary groove wear greater than 0.100"
IV: 3% rejected w/o excessive secondary groove wear
15% total rejected

Figure 25. Gun Tube Population Disposition after a 20% Reduction in Primary Land Wear

If the APDS-type projectile (M392/724/728) will not perform adequately in current tests under some conditions of wear other than those defined by the current condemnation criteria, a new condemnation criteria must be established. This criteria could take many forms such as:

a. Secondary Land Wear

b. Primary Groove Wear

c. Secondary Groove Wear

d. Differential Groove Wear (i.e. primary vs. secondary groove wear)

e. Differential Land Wear

f. Differential Land to Groove Secondary Wear

g. Differential Land to Groove Primary Wear

In any of the above failure modes, a trade-off analysis would have to be conducted to determine which type of tube condemnation criteria is required to provide the best performance at least cost. For example, the simplest solution might turn out to be to pull over gage the tubes at 25.25 and 33 inch locations and condemn when the differential wear reaches a specified value. The trade-off analysi demonstrated above will permit the analysis of the impact of any such revision in condemnation criteria.

CONCLUSIONS

1. Secondary wear is present in fielded weapons in both lands and grooves.

2. Secondary wear is not influenced by location, time of tube manufacture, or manufacturing technique.

3. If secondary wear is found to be detrimental to the accuracy of the M392-type cartridge, a technique is available to assess the action necessary to lower the wear to an acceptable level through modification of condemnation criteria. This technique will also provide a good estimate of the cost effect of this decision.

4. The tubes in FRG do not exhibit as high a degree of secondary wear as CONUS tubes because they were manufactured at a time when ammunition additive was not available and exhibit high initial wear.

5. No valid relationship exists between rounds fired and wear observed due to the intermix of ammunition used. For example, the M392A1 cartridge has been fabricated with two distinctly different plastic liners (from a wear standpoint) and a titanium dioxide liner.

6. A significant quantity of tubes have been condemned for secondary wear related characteristics since 1967. This information has been determined through an exhaustive analysis of firing records (DA 2408-4 Weapon Record Data) for M68 guns. A detailed summary of tube condemnations will be available upon completion of firing record analysis. It has not been determined that these tubes were exhibiting loss of accuracy or unacceptable performance of a related nature.

RECOMMENDATIONS

1. The ballistic test on the four selected tubes should be completed to determine if secondary wear is the accuracy limiting factor. Should secondary wear be found a limiting factor, then more tests must be conducted to determine whether it is land wear, groove wear or just differential wear that is causative.

2. If the wear limit has to be lowered, an acceptable level of failure must be established because the variation in wear is such that some tubes will always exceed the criteria. If an extremely low failure level is specified, the cost could be excessive. One should also remember that a 10% variation in field measurements would not be unusual.

3. If a new wear limit must be established it should apply only to combat-ready equipment. Training weapons should not be condemned by this criteria as the M490 cartridge is, and will continue for many years to be, the main training round. This round performs adequately with the current condemnation criteria.

4. Completion of the computer analysis of M68 firing records will provide information necessary to assess the characteristics of the total fielded population of M68 Gun tubes and establish a critical summary of gun tube life histories during the past ten to fifteen years. For example, preliminary results indicate that approximately 40% of all tubes condemned did not reach the wear limit of 0.075 inch, being condemned under criteria other than that imposed by the specified wear limit. [5]

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[5] TM 9-1000-202-35, Evaluation of Cannon Tubes, DA, November, 1969.

APPENDIX A

PROCEDURE FOR CANDIDATE GUN TUBE SELECTION

The purpose of this procedure was to establish a method of selecting 105MM M68 gun tubes representative of the fielded population. The specific requirement was for selection of one gun tube from each quarter of tube wear life for use in accuracy firing tests.

Wear measurements from a total of 153 gun tubes were segregated into samples representing the four quarters of wear life as defined by the land wear measurement at the pull over location (25.25" from the rear face of tube) and a wear limit of 0.075". The mean values for land wear and for groove wear in each quarter were calculated and the sum of squares of the deviations from the calculated mean measurements for each member gun tube computed. Candidate gun tube ranking was established by the total of summed land and groove wear mean square deviations.

Figure A1 shows the results of this procedure for the sample of gun tubes in the fourth wear quarter. Groove wear measurements were not taken for Tubes Serial Number 8337 and 10483. As mentioned in the text, final candidate selection was restricted by gun tube availability and additional wear resulting from tube firing after measurements were taken.

Figures 15 and 16 depict the actual measurements for Tube Serial Number 7503, selected as the fourth wear quarter candidate, and one sample standard deviation limits computed under the assumption of a normal distribution of wear measurements within the sample region.

QUARTILE NO. 4 (SAMPLE SIZE=28)

TUBE S.N.	SUM OF S.E. FOR LANDS	SUM OF S.E. FOR GROOVES	TOTAL S.E.
10875	725	4334	5059
11568	436	5166	5662
7503	2569	3154	5723
3461	1608	5112	6720
2232	1805	5589	7394
3765	2007	5792	7799
1926	564	7557	8121
6279	1120	7061	8181
3473	1620	7984	9604
5424	999	8707	9706
3749	3539	6309	9848
3046	5315	4963	10278
6211	1508	9144	10652
3463	1272	9513	10785
5493	3729	10893	14622
4654	1489	15685	17174
6303	3381	14698	18079
5632	7759	10373	18132
1414	1348	18427	19775
4065	4404	18379	22783
9848	2208	20826	23034
1957	1030	25707	26737
9716	8534	22744	31278
5301	5501	32253	37754
5772	27095	70743	97838
9761	42497	60881	103378
8337	29610	******	******
10483	36829	******	******

STANDARD ERRORS HAVE BEEN CALCULATED FOR THE MEASUREMENTS FROM 25.25 TO 60.00 INCHES FROM RFT.

THE SUM OF THE STANDARD LAND ERRORS FOR TUBE NO. 11568 IS THE LEAST FOR THE 28 TUBES IN THIS GROUP.

THE SUM OF THE STANDARD GROOVE ERRORS FOR TUBE NO. 7503 IS THE LEAST FOR THE 26 TUBES IN THIS GROUP FOR WHICH GROOVE MEASUREMENTS WERE TAKEN .

Figure A1. Candidate Gun Tube Selection

APPENDIX B

RELATING PRIMARY AND SECONDARY WEAR MEASUREMENTS

A number of models for relating secondary wear characteristics to other characteristics of the fielded M68 Gun Tube have been investigated. The immediate requirement is for a means of predicting the amplitude of secondary land and groove wear from measurements taken at the pull over location.

Selected data points are shown in Figures 17, 18, and 19. The lines shown in these three figures indicate predicted mean response determined by fitting curvilinear regression equations defined by third order polynomials to the respective data sets.

The following model has been assumed:

$$y = B_0 + B_1x + B_2x^2 + B_3x^3 + e$$

$$E\ (e) = 0$$

$$E\ (e^2) = \text{True population variance}$$

$$E\ (e_ie_j) = 0 \quad i \neq j$$

$$X = \text{primary (origin of rifling) measurement}$$

APPENDIX C

GUN TUBE SAMPLE GROUPINGS

The distribution of M68 gun tubes in the field sample, grouped by location and serial number groups, follows:

S.N. \ Location	1	2	3	4	5	6	7	8	9	10	11	TOTAL
A	1	1		1			7	7	4	19	10	50
B	2	1	2	2				2		1	2	12
C	8	1	3	7	2	9				5	7	42
D		1	3	3	7		1					15
E	14			12		1						27
F		2		3								5
TOTAL	25	6	8	28	9	10	8	9	4	25	19	151

Location Groups

1: Ft. Hood
2: APG
3: Ft. Lewis
4: Ft. Knox, CDE
5: Ft. Riley
6: Ft. Carson
7: Friedberg, Germany (1/32)
8: Kirchgon, Germany (2/32)
9: Friedberg, Germany (3/32)
10: Mannheim, Germany (3/68)
11: Mannheim, Germany (5/68)

Serial Number Groups

A: 1-4299
B: 4300-5299
C: 5300-7299; 8800-10399
D: 7300-8799
E: 10400-11599
F: 11600-

Figures C1 through C6 depict expected values of secondary wear, calculated under the model described in Appendix B, for the following data groups:

CONUS Serial Numbers

FRG Serial Numbers

Combined CONUS/FRG Serial Numbers

CONUS Locations

FRG Locations

Combined CONUS and FRG Locations

These comparative analyses are limited by the sample size for given groups and the region defined by available wear measurements within each group. As an example, the four CONUS Serial Number Groups represented in Figure C1 allow 3, 26, 10 and 23 degrees of freedom, respectively, for error estimation and span primary wear ranges indicated by the ranges of points shown in the figure. When these considerations are included with the condition of high initial wear in low serial number tubes described in the text, the variously grouped analyses can be taken to indicate a uniform tendency.

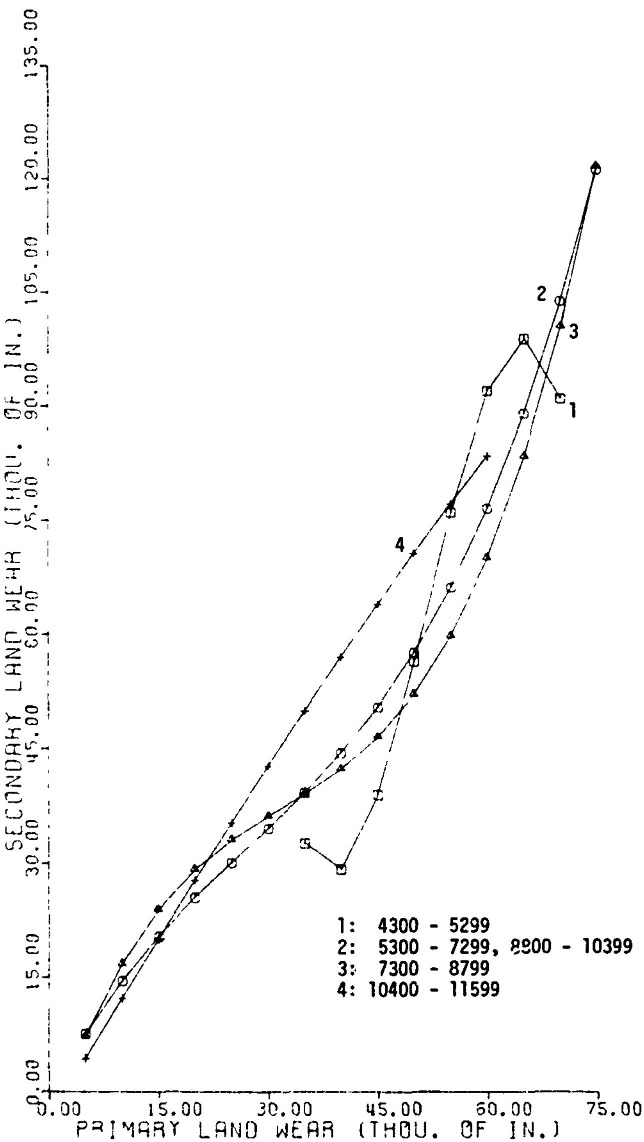

Figure C1. Primary vs. Secondary Land Wear - Regression Lines for CONUS Serial Number Groups

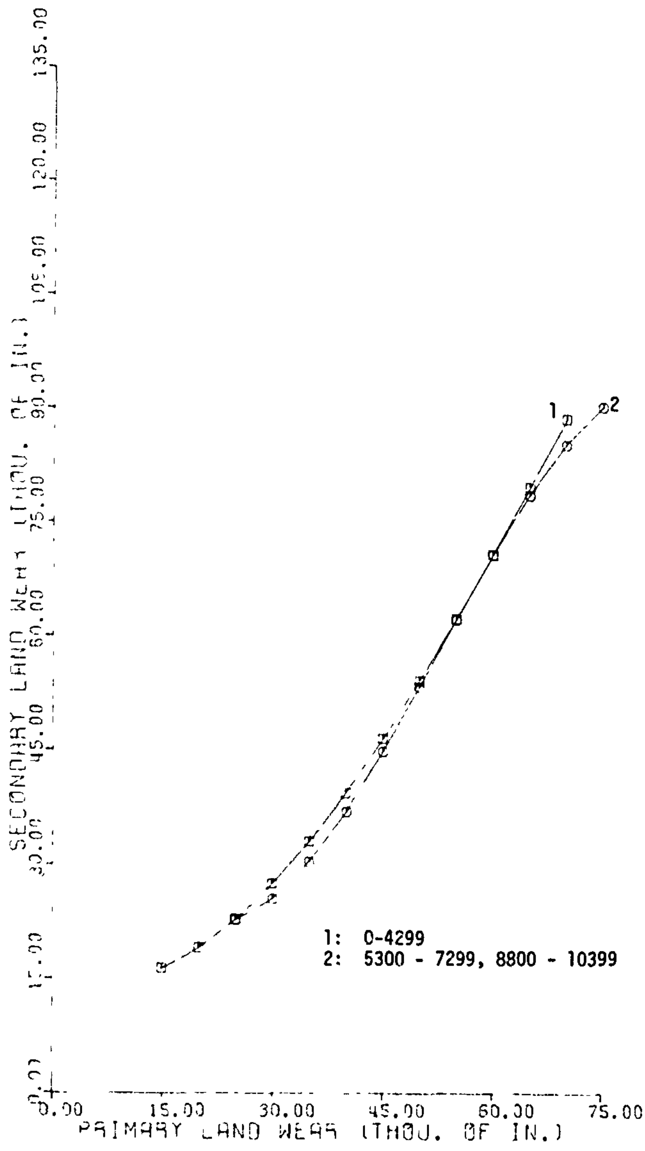

Figure C2. Primary vs. Secondary Land Wear - Regression Lines for FRG Serial Number Groups

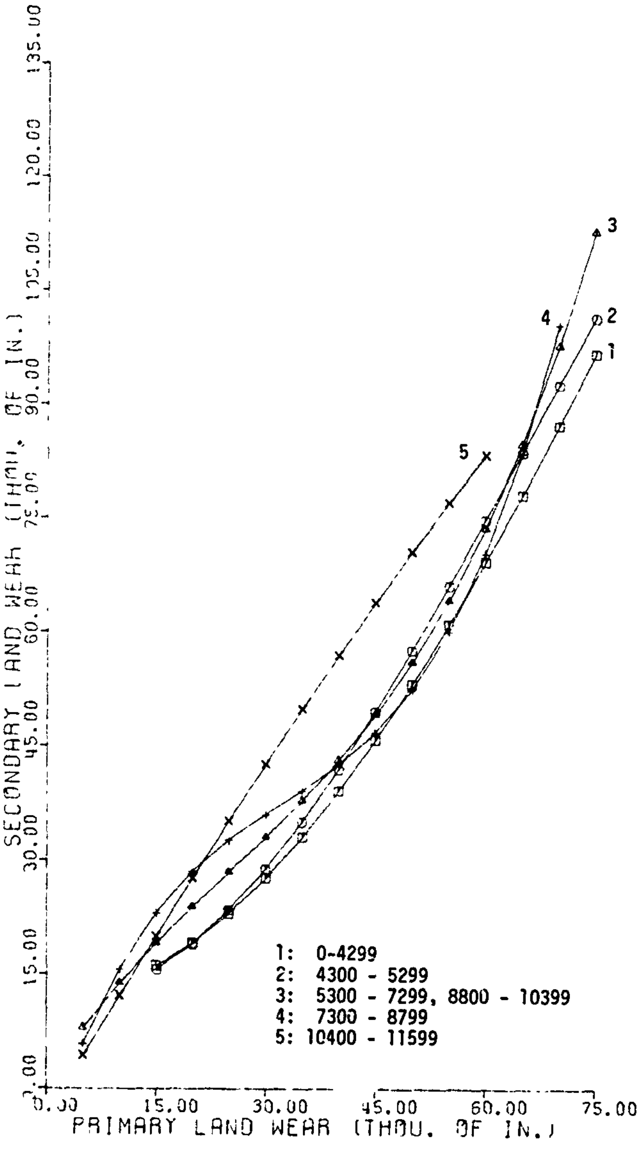

Figure C3. Primary vs. Secondary Land Wear - Regression Lines for CONUS and FRG Samples by Serial Number Group

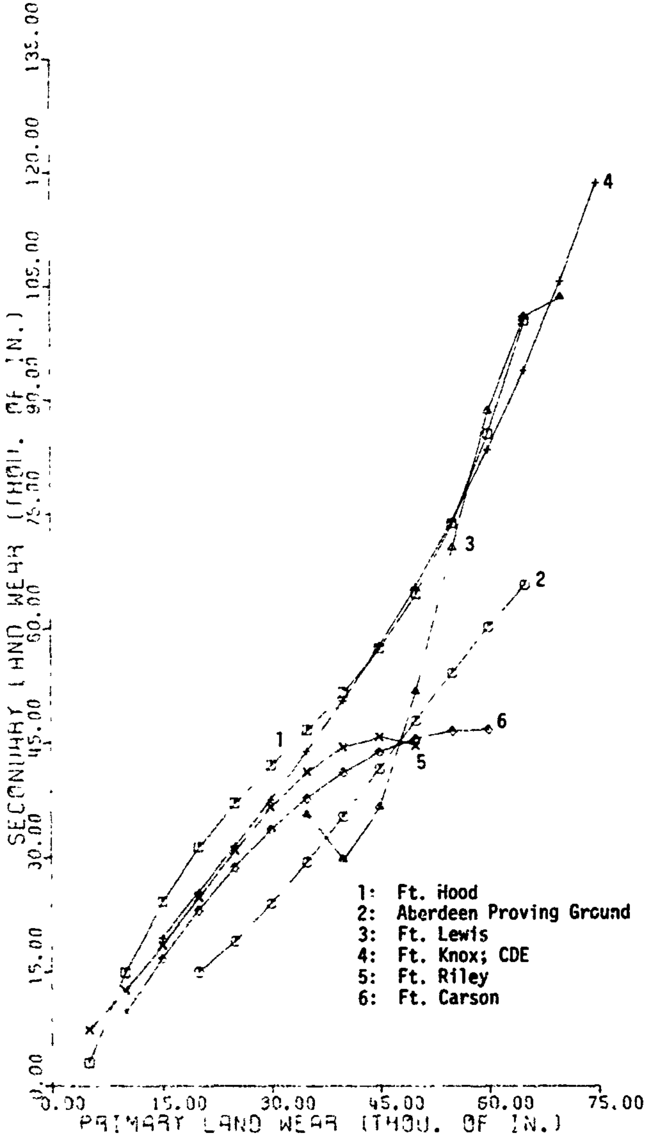

Figure C4. Primary vs. Secondary Land Wear - Regression Lines for CONUS Location Groups

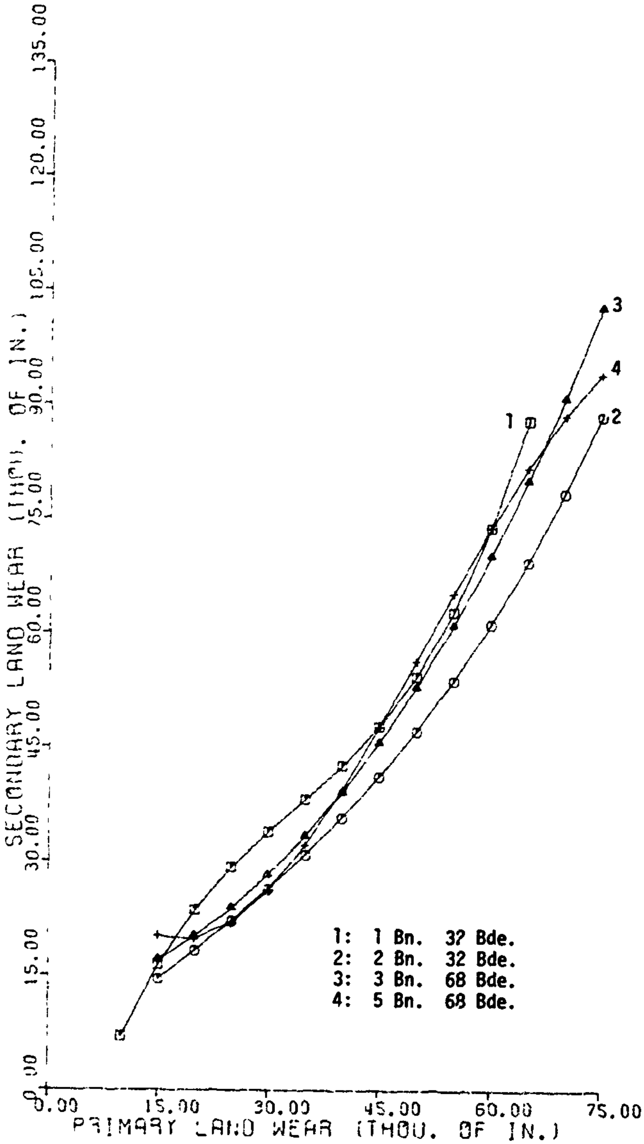

Figure C5. Primary vs. Secondary Land Wear - Regression Lines for FRG Location Groups

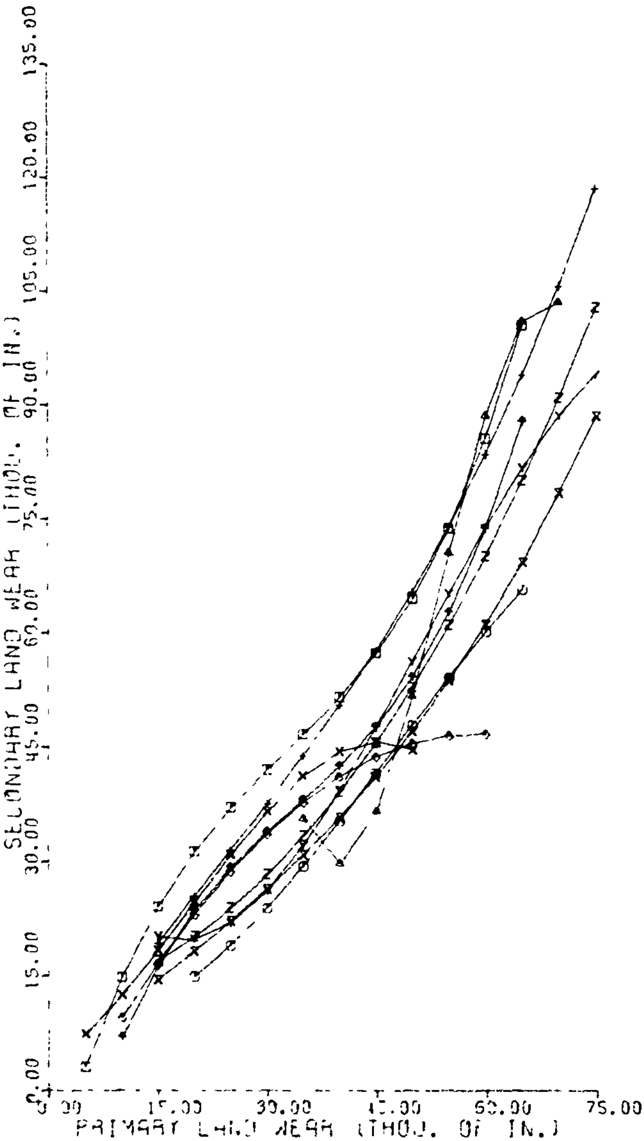

Figure C6. Primary vs. Secondary Land Wear - Regression Lines for CONUS and FRG Location Groups

APPENDIX D

IMPACT OF CHANGING TUBE WEAR CONDEMNING LIMITS

This procedure is designed to reflect the impact of revising the wear condemning limit for the M68 Gun Tube. The results indicate the characteristics of the fielded gun tube population after assignment of a revised criteria.

Wear measurements from the gun tube sample described in the text are indicated by "+" marks on Figures 17, 18 and 19. Assuming that the fielded gun tube population is represented by this sample, response to condemnation criteria revision can be calculated as ratio response. By assigning acceptable values of primary wear (X) and secondary wear (Y), four regions are established in Figures 17, 18 and 19. If X_o represents the existing wear limit with x and y representing actual measurements, then defining:

$y > Y,$	$X < x < X_o$	as Region I
$y > Y,$	$0 < x < X$	as Region II
$0 < y < Y,$	$0 < x < X$	as Region III
$0 < y < Y,$	$X < x < X_o$	as Region IV,

gun tubes in the four regions are as follows:

Region I: unacceptable under revised criteria (X,Y), acceptable at the existing wear limit (X_o), and unacceptable at the assigned level of secondary wear (Y).

Region II: acceptable at the revised primary wear limit X,
unacceptable at the secondary wear limit Y.

Region III: acceptable at (X,Y)

Region IV: unacceptable at X, acceptable at Y.

Using the number of data points in the representative sample (N), with N1, N2, N3 and N4 corresponding to the number of points in Regions I, II, III, and IV, respectively,

$\frac{N1}{N}$ represents the fraction of tubes <u>unacceptable</u> under the primary and secondary wear criteria,

$\frac{N2}{N}$ represents the fraction of tubes <u>acceptable</u> under the primary wear criteria and <u>unacceptable</u> under the secondary wear criteria,

$\frac{N3}{N}$ represents the fraction of tubes <u>acceptable</u> under the primary and secondary wear criteria,

$\frac{N4}{N}$ represents the fraction of tubes <u>unacceptable</u> under the primary wear criteria and <u>acceptable</u> under the secondary wear criteria.

If gun tubes are rejected based on a primary wear criteria with a functional, but unmeasured, secondary wear limit, then Regions II and III will include the gun tubes in use and N3/(N2+N3) will be the fraction of tubes in use with an acceptable level of secondary wear. Similarly, N4/(N1+N4) will be the fraction of gun tubes rejected under the same primary wear criteria with an acceptable level of secondary wear.

Figures D1, D2, and D3 show tabular results for the three types of criteria described in the text.

REVISED LIMIT	ALLOWED SECONDARY MAXIMUM	N1	N2	N3	N4	N	N1/N	N2/N	N3/N	N4/N	N3/(N2+N3)	N4/(N1+N4)
50.0	100.0	21	0	71	56	148	0.142	0.0	0.480	0.378	1.000	0.727
55.0	100.0	21	0	77	50	148	0.142	0.0	0.520	0.338	1.000	0.704
60.0	100.0	20	1	89	38	148	0.135	0.007	0.601	0.257	0.989	0.655
65.0	100.0	20	1	96	31	148	0.135	0.007	0.649	0.209	0.990	0.608
70.0	100.0	19	2	109	18	148	0.128	0.014	0.736	0.122	0.982	0.486
75.0	100.0	17	4	116	11	148	0.115	0.027	0.784	0.074	0.967	0.393
80.0	100.0	16	5	122	5	148	0.108	0.034	0.824	0.034	0.961	0.238
85.0	100.0	11	10	125	2	148	0.074	0.068	0.845	0.014	0.926	0.154
90.0	100.0	7	14	127	0	148	0.047	0.095	0.858	0.0	0.901	0.0
95.0	100.0	4	17	127	0	148	0.027	0.115	0.858	0.0	0.882	0.0

NOTE-REVISED LIMIT REFERS TO PERCENT OF CURRENT CONDEMNING LIMIT (0.075 IN.)
-ALLOWED SECONDARY MAXIMUM CORRESPONDS TO 0.075 IN.

Figure D1. Trade-off Analysis - Secondary vs. Primary Land Wear

REVISED LIMIT	ALLOWED SECONDARY MAXIMUM	N1	N2	N3	N4	N	N1/N	N2/N	N3/N	N4/N	N3/(N2+N3)	N4/(N1+N4)
50.0	73.5	13	22	99	1	135	0.096	0.163	0.733	0.007	0.818	0.071
55.0	73.5	10	25	100	0	135	0.074	0.185	0.741	0.0	0.800	0.0
60.0	73.5	5	30	100	0	135	0.037	0.222	0.741	0.0	0.769	0.0
65.0	73.5	2	33	100	0	135	0.015	0.244	0.741	0.0	0.752	0.0
70.0	73.5	1	34	100	0	135	0.007	0.252	0.741	0.0	0.746	0.0
75.0	73.5	1	34	100	0	135	0.007	0.252	0.741	0.0	0.746	0.0
80.0	73.5	1	34	100	0	135	0.007	0.252	0.741	0.0	0.746	0.0
85.0	73.5	1	34	100	0	135	0.007	0.252	0.741	0.0	0.746	0.0
90.0	73.5	1	34	100	0	135	0.007	0.252	0.741	0.0	0.746	0.0
95.0	73.5	1	34	100	0	135	0.007	0.252	0.741	0.0	0.746	0.0

NOTE-REVISED LIMIT REFERS TO PERCENT OF CURRENT MAXIMUM GROOVE WEAR
-ALLOWED SECONDARY MAXIMUM (73.5 PERCENT) CORRESPONDS TO 0.100 IN. GROOVE WEAR

Figure D2. Trade-off Analysis - Secondary vs. Primary Groove Wear

REVISED LIMIT	ALLOWED SECONDARY MAXIMUM	N1	N2	N3	N4	N	N1/N	N2/N	N3/N	N4/N	N3/(N2+N3)	N4/(N1+N4)
50.0	100.0	32	3	65	35	135	0.237	0.022	0.481	0.259	0.956	0.522
55.0	100.0	32	3	70	30	135	0.237	0.022	0.519	0.222	0.959	0.484
60.0	100.0	30	5	77	23	135	0.222	0.037	0.570	0.170	0.939	0.434
65.0	100.0	29	6	83	17	135	0.215	0.044	0.615	0.126	0.933	0.370
70.0	100.0	24	11	90	10	135	0.178	0.081	0.667	0.074	0.891	0.294
75.0	100.0	19	16	93	7	135	0.141	0.119	0.689	0.052	0.853	0.269
80.0	100.0	16	19	96	4	135	0.119	0.141	0.711	0.030	0.835	0.200
85.0	100.0	10	25	98	2	135	0.074	0.185	0.726	0.015	0.797	0.167
90.0	100.0	6	29	100	0	135	0.044	0.215	0.741	0.0	0.775	0.0
95.0	100.0	3	32	100	0	135	0.022	0.237	0.741	0.0	0.758	0.0

NOTE–REVISED LIMIT REFERS TO PERCENT OF CURRENT CONDEMNING LIMIT (0.075 IN.)
–ALLOWED SECONDARY MAXIMUM CORRESPONDS TO 0.100 IN. GROOVE WEAR

Figure D3. Trade-off Analysis - Secondary Groove Wear vs. Primary Land Wear