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INVESTIGATION OF GREASE-LUBRICATED EXPENDABLE SPLINE CONNECTION--ETC(U)

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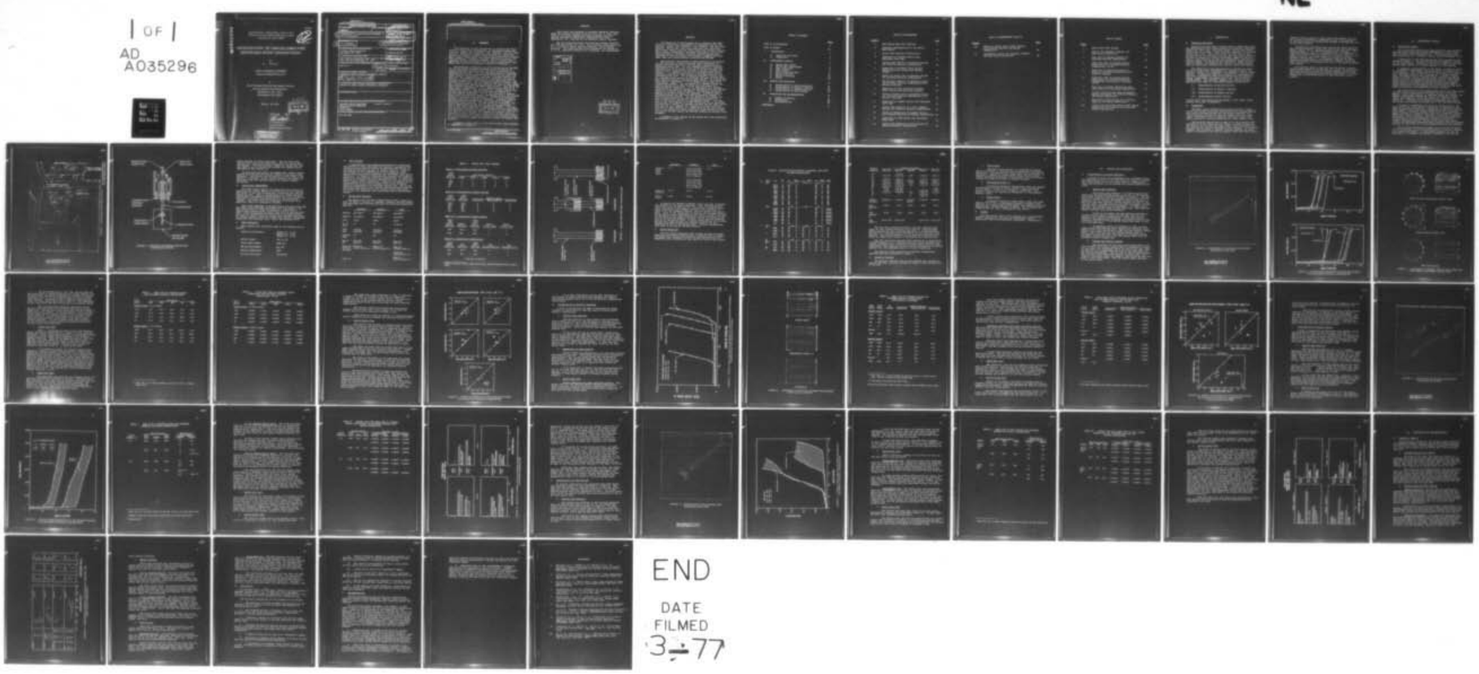

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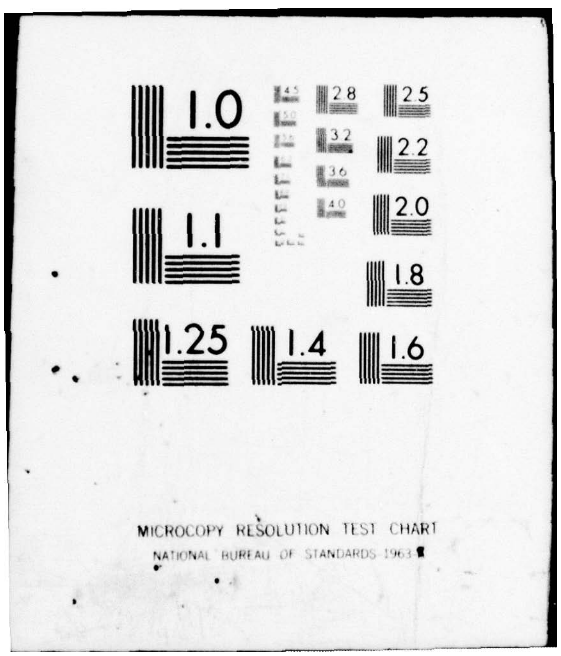
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Post Office Drawer 28510, 8500 Culebra Road
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INVESTIGATION OF GREASE-LUBRICATED EXPENDABLE SPLINE CONNECTIONS

by
M. L. Valtierra

FINAL TECHNICAL REPORT
Contract N68335-75-C-1117

to

Naval Weapons Engineering Support Activity
Systems Engineering Department
Washington Navy Yard
Washington, D.C. 20374

October 20, 1976

Approved:

R. D. Quillian, Jr.
Vice President
Mobile Energy Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See next page.

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20. **ABSTRACT**

The objective of this program was to evaluate the feasibility of three basic arrangements of expendable spline connections, namely, the "standard," the "dogbone," and the "muff" splines. Spline wear tests were performed with three SwRI spline wear testers operated under controlled angular misalignment, torque, temperature, and speed conditions, using a MIL-G-81322B grease. Standard, dogbone, and muff spline test specimens of various material and hardness combinations were used, some with varied metallic coatings and designs. → p.48

The principal conclusions of this program are as follows: (1) The selection of mating standard spline materials for grease-lubricated splines is not the major consideration in extending spline life. (2) For standard splines, a hardness combination of R_C of 62-65 and R_C of 48-50 for the outer and inner splines, respectively, provides a reliable mating connection. (3) A metallic coating on a standard outer spline (operating against an inner spline of the same material) can increase spline life. (4) An effective metallic coating used on a standard outer spline can minimize the wear of that spline when operated against a noncoated inner spline. This makes the inner spline "expendable." (5) A dogbone can be used as an "expendable" member. (6) The design of a dogbone spline connection appears to be more critical than the design of a standard spline connection. (7) In the design of a dogbone, steps should be taken to contain the dogbone within the desired location to prevent axial movement. (8) Material selection appears to be more critical for dogbones. A dogbone made of through-hardened AISI M50 steel was unreliable, because it fractured during testing. (9) The length of the dogbone can have a large effect on the life of the spline connection. (10) A muff can be used as an "expendable" member. (11) The wear on the outer spline in a muff connection can be minimized by providing a "small" fit between the muff and the outer spline (12) The use of a "medium" fit (typical of current aircraft practice) on muff splines will create wear on the outer spline. (13) In the design of a muff connection, steps should be taken to contain the muff within the desired location to prevent axial movement.

A summary of the results of the spline wear tests performed is presented in Figure 17.

FOREWORD

This report was prepared at Southwest Research Institute under Navy Contract N68335-75-C-1117 with Mr. F. Hall (ESA-7136) of the Naval Weapons Engineering Support Activity, Systems Engineering Department, Washington Navy Yard, Washington, D.C., serving as the Technical Project Engineer.

The work reported herein was performed between February 24, 1975 and October 20, 1976. The principal investigator was M. L. Valtierra, Senior Research Engineer, Mobile Energy Division. The consultations given throughout the program by P. M. Ku, Institute Scientist for Tribology, are acknowledged.

ABSTRACT

The objective of this program was to evaluate the feasibility of three basic arrangements of expendable spline connections, namely, the "standard," the "dogbone," and the "muff" splines. Spline wear tests were performed with three SwRI spline wear testers operated under controlled angular misalignment, torque, temperature, and speed conditions, using a MIL-G-81322B grease. Standard, dogbone, and muff spline test specimens of various material and hardness combinations were used, some with varied metallic coatings and designs.

The principal conclusions of this program are as follows: (1) The selection of mating standard spline materials for grease-lubricated splines is not the major consideration in extending spline life. (2) For standard splines, a hardness combination of R_C of 62-65 and R_C of 48-50 for the outer and inner splines, respectively, provides a reliable mating connection. (3) A metallic coating on a standard outer spline (operating against an inner spline of the same material) can increase spline life. (4) An effective metallic coating used on a standard outer spline can minimize the wear of that spline when operated against a noncoated inner spline. This makes the inner spline "expendable." (5) A dogbone can be used as an "expendable" member. (6) The design of a dogbone spline connection appears to be more critical than the design of a standard spline connection. (7) In the design of a dogbone, steps should be taken to contain the dogbone within the desired location to prevent axial movement. (8) Material selection appears to be more critical for dogbones. A dogbone made of through-hardened AISI M50 steel was unreliable, because it fractured during testing. (9) The length of the dogbone can have a large effect on the life of the spline connection. (10) A muff can be used as an "expendable" member. (11) The wear on the outer spline in a muff connection can be minimized by providing a "small" fit between the muff and the outer spline. (12) The use of a "medium" fit (typical of current aircraft practice) on muff splines will create wear on the outer spline. (13) In the design of a muff connection, steps should be taken to contain the muff within the desired location to prevent axial movement.

A summary of the results of the spline wear tests performed is presented in Figure 17.

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I. INTRODUCTION

A. Objective and Scope

Grease-lubricated steel interface spline connections enjoy the advantages of high torque-transmitting capacity, mechanical simplicity, small size, and light weight; and are thus extensively used on aircraft. Their principal drawback is the rather limited wear life. One way to extend the wear life of such connections is to arrange to have the wear take place mostly on the more accessible or readily replaceable member of the connection, but negligibly on the less accessible or difficult-to-replace member. By replacing the "expendable" member periodically as needed, the overall wear life of the connection may thus be effectively increased with minimal effort and expense.

The objective of this program was to evaluate the feasibility of three basic arrangements of expendable spline connections, namely, the "standard," the "dogbone," and the "muff" splines. A program was devised to compare the performance of the three arrangements under controlled angular misalignment, torque, temperature, and speed conditions, using a MIL-G-81322B grease. The standard, dogbone, and muff spline test specimens were used in a four-phase program listed below:

I. Investigation of spline materials

II. Investigation of metallic coatings

III. Investigation of dogbone splines

IV. Investigation of muff splines

A total of 97 wear tests were performed in this study, representing 6500 hours of operation.

B. Background

The major spline problem area on Navy aircraft is associated with grease-lubricated interface splines located between the engine accessory gearbox and the mating accessory.[1-3] These interface splines are used to transmit power and drive various accessories such as starters, hydraulic pumps, fuel pumps, generators, constant-speed drives, power takeoff, etc.

The interface connection is made of an outer spline (also referred to as the female spline) which is usually located on the gearbox, mating with the inner spline (also referred to as the male spline) usually attached to the accessory. In practice, whenever the accessory is removed from the gearbox, the inner spline is accessible and easy to replace, while the outer spline (which is usually part of a gear within the gearbox) can only be replaced by completely disassembling the entire gearbox. It is obvious that all efforts must be made to further the life of the outer splines.

Designers of accessories must provide the inner spline as part of the accessory. This inner spline can take three basic forms, namely: (1) a removable standard inner spline, (2) a removable dogbone, and (3) a removable muff. All types of inner splines must have the capability of mating with the outer gearbox splines. By proper choice of materials, surface coatings, and designs, it is possible to make one of these grease-lubricated members as "expendable" member, and at the same time minimize or eliminate the wear on the hard-to-replace outer member.

The approach taken in this work was to devise a comprehensive test program to investigate the effects of spline materials and metallic coatings on standard splines and to study the effects of dogbone and muff spline connections, all lubricated with a MIL-G-81322B grease to meet the goals of this program.

II. EXPERIMENTAL DETAILS

A. Spline Wear Tester

All of the experimental work reported herein was conducted with two SwRI spline wear testers designated S-1 and S-2 and one Navy-owned tester designated N-1. The testers have been used extensively on a variety of spline research programs.[4-10]

A photograph of the SwRI spline wear test facility is presented in Figure 1. The facility has three independent testers of identical design. Testers S-1 and S-2 are shown in the foreground, while tester N-1 is shown adjacent to the operator.

A schematic representation of the tester is given in Figure 2. As noted in this figure, the outer spline is clamped in a fixed position. The flanged end of the inner spline is attached to a diaphragm, gyrator, and a torque rod. During a typical test, the flanged end of the inner spline is caused to gyrate without rotating, thereby simulating the relative oscillatory motion of a pair of angularly misaligned splines. This oscillatory motion is produced by placing the nonrotating gyrator shaft eccentrically within the hollow rotating drive shaft. A timing belt drive is used between the drive shaft and the drive motor to eliminate the possibility of belt slippage.

The eccentricity of the flanged upper end of the inner spline relative to the centerline of the outer spline is fixed by design. Using inner splines of standard length (see later), the angular misalignment between the two spline members is fixed (0.32° for tester S-1, 0.33° for tester S-2, and 0.34° for tester N-1). Earlier work revealed no measurable bias due to the slight misalignment variations built into the three testers.

In order to accommodate the built-in eccentricity at the upper end of the inner spline, a diaphragm is employed to provide the necessary flexibility between the gyrator shaft and the drive shaft. A flexible torque-transmitting rod is extended upward through the hollow gyrator shaft to a convenient location where the torque is applied. Since the torque rod is mounted vertically, a lever system is provided to allow the application of torsional load with deadweight in either a forward or reverse loading direction. As the spline teeth wear during a test, the deadweight gradually moves downward, and the changing position of the load arm is continuously monitored and recorded.

The vertical mounting arrangement of the spline specimens is for the purpose of facilitating operation in either a gaseous or a liquid environment. In the current program, dry air is directed to a rotameter and through a preheater coil into the

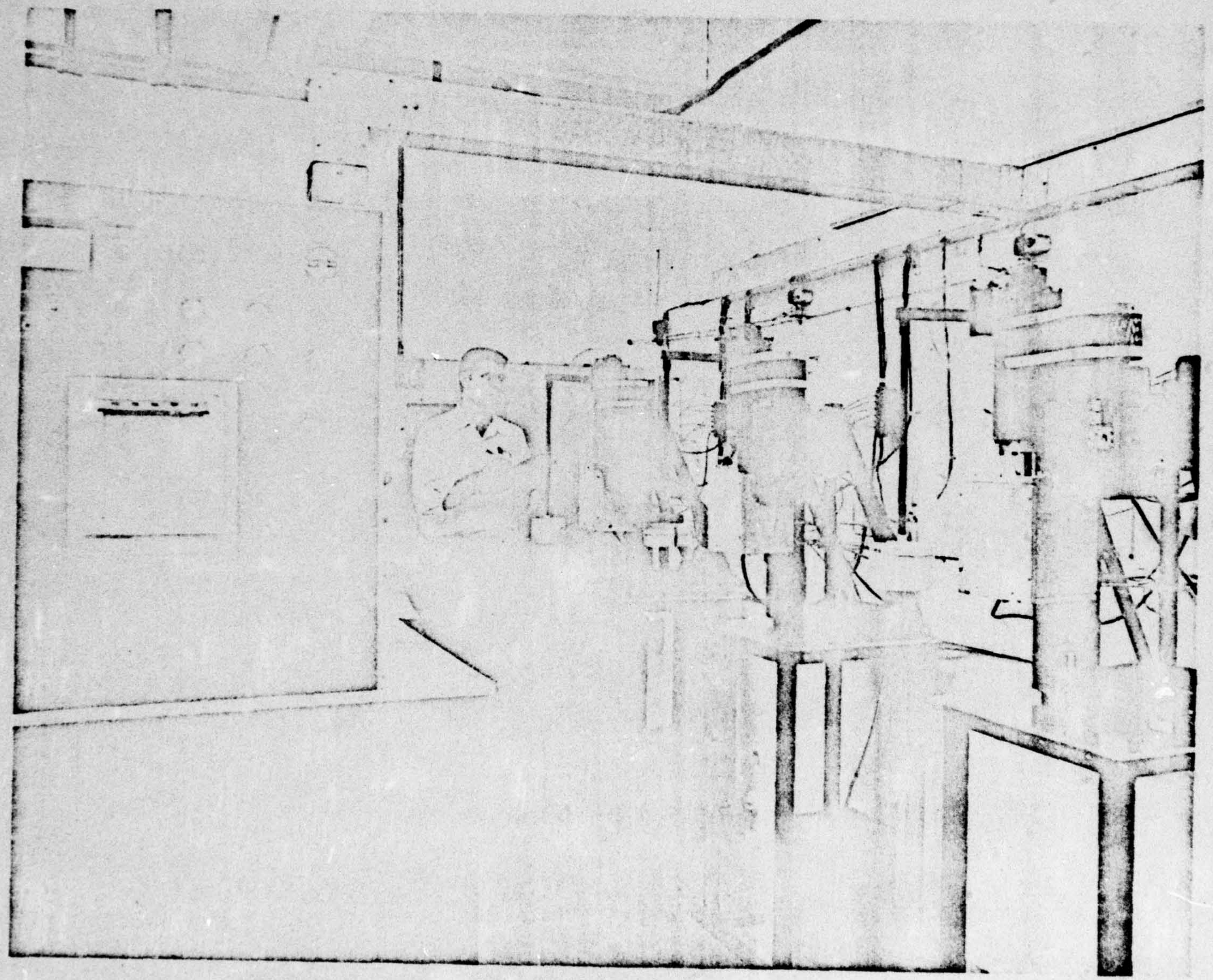

FIGURE 1. SwRI SPLINE WEAR TEST FACILITY

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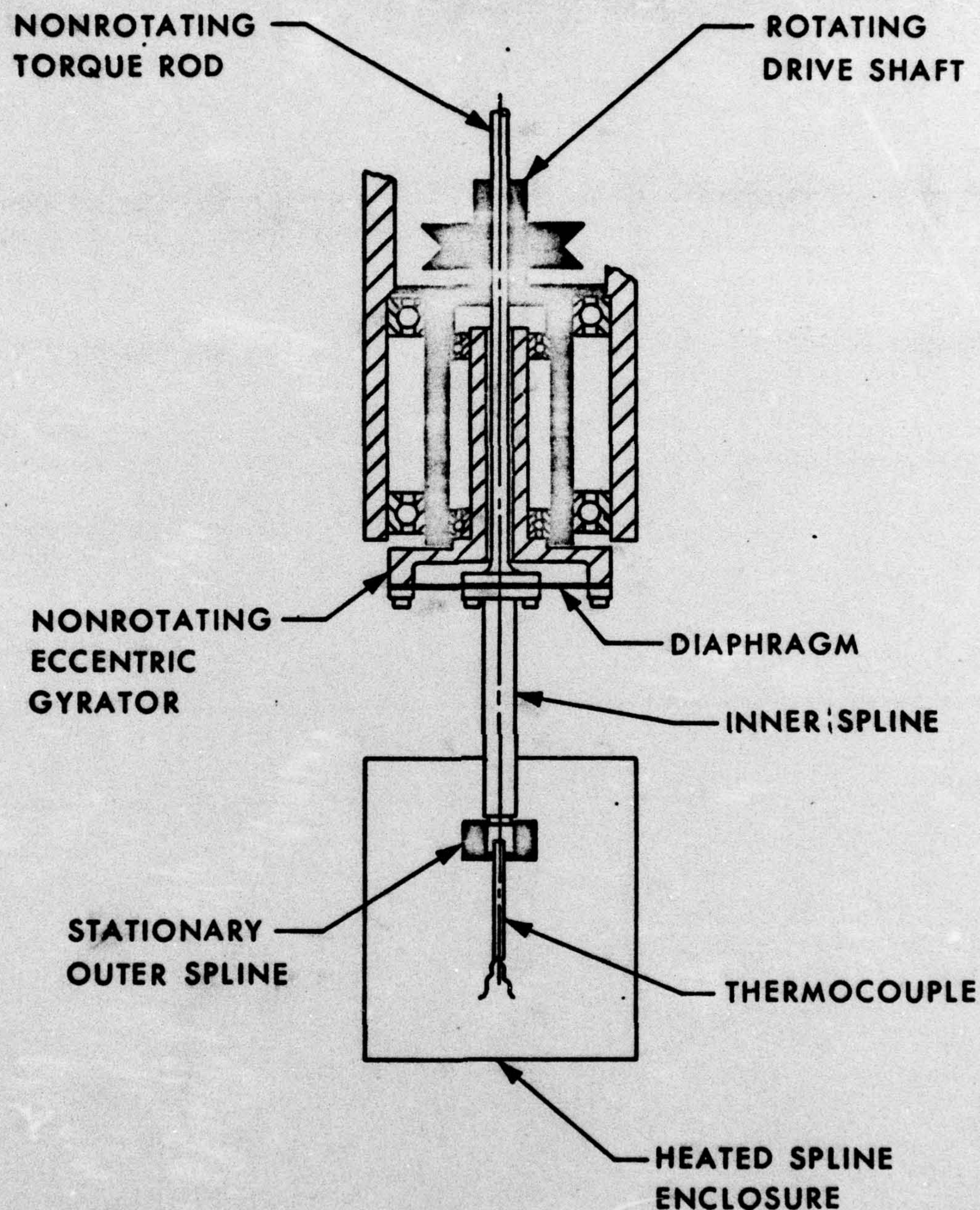


FIGURE 2. SCHEMATIC REPRESENTATION OF THE SPLINE WEAR TESTER

region beneath the spline specimens. The air then flows through slots around the outer spline into the region above the splines. The slots provide a bypass to ensure that any wear debris are not forced from between the engaged spline specimens by the flowing air.

As mentioned previously, the symmetrical loading system permits both forward and reverse loading of the spline test specimens. This allows the utilization of both sides of the splines, if desired. In the current program, the tests were performed under the forward loading and reverse loading directions.

B. Spline Wear Measurement

The total spline wear of the inner and outer splines is sensed by the gradual change in the position of the load arm. The change in the load arm position is continuously recorded during the test. This is accomplished by a linear variable differential transformer located between the load arm and the stationary lathe bed interconnected by a ball-and-socket linkage. The signal from the transducer is directed to an amplifier, then to a multipoint recorder.

Each spline specimen is weighed before and after each test. The weight loss data were correlated with the change in the load arm position in order to establish a quantitative relationship between actual spline wear and the load arm position. This relationship has been found to be substantially the same for several types of spline test specimens subjected to various torques, with both unlubricated splines and splines lubricated with different oils, fuels, and greases.[4-10]

C. Test Conditions

The standard test conditions used in this program are as follows:

Angular misalignment:	Tester S-1	0.32°
	Tester S-2	0.33°
	Tester N-1	0.34°
Spline torque:	350 in.-lb	
Drive shaft speed:	4400 rpm	
Spline environment:	Dry air	
Spline temperature:	250F	
Dry air flow rate:	115 ml/min	

D. Test Program

A comprehensive test program was devised to investigate the effects of spline materials and metallic coatings on the standard splines and the effects of materials and designs on the dogbone and muff splines, as noted in Table 1. Phase I was devoted to the investigation of five different inner spline materials operating against four different outer spline materials. In Phase II, three metallic coatings were investigated with five different material combinations. In Phase III, dogbones of different material combinations with two different design lengths were investigated. Phase IV was devoted to the investigation of muff spline connections having different material combinations with different mating fits. The spline tests were performed in the forward loading direction with the duplicate tests performed in the reverse loading direction. All spline test specimens were lubricated with a MIL-G-81322B grease.

E. Spline Test Specimen

The spline test specimen configurations used in this program are shown in Figure 3. Standard, dogbone, and muff spline test specimens were designed and have the following dimensional details:

	Standard	Dogbone	Muff
Material	See Table 1	See Table 1	See Table 1
Hardness	See Table 1	See Table 1	See Table 1
Pitch	20/40	20/40	20/40
No. of teeth	12	12	12 and 24
Tooth form	Involute, uncrowned	Involute, uncrowned	Involute, uncrowned
Pressure angle	30°	30°	30°
Type of fit	Flat-root, side fit	Flat-root, side fit	Flat-root, side fit
Spline fit (circular clearance)	Medium fit (0.0077-0.0101 in.)	Medium fit (0.0077-0.0101 in.)	Small fit (0.0034-0.0058 in.) Medium fit (0.0077-0.0101 in.) Large fit (0.0117-0.0141 in.)

(Cont'd)

TABLE 1. SPLINE WEAR TEST PROGRAM

Phase I — Investigation of Spline Materials

Outer Spline (62-65 R_C)	Inner Spline (48-50 R_C) 9310	6475	M50	X2	4130
9310	2	2	2	2	2
6475	2	2	2	2	2
M50	2	2	2	2	2
X2	2	2	2	2	2

Phase II — Investigation of Metallic Coatings

Outer Spline (62-65 R_C)	Inner Spline (48-50 R_C)	Metallic Coating: Electrolize	Elec. Nickel II	Nickel Boron
9310	9310	2	2	2
6475	6475	2	2	2
M50	M50	2	2	2
X2	X2	2	2	2
9310	4130	1*	1*	-

Phase III — Investigation of Dogbone Splines

Upper Outer Spline (62-65 R_C)	Dogbone (48-50 R_C)	Lower Outer Spline (62-65 R_C)	Dogbone (2.5-in. Long)	Dogbone (5.0-in. Long)
9310	4130	9310	4	4
9310	M50	9310	4	3*

Phase IV — Investigation of Muff Splines

Inner Spline (62-65 R_C)	Muff (48-50 R_C)	Outer Spline (62-65 R_C)	Muff (Medium/Medium Fit)	Muff (Large/Small Fit)
9310	4130	9310	4	4
9310	M50	9310	4	4

Total No. of Tests 97

* Unable to perform reverse tests since spline fractured during forward loading test.

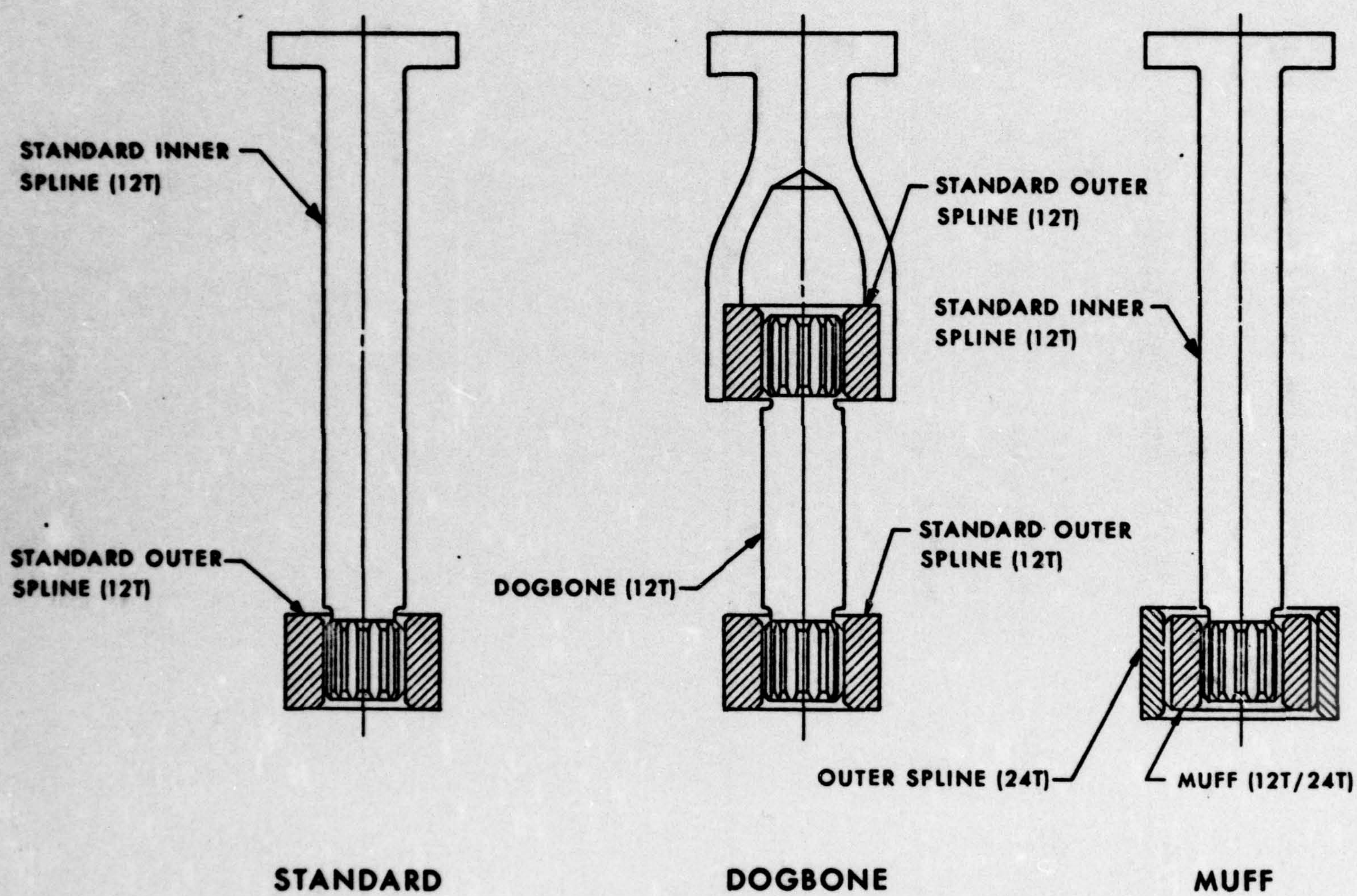


FIGURE 3. SPLINE TEST SPECIMEN CONFIGURATION

	Standard	Dogbone	Muff
Flange to spline pivot length	5 in.	2.5 in. to upper outer spline and 5.0 in. to lower outer spline (for 2.5 in. dogbone) 2.5 in. to upper outer spline and 7.5 in. to lower outer spline (for 5.0 in. dogbone)	5 in.
Length of engagement	1/2 in.	1/2 in.	1/2 in.
Surface finish	32 rms	32 rms	32 rms

A superficial Rockwell hardness tester was used to measure the hardness of the spline specimens. Four hardness measurements were taken on each spline. The average hardness values (with appropriate test numbers indicated) are presented in Table 2 for the standard, dogbone, and muff spline test specimens. Since it was impractical to measure the hardness directly on the spline teeth, measurements were taken at other locations. The hardness of the inner and dogbone splines was taken on the end of the specimen between the drill center and the chamfered portion of the spline teeth. Hardness measurements on the outer splines were taken between the outside diameter and the chamfered portion of the spline teeth. Hardness measurements were made on the end of the muff splines.

F. Spline Materials

The five spline materials used in this program are noted below with the nominal compositions, methods of heat treatment, and approximate attainable ranges of case hardness with corresponding core hardness and case depth for each of the steels:

TABLE 2. DETAILS FOR STANDARD, DOGBONE, AND MUFF SPLINE CONNECTIONS

Phase	Spline Connection	Test No.	Spline No.	Material	Measured Hardness, R_c	Material	Measured Hardness, R_c	Material	Measured Hardness, R_c	Metallic Coating
I	Standard			Inner		None		Outer		
		161F/170R	1NY	9310	51			9310	62	None
		169F/171R	2NY	6475	49			9310	61	None
		162F/172R	3NY	M50	50			9310	61	None
		164F/173R	4NY	X2	49			9310	60	None
		163F/174R	5NY	4130	53			9310	61	None
		43F/45R	6NY	6475	49			6475	64	None
		35F/46R	7NY	9310	50			6475	66	None
		36F/47R	8NY	M50	49			6475	65	None
		38F/48R	9NY	X2	49			6475	65	None
		37F/49R	10NY	4130	54			6475	65	None
		165F/175R	11NY	M50	49			M50	61	None
		166F/176R	12NY	9310	49			M50	62	None
		44F/50R	13NY	6475	50			M50	62	None
		39F/51R	14NY	X2	48			M50	62	None
		40F/52R	15NY	4130	53			M50	62	None
		41F/53R	16NY	X2	49			X2	61	None
		42F/54R	17NY	9310	49			X2	61	None
		55F/56R	18NY	6475	65			X2	60	None
		167F/177R	19NY	M50	48			X2	64	None
		168F/178R	20NY	4130	53			X2	62	None
II	Standard			Inner		None		Outer		
		179F/185R	21NY	9310	48			9310	61	Electrolize
		180F/186R	22NY	9310	50			9310	61	Elec.Nickel II
		181F/187R	23NY	9310	49			9310	62	Nickel Boron
		182F/188R	24NY	6475	49			6475	66	Electrolize
		183F/189R	25NY	6475	49			6475	67	Elec.Nickel II
		184F/190R	26NY	6475	49			6475	67	Nickel Boron
		57F/63R	27NY	M50	48			M50	61	Electrolize
		58F/64R	28NY	M50	48			M50	61	Elec.Nickel II
		59F/65R	29NY	M50	47			M50	60	Nickel Boron
		60F/66R	30NY	X2	49			X2	64	Electrolize
		61F/67R	31NY	X2	50			X2	64	Elec.Nickel II
		62F/191R	32NY	X2	49			X2	65	Nickel Boron
		80F/-	49NY	4130	50			9310	61	Elec.Nickel F
		72F/-	50NY	4130	61			9310	61	Electrolize
III	Dogbone			Upper Outer		Dogbone		Lower Outer		
	2.5 in.	194F/199R	39NY	9310	65	4130	51	9310	65	None
		196F/200R	40NY	9310	65	4130	51	9310	65	None
		192F/197R	37NY	9310	65	M50	49	9310	64	None
		193F/198R	38NY	9310	65	M50	52	9310	65	None
	5.0 in.	203F/206R	35NY	9310	65	4130	52	9310	65	None
		204F/207R	36NY	9310	65	4130	55	9310	65	None
		201F/ -	33NY	9310	65	M50	50	9310	65	None
		202F/205R	34NY	9310	65	M50	51	9310	65	None
IV	Muff			Inner		Muff		Outer		
	Medium	62F/76R	43NY	9310	66	4130	52	9310	62	None
	Medium Fit	63F/77R	44NY	9310	65	4130	53	9310	62	None
		71F/74R	41NY	9310	66	M50	51	9310	62	None
		72F/75R	42NY	9310	66	M50	56	9310	63	None
	Large	66F/70R	47NY	9310	64	4130	51	9310	62	None
	Small Fit	67F/71R	48NY	9310	64	4130	51	9310	62	None
		64F/68R	45NY	9310	66	M50	51	9310	62	None
		65F/69R	46NY	9310	65	M50	51	9310	62	None

Alloying Elements	Material Designation AISI 9310	AMS 6475	AISI M50	Vasco X2	AISI 4130
Al	-	1.1-1.4	-	-	-
C	0.08-0.13	0.21-0.26	0.80	0.20-0.25	0.28-0.33
Co	-	-	-	-	-
Cr	1.00-1.40	1.00-1.25	4.1	4.75-5.25	0.80-1.10
Fe	Balance	Balance	Balance	Balance	Balance
Mn	0.45-0.65	0.50-0.70	0.30	0.20-0.40	0.40-0.60
Mo	0.08-0.15	0.20-0.30	4.25	1.30-1.50	0.15-0.25
Ni	3.00-3.50	3.25-3.75	-	-	-
P	0.025	0.04 max	-	-	0.040
S	0.025	0.04 max	-	0.025 max	0.040
Si	0.20-0.35	0.20-0.40	0.25	0.80-1.00	0.20-0.35
V	-	-	1.1	0.40-0.50	-
W	-	-	-	1.20-1.50	-
Surface treatment	Carburize	Nitride	Through-harden	Carburize	Carburize
Case hardness, R_c	62-65	62-65	62-65	62-65	62-65
Core hardness, R_c	35-40	35-40	62-65	45-50	35-40
Case depth, in.	0.015-0.025	0.015-0.025	-	0.015-0.025	0.015-0.025

The AISI 9310 carburized steel is the most commonly used steel for the gearbox interface outer splines. Many aircraft engine accessories use a nitrided AMS 6475, a through-hardened AISI M50 or a carburized AISI 4130 steel for the interface inner splines. The Vasco X2 material is an advanced carburized steel which has shown great promise in helicopter gear applications.

The AISI 4130 steel has been used extensively in SwRI spline research programs as a "reference material" which possesses good overall properties and a good but not particularly superior wear resistance. This material and AISI M50 was selected as a suitable material for the expendable part of a spline connection.

The specific spline material and hardness combinations selected have been presented in Table 1.

G. Metallic Coatings

The metallic coatings used in this program were applied to some of the outer splines, as noted in Table 2, and are described as follows:

1. Electrolize

The Electrolize process is a proprietary process which was applied by Electrolizing Incorporated, Los Angeles, California. The manufacturer claims that "the Electrolize is basically a deposit of a high chrome alloy having a small crystal structure producing a hard surface of R_c 70-72 with a uniform thickness of 0.0005 in. without buildup."

2. Electroless Nickel II

A metallic coating of electroless nickel was applied in accordance with MIL-C-26074B, Class 2 (heat-treated R_c 65-70), Grade A (0.001 in. ± 0.0002 in. thickness). The metallic coating was applied by Schumacker Co. Incorporated, Houston, Texas.

3. Nickel Boron

A metallic coating of nickel boron, under the trade name of "Sylek 103" (a proprietary process of DuPont; also referred to as electroless nickel boron) was applied by Plating Specialities, Madison Heights, Michigan. The thickness was 0.0009-0.0011 in. with a hardness of 1200 Knoop.

H. Grease

The test grease used in this program was a MIL-G-81322B grease, furnished by the Naval Air Development Center, Aeronautical Materials Department, Warminster, Pennsylvania.

III. RESULTS AND DISCUSSIONS

A. Investigation of Spline Materials

A series of tests were performed using "standard" spline test specimens similar to the ones shown in Figure 4 to study the effectiveness of various spline material combinations. Tests were performed in the forward and reverse loading directions.

1. Typical Wear Behavior

The typical wear behavior of standard splines operating with the MIL-G-81322B grease in dry air in the forward and reverse loading directions is shown in Figure 5. The wear curves are presented with the abscissa denoting the hours of operation and the ordinate denoting the total spline wear of the inner and outer splines. Hollow symbols are used to indicate the first (forward loading) test with the repeat (reverse loading) test indicated by a solid symbol. In these tests, the outer splines were made of AISI 9310 steel, each operated against various inner spline materials.

In all of the tests, the test splines exhibited an initial minimal amount of wear of less than 0.001 in. for virtually all material combinations. After this initial period of negligible wear (referred to in earlier work as the "induction period"),[4,5] the spline connections began to wear at a very high rate.

An important factor to recognize is that, in most cases, the forward loading tests (which were performed first) operated for a shorter period of time than the reverse loading tests. The longer life of the reverse loading tests is attributed to the fact that more grease is available within the spline connection due to the worn spline teeth from the preceding forward loading test.

2. Forward and Reverse Loading

The appearance of the inner spline teeth before and after forward and reverse loading tests is presented in Figure 6. The lower left photograph shows the end of the "new" inner spline with the accompanying side view of the same spline on the adjacent photograph. The end view of the new spline shows the 12 spline teeth having the typical involute form. The adjacent photograph shows the length of the spline and the full width of the spline teeth. Note the smooth unworn surfaces on the spline teeth.

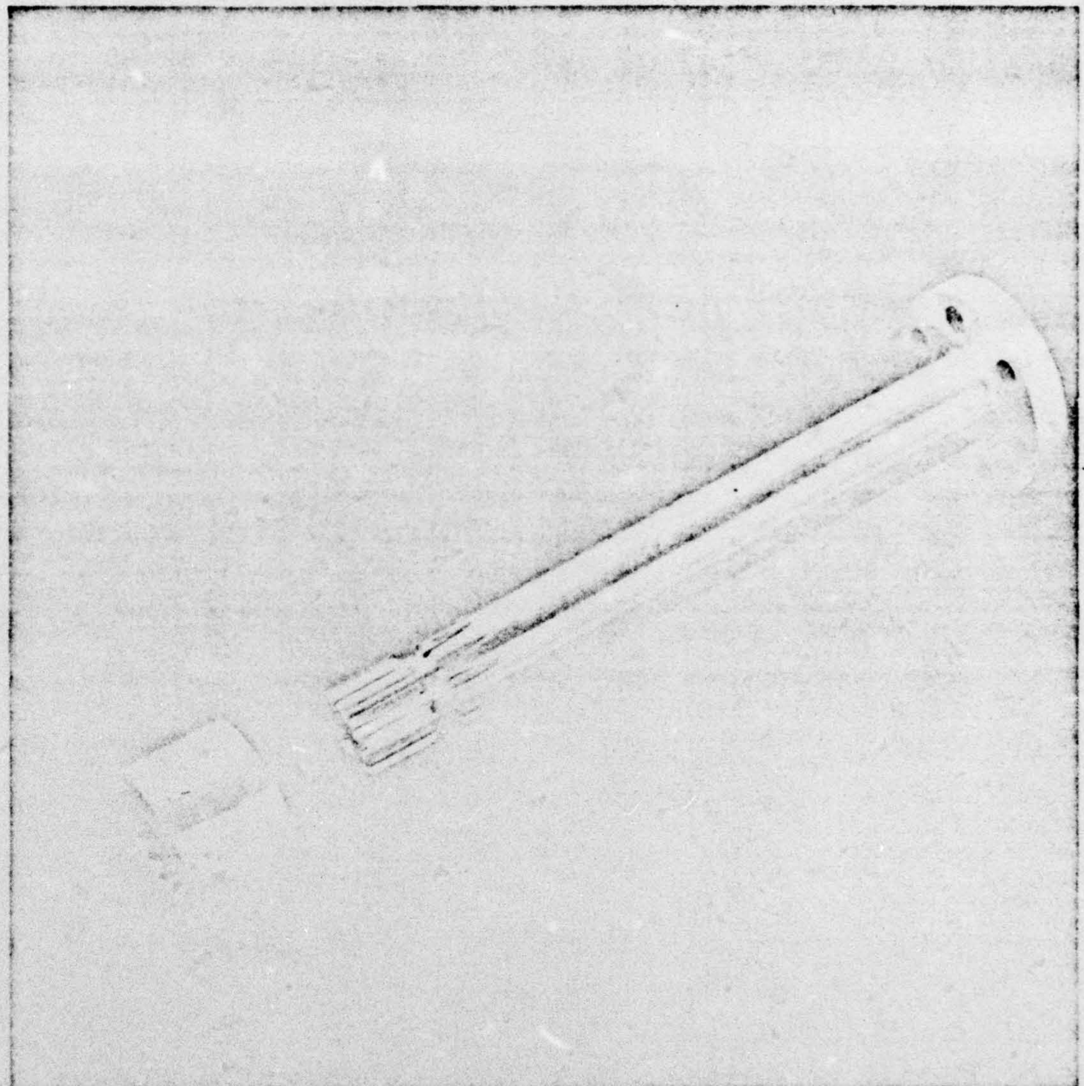


FIGURE 4. APPEARANCE OF STANDARD SPLINE TEST SPECIMENS AFTER TEST

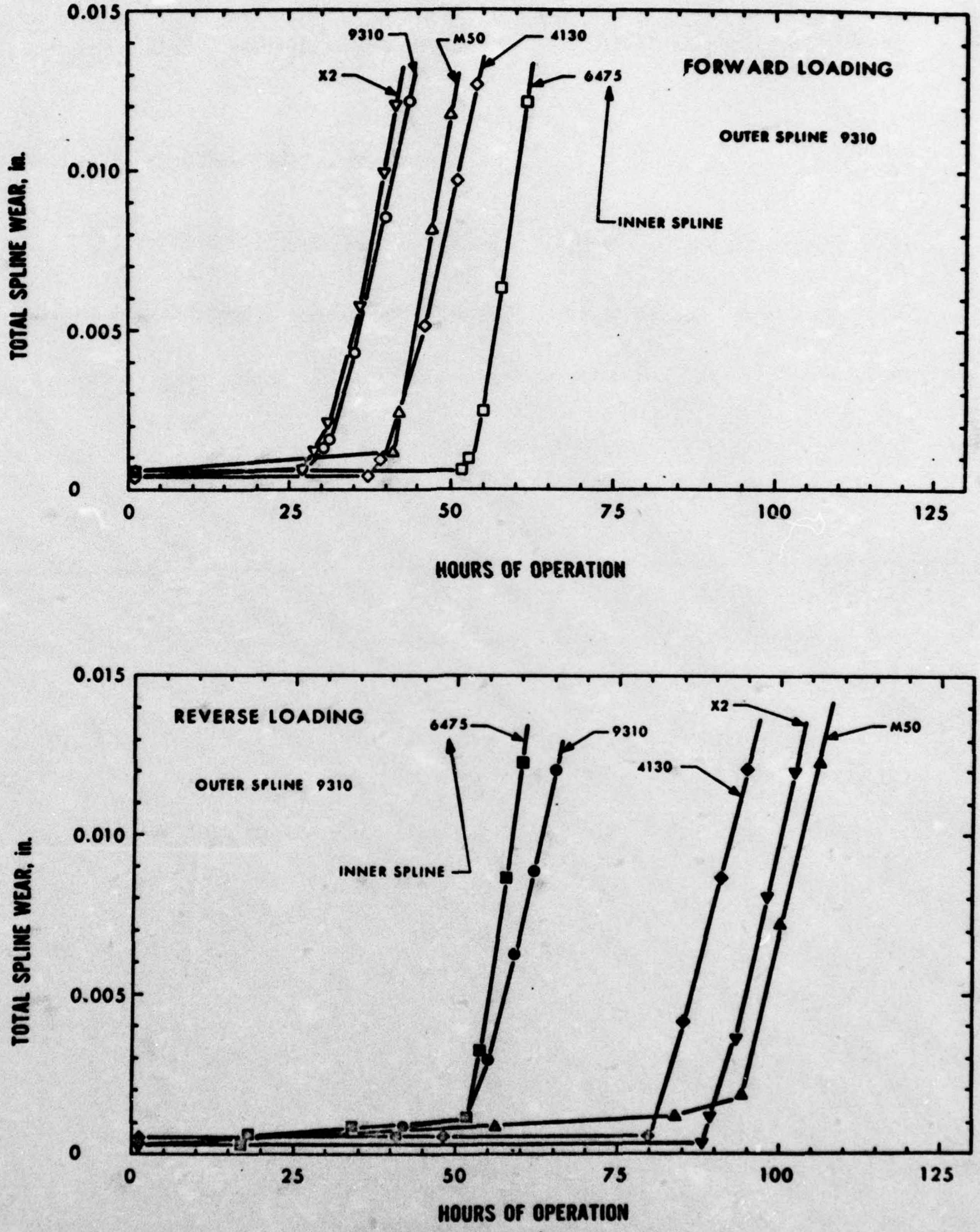
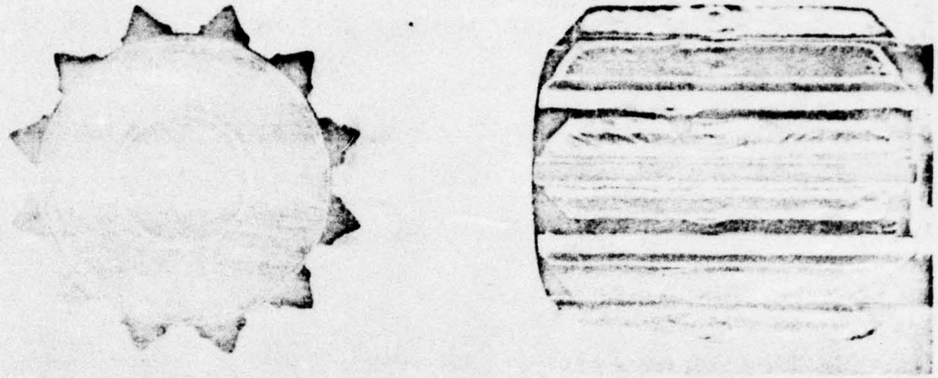
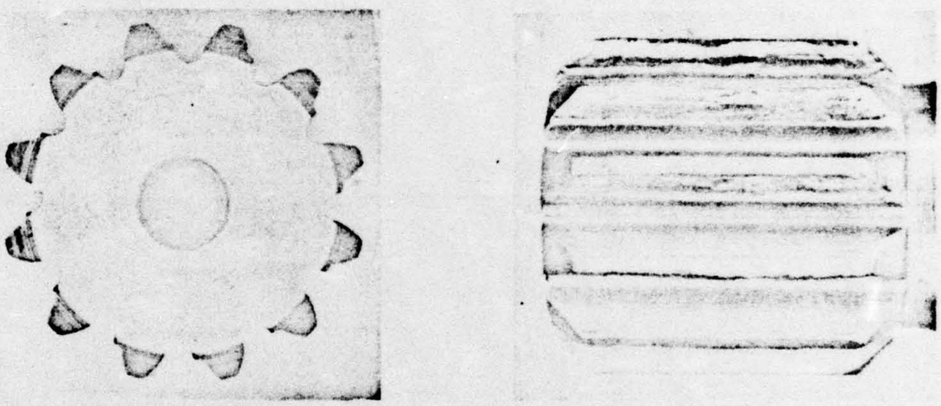


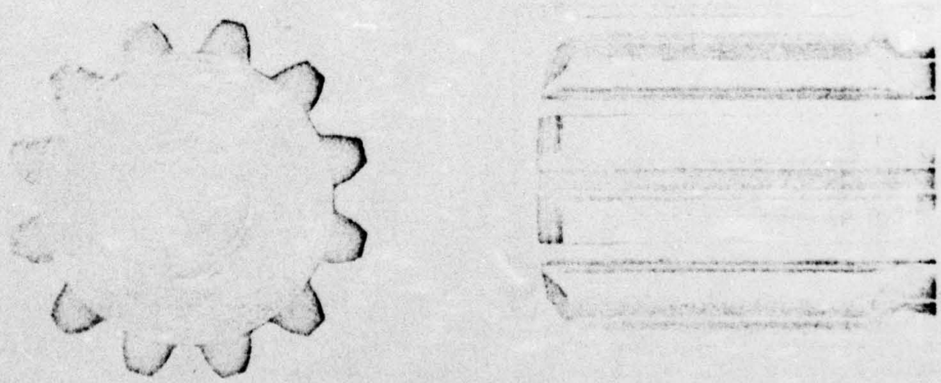
FIGURE 5. TYPICAL WEAR BEHAVIOR OF STANDARD SPLINES FOR DIFFERENT MATERIAL COMBINATIONS



After Forward and Reverse Loading Tests



After Forward Loading Test



New Inner Spline

FIGURE 6. APPEARANCE OF STANDARD INNER SPLINES BEFORE AND AFTER FORWARD AND REVERSE LOADING TESTS

The photographs above the "new" splines show the wear step which is generated during the forward loading test. In most cases, the spline connections are allowed to operate for about 0.012 in. of total spline wear for the inner and outer splines. Therefore, after a typical forward loading test, the inner spline wears about 0.006 in. The photograph on the right shows the wear on one side of the spline teeth.

The top photographs show the appearance of the splines after operation in the forward and reverse loading directions. The end view of the teeth show the wear steps on both sides of the teeth. In actual practice, only one side of the teeth are worn similar to the "after forward loading test" condition. In rare instances, as in the case of an aircraft engine starter, both sides of the spline teeth receive some wear. In this program, tests were performed in the forward and reverse loading directions to alleviate the cost of the test specimens.

3. Spline Wear Life

Table 3 illustrates the wear life of the standard spline connections investigated. A total of forty tests were performed. Twenty tests were performed in the forward loading direction with the repeat tests performed in the reverse loading direction. Inner spline materials made of AISI 9310, AMS 6475, AISI M50, Vasco X2, and AISI 4130 steels were operated against outer splines made of AISI 9310, AMS 6475, AISI M50, and Vasco X2 steels. The wear life in hours is defined as that for 0.012 in. of total spline wear.

In virtually all cases, the reverse loading tests exhibited a longer life than did the forward loading tests (except for the AISI 9310 outer/AMS 6475 inner, and the AISI M50 outer/AISI M50 inner tests). For all of the material combinations investigated, the forward loading tests exhibited a wear life range of 37.0 to 79.0 hr with an average of 51.6 hr. The most common aircraft engine gearbox-accessory spline connection uses an outer spline made of AISI 9310 with an inner spline of AISI 4130. This spline material combination tested exhibited 53.5 hr which is not significantly different from the average 51.6 hr. The average wear life for the reverse loading tests was 74.9 hr.

4. Rapid Wear Rate

The rapid wear rate data for the standard spline connections evaluated are presented in Table 4. The data have been tabulated in the same form as the wear life data with the forward loading and reverse loading tests indicated. The rapid wear rate can also be seen in the curves presented earlier in Figure 5. Note the similarity of the rapid wear rates in the forward and reverse loading tests.

TABLE 3. WEAR LIFE OF STANDARD SPLINES FOR DIFFERENT MATERIAL COMBINATIONS*

Outer Spline	Inner Spline				
	9310	6475	M50	X2	4130
Forward Loading (51.6 Average)					
9310	43.5	62.0	50.0	41.5	53.5
6475	49.5	45.5	48.0	37.0	55.5
M50	47.0	53.6	79.0	48.5	44.0
X2	63.8	61.5	43.5	52.6	52.2
Reverse Loading (74.9 Average)					
9310	65.5	60.5	106.0	102.0	94.5
6475	60.5	46.0	86.5	66.5	104.3
M50	55.0	60.2	73.5	78.2	72.0
X2	73.9	77.4	72.3	69.1	74.4

* Wear life, hr, is herein defined as that for 0.012 in. of total spline wear.

TABLE 4. RAPID WEAR RATE OF STANDARD SPLINE CONNECTIONS FOR DIFFERENT MATERIAL COMBINATIONS, in./hr

Outer Spline	Inner Spline				
	9310	6475	M50	X2	4130
Forward Loading (0.00093 Average)					
9310	0.00089	0.00140	0.00120	0.00104	0.00092
6475	0.00086	0.00126	0.00067	0.00071	0.00067
M50	0.00092	0.00114	0.00086	0.00069	0.00071
X2	0.00100	0.00100	0.00096	0.00075	0.00096
Reverse Loading (0.00096 Average)					
9310	0.00089	0.00141	0.00089	0.00100	0.00080
6475	0.00089	0.00126	0.00077	0.00096	0.00100
M50	0.00100	0.00104	0.00100	0.00100	0.00083
X2	0.00080	0.00073	0.00120	0.00089	0.00080

The rapid wear rates presented in Table 4 exhibited a range of 0.00069 to 0.00140 in./hr with an average of 0.00093 in./hr for the forward loading tests. The tests performed with the inner splines made of AISI 6475 steel exhibited somewhat higher wear rates than the other material combinations.

The reverse loading tests exhibited very similar results with the rapid wear rates ranging from 0.00073 to 0.00141 in./hr with an average of 0.00096 in./hr.

These high wear rates are typical of grease-lubricated spline connections operated beyond the induction period.(4-10)

5. Spline Weight Loss

Each spline test specimen is weighed before and after each test to study the effect of spline weight loss. Figure 7 illustrates the effect of weight loss on standard splines for the different material combinations evaluated. As noted in the legend, the outer spline materials were made of AISI 9310, AMS 6475, AISI M50, and Vasco X2 steels, with the appropriate symbols listed. Each of the five plots are presented with the abscissa denoting the inner spline weight loss in grams and the ordinate denoting the outer spline weight loss in grams. The abscissa and ordinant are plotted on the same scale. A 45° dash line has been provided to assist in analyzing the data.

The upper two plots show the weight loss data for the inner splines made of AISI 9310 and AISI 4130 steels. In most cases, both the inner and outer splines exhibited about the same amount of weight loss, as can be seen from the data surrounding the 45° dash line.

The plots in the middle of the page show the weight loss data for the inner splines made of AISI M50 and Vasco X2 materials. In both cases the predominant weight loss was with the outer splines, indicating that these spline material combinations would not be too desirable for gearbox-accessory connections.

The bottom plot in Figure 7 shows the weight loss data for the inner splines made of AMS 6475 steel operating against other spline materials. The results clearly show the protection to the outer splines by using AMS 6475 steel as the inner spline material. In all cases the inner splines exhibited more weight loss than the outer splines. When compared to the most commonly used outer spline material AISI 9310 steel (see the clear and solid circle symbols), the inner splines exhibited about four times the wear of the outer AISI 9310 splines.

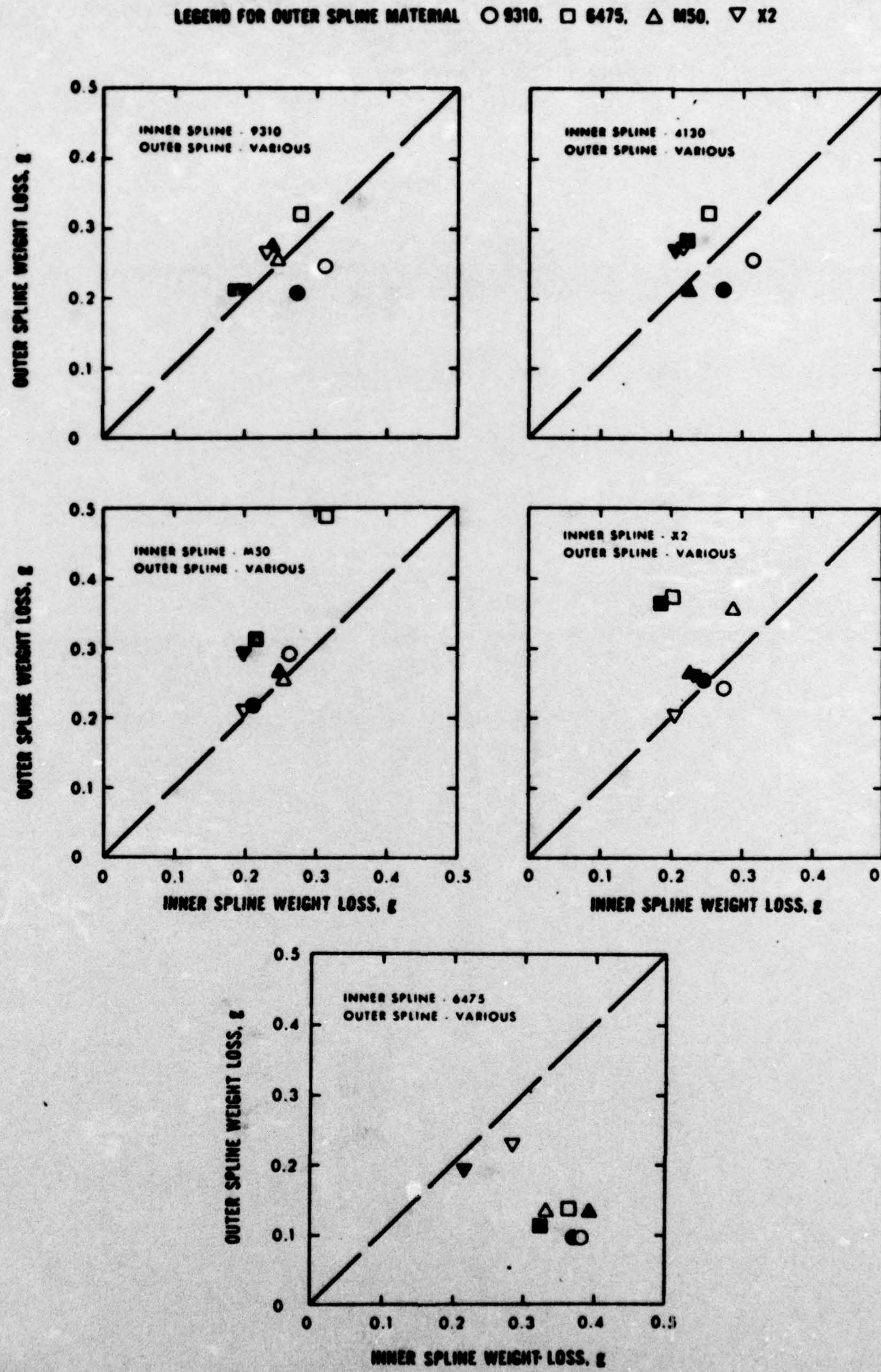


FIGURE 7. EFFECT OF WEIGHT LOSS ON STANDARD SPLINES FOR DIFFERENT MATERIAL COMBINATIONS

It is also interesting to note that virtually no differences in weight loss were noted between the forward and reverse loading tests for all of the material combinations investigated.

B. Investigation of Metallic Coatings

A brief investigation was made to determine the effectiveness of three metallic coatings used on various spline material combinations.

1. Typical Wear Behavior

The wear behavior of three spline tests performed with standard splines with various metallic coatings is portrayed in Figure 8. The curves represent tests performed with AISI 9310 inner and outer splines operated in the forward loading direction. Metallic coatings were applied to the outer splines only.

In all cases the use of nickel boron, electroless nickel II, or Electrolize improved the spline life by at least two- to three-fold for the AISI 9310 inner and AISI 9310 outer spline combinations. The Electrolize coating was most effective in extending the induction period from 25 hr for the "no-coating" test to 75 hr—a three-fold improvement. In each case the splines were allowed to operate for about 0.012 in. of total spline wear.

2. Appearance of Outer Splines

Figure 9 shows the appearance of the worn outer splines with metallic coatings. Three outer splines having Electrolize, electroless nickel II, and nickel boron were sectioned and photographed. Each photograph shows the wear steps which resulted on all of the twelve teeth. The wear steps on each spline tooth show up "dark" as a result of the forward and reverse loading tests.

It is clear that in each of the three photographs that all of the inner splines were in full contact with the outer splines. All of the test splines used in this program were designed in this manner—typical of current aircraft design practice.

3. Spline Wear Life

Similar Materials for Inner and Outer Splines. The spline wear life for various similar material combinations having different metallic coatings is presented in Table 5. In this investigation similar inner and outer spline materials were used for most of the tests.

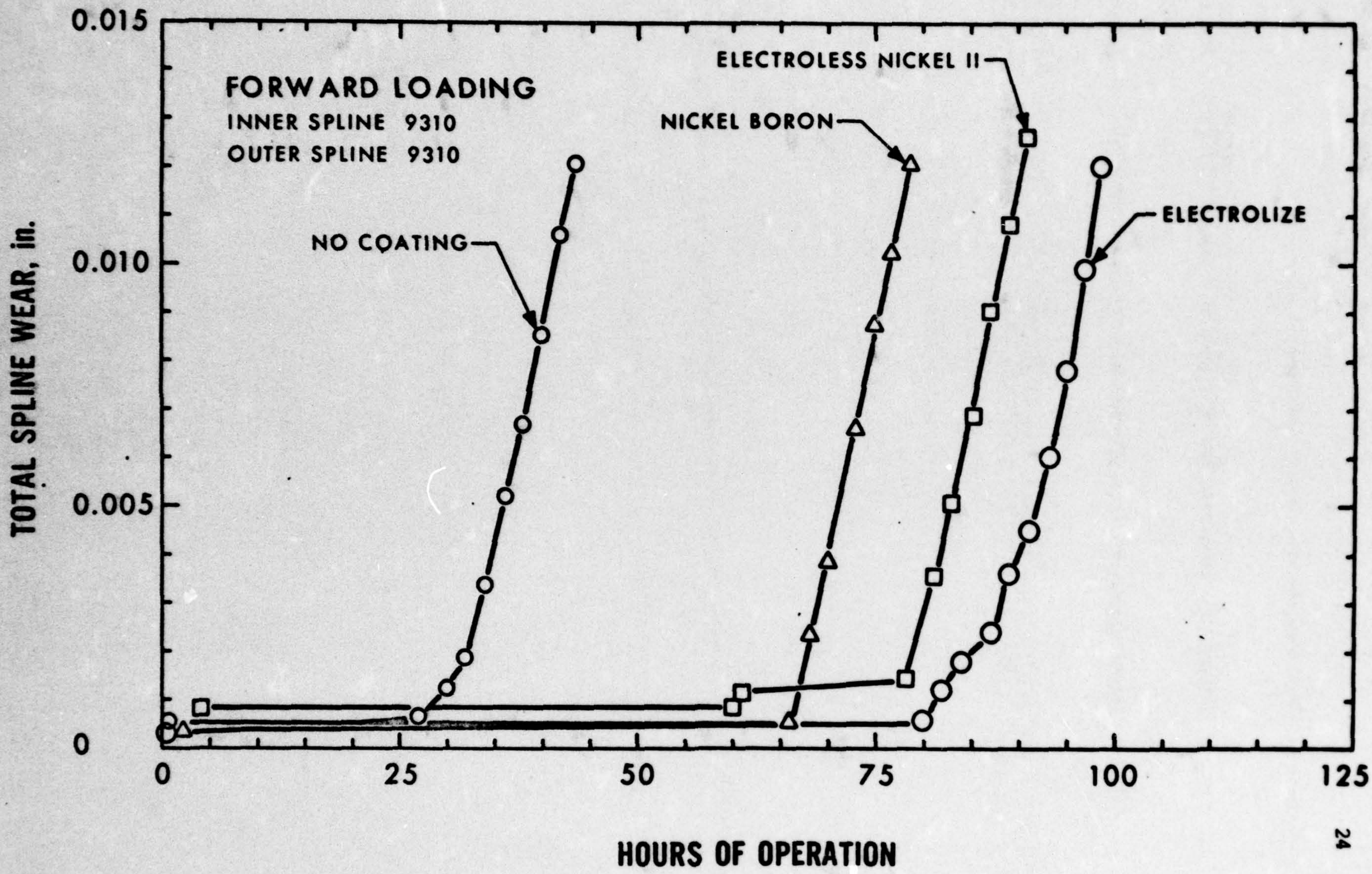
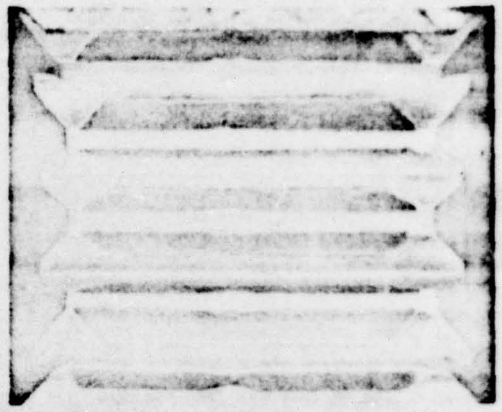
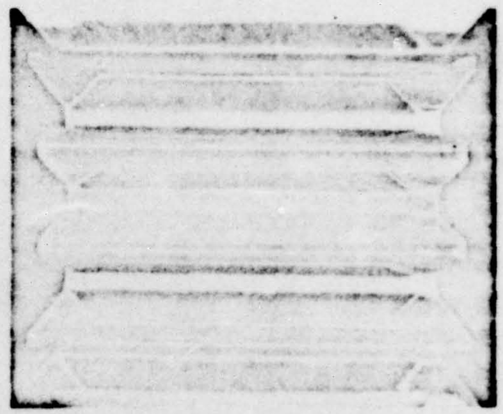


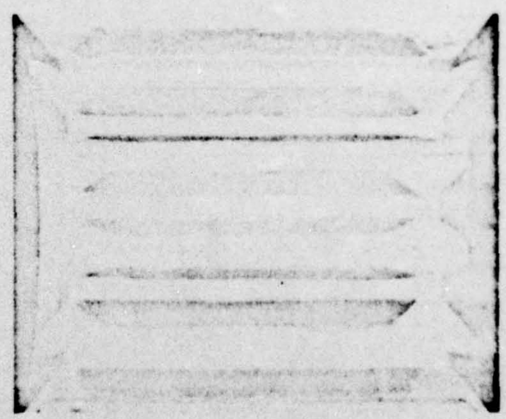
FIGURE 8. TYPICAL WEAR BEHAVIOR OF STANDARD SPLINES FOR DIFFERENT MATERIAL COMBINATIONS WITH METALLIC COATINGS



NICKEL BORON



ELECTROLESS NICKEL II



ELECTROLIZE

FIGURE 9. APPEARANCE OF SECTIONED STANDARD OUTER SPLINES WITH METALLIC COATINGS

TABLE 5. WEAR LIFE OF STANDARD SPLINES FOR DIFFERENT MATERIAL COMBINATIONS WITH METALLIC COATINGS*

Outer Spline	Inner Spline	No Coating	Metallic Coating		
			Electrolize	Elec. Nickel II	Nickel Boron
Forward Loading					
9310	9310	43.5	99.0	90.5	78.5
6475	6475	49.5	91.5	52.6	47.0
M50	M50	79.0	83.0	61.0	61.0
X2	X2	52.6	90.6	77.0	65.5
Average	→	55.6	91.0	70.3	63.0
9310	4130	53.5	140.0**	144.0**	—
Reverse Loading					
9310	9310	65.5	126.5	94.5	80.5
6475	6475	46.0	119.3	68.7	61.2
M50	M50	73.5	102.5	97.6	74.4
X2	X2	69.1	102.7	84.5	71.9
Average	→	69.7	112.8	86.3	72.0
9310	4130	94.5	***	***	—

* Wear life, hr, is herein defined as that for 0.012 in. of total spline wear. Metallic coating on outer spline only.

** Inner spline fractured near end of test.

*** No tests performed—inner splines fractured during forward loading tests.

The test results clearly indicate, for both the forward and reverse loading tests, that the Electrolize coating was the best. The average wear life (irrespective of material combination) was 91.0 hr for the Electrolize coating tests, while the reference "no-coating" tests produced an average of 55.6 hr. The electroless nickel II was next best with 70.3 hr, while the nickel boron provided some spline protection to 63.0 hr.

Similar results were obtained in the tests performed in the reverse loading direction with average wear lives for the Electrolize, electroless nickel II, and nickel boron of 112.8, 86.3, and 72.0 hr, respectively.

Dissimilar Materials for Inner and Outer Splines. Two tests were performed with the inner splines of AISI 4130 steel and the outer splines of AISI 9310 steel with Electrolize and electroless nickel II coatings. These splines were designed with a "large fit" within the connection to provide a larger grease volume. The results of these tests are also shown in Table 6, below the forward and reverse averages.

The near three-fold improvement in spline wear life (140 hr for Electrolize, reference 53.5 hr; and 144 hr for electroless nickel II, reference 53.5 hr) can be attributed to the larger available grease volume and the effective metallic coating.

In both tests the inner splines fractured near the end of the tests. The fracture may have been caused by the fact that the inner splines were too hard (R_c of 59-61 instead of 48-50) due to an error in heat treatment by the vendor.

4. Rapid Wear Rate

The rapid wear rate for the standard spline connections with various material combinations and metallic coatings is presented in Table 6. The average wear rates for the forward and reverse loading tests were about the same as those obtained for the uncoated tests presented in Table 4 (0.00093 in./hr for forward loading and 0.00096 in./hr for the reverse loading).

5. Spline Weight Loss

Figure 10 illustrates the effect of weight loss on standard splines for the different material and metallic coating combinations evaluated. Plots are provided for each of the three metallic coatings investigated.

The weight loss data for the electroless nickel II and nickel boron tests are presented at the top of Figure 10. In these plots most of the weight loss was nearly equal for the

TABLE 6. RAPID WEAR RATE OF STANDARD SPLINE CONNECTIONS FOR DIFFERENT MATERIAL COMBINATIONS WITH METALLIC COATINGS, in./hr

Outer Spline	Inner Spline	Metallic Coating		
		Electrolize	Elec. Nickel II	Nickel Boron
Forward Loading				
9310	9310	0.00100	0.00083	0.00089
6475	6475	0.00114	0.00160	0.00171
M50	M50	0.00096	0.00086	0.00089
X2	X2	0.00065	0.00075	0.00071
Average →		0.00094	0.00101	0.00105
9310	4130	0.00067	0.00060	—
Reverse Loading				
9310	9310	0.00089	0.00100	0.00096
6475	6475	0.00133	0.00141	0.00126
M50	M50	0.00067	0.00071	0.00077
X2	X2	0.00065	0.00060	0.00100
Average →		0.00089	0.00093	0.00100
9310	4130	*	*	—

* No tests performed—inner splines fractured during forward loading tests.

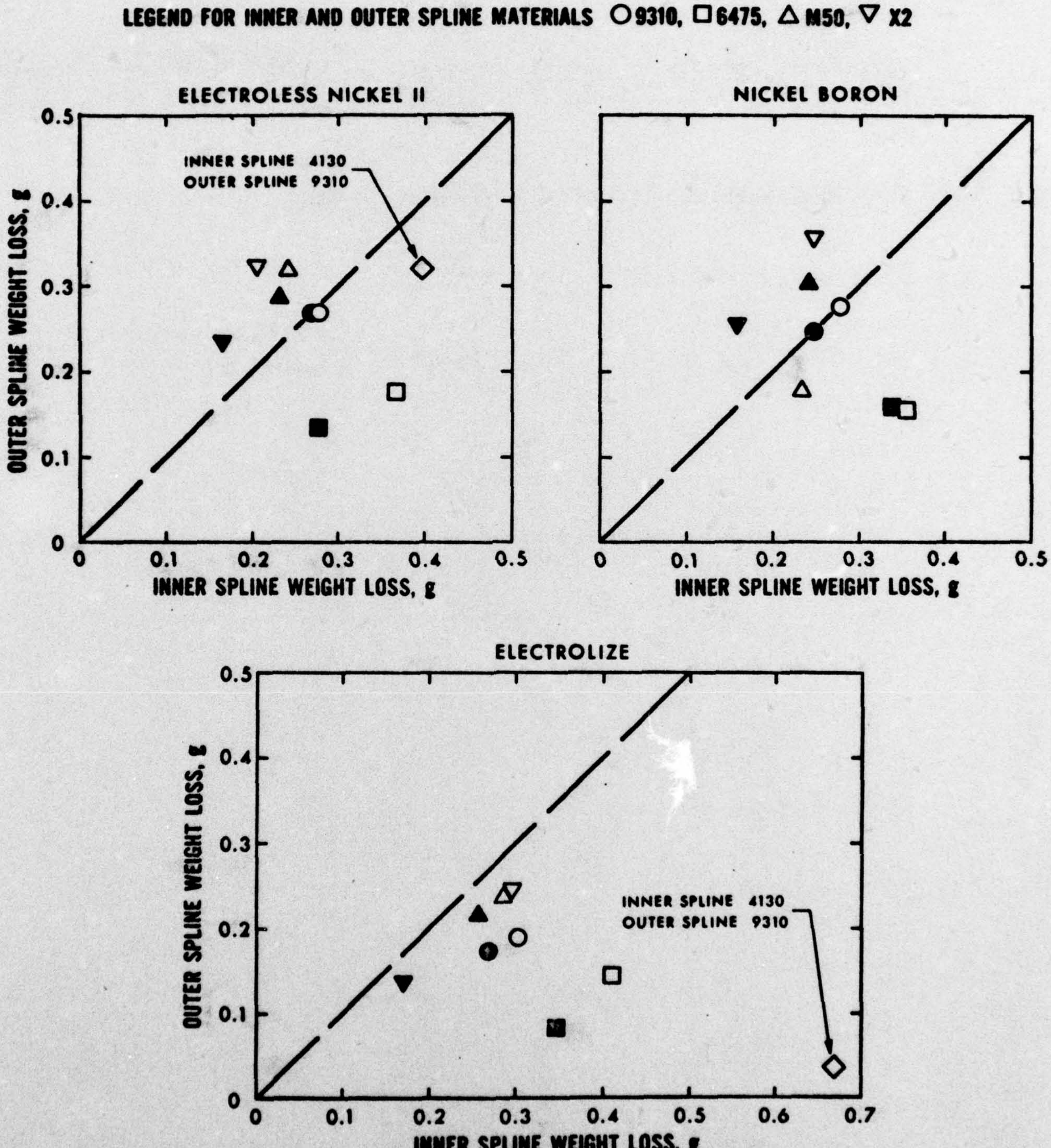


FIGURE 10. EFFECT OF WEIGHT LOSS ON STANDARD SPLINES FOR DIFFERENT MATERIAL COMBINATIONS WITH METALLIC COATINGS

inner and outer splines, indicating that the metallic coating on the outer spline was of little value in protecting the outer spline.

The plot for the Electrolize coating (bottom center) resulted in considerable protection to the outer spline irrespective of the material combinations investigated. The one test performed with the Electrolize coating on the outer AISI 9310 and inner AISI 4130 splines resulted in an 18-fold weight loss protection for the outer spline. Virtually no protection resulted when electroless nickel II was used with AISI 4130 inner and AISI 9310 outer splines.

C. Investigation of Dogbone Splines

A brief investigation was performed using dogbone spline test specimens similar to the ones shown in Figure 11. The short 2.5 in. and long 5 in. dogbones have the same basic design as the standard 12-tooth inner splines. A "medium" fit was selected. Spline tests were allowed to operate for about 0.012 in. and 0.025 in. of total spline wear, depending upon the length of the dogbone and material used.

1. Typical Wear Behavior

The typical wear behavior of a 2.5 in. dogbone operating with the MIL-G-81322B grease in dry air in the forward and reverse loading directions is shown in Figure 12. In these tests the upper and lower outer splines were made of AISI 9310 steel, while the dogbone (inner spline) was made of AISI 4130 steel. These tests were allowed to operate for about 0.025 in. of total spline wear (i.e., the total wear of all three members).

The wear behavior of these dogbone splines was quite similar to the standard splines, with the exception that after the typical run-in, some tests showed a low initial wear rate. This low wear rate continued up to the end of the induction period followed by a rapid increase in wear.

It was noted that the dogbone had a tendency to move up within the two outer splines when a misalignment was present. Therefore, the dogbone was axially restrained in the tests by the sheath thermocouple at the upper dogbone location. The vertical movement was due to the vertical force component imparted by the imposed spline misalignment.

2. Spline Wear Life

A summary of the spline wear life for the dogbone spline tests performed is presented in Table 7. Two different spline lengths were used in evaluating the AISI 9310 and AISI M50 dogbone spline materials.

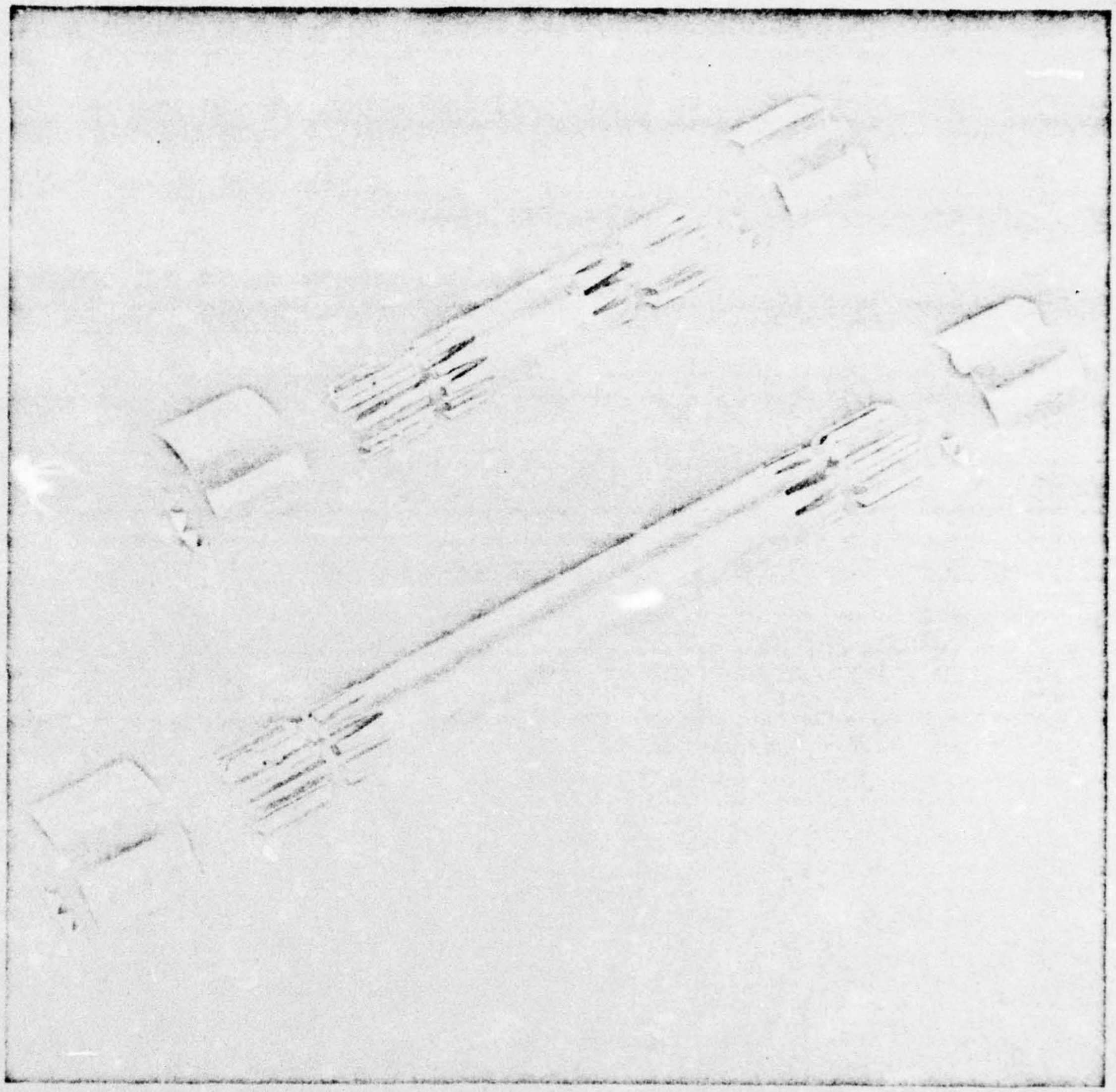


FIGURE 11. APPEARANCE OF DOGBONE SPLINE TEST SPECIMENS AFTER TEST

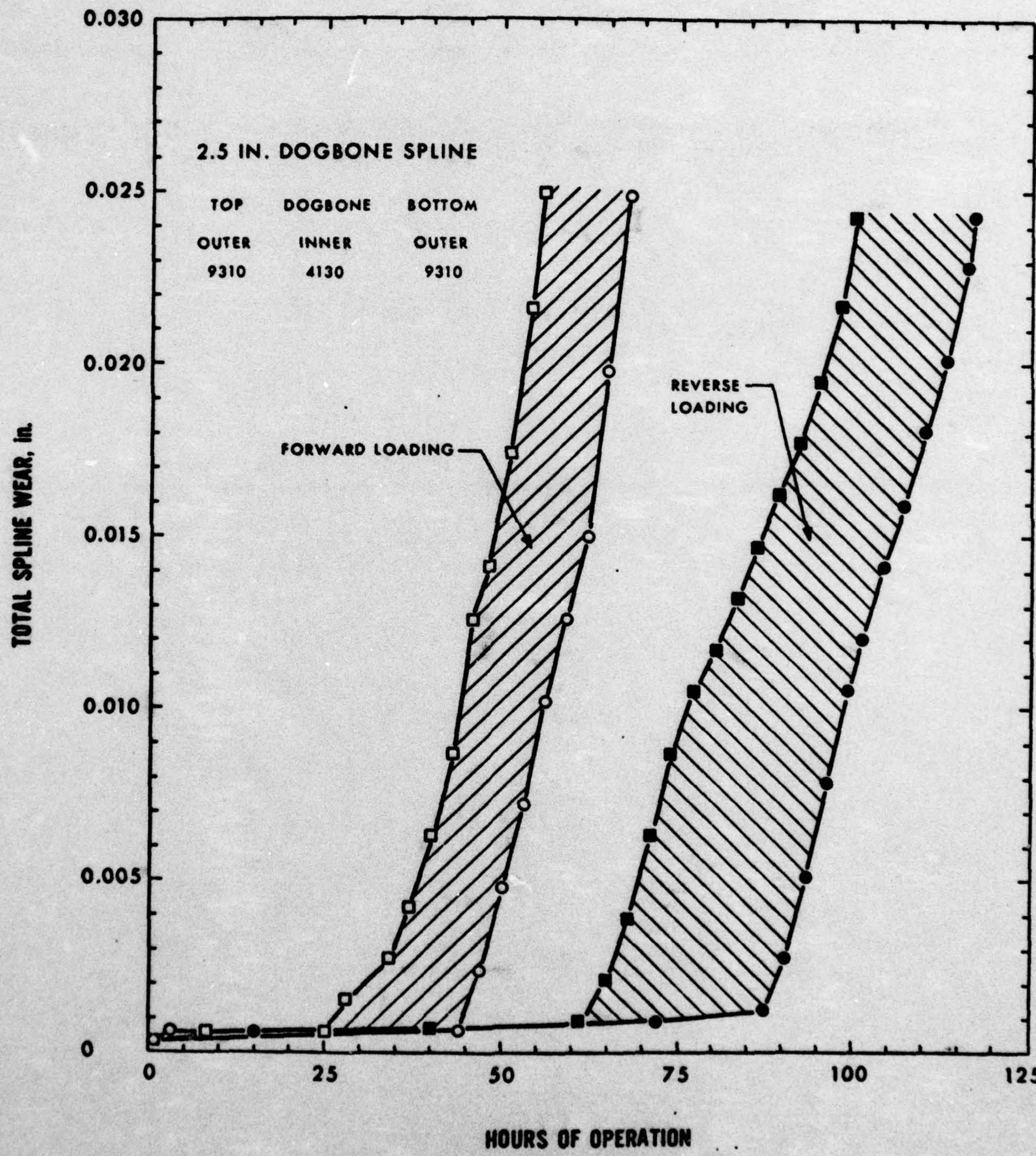


FIGURE 12. TYPICAL WEAR BEHAVIOR OF 2.5-IN. DOGBONE SPLINES FOR DIFFERENT MATERIAL COMBINATIONS

TABLE 7. WEAR LIFE OF DOGBONE SPLINES FOR DIFFERENT MATERIAL AND DESIGN COMBINATIONS*

Design Length, in.	Spline Material: Upper Outer	Spline Material: Dogbone	Spline Material: Lower Outer	Wear Life, hr — Spline Loading: Forward	Wear Life, hr — Spline Loading: Reverse
2.5	9310	4130	9310	59	101
				45	81
	9310	M50	9310	56	115**
				77	127**,***
5.0	9310	4130	9310	217	334
				205	305
	9310	M50	9310	262**,***	-
				255	368**,***

*Wear life, hr, is herein defined as that for 0.012 in. of total spline wear.

**Dogbone mating with lower outer spline broke at or near pivot point.

***Extrapolated.

2.5 in. Dogbone Spline Tests. The tests performed with the 2.5 in. AISI 4130 dogbones resulted in spline wear lives of 59 and 45 hr and 101 and 81 hr for the forward and reverse tests, respectively. When the dogbone material was changed to AISI M50 steel, the wear life was about the same as the AISI 4130 tests in the forward loading direction (56 and 77 hr).

In both of the reverse loading tests performed with the AISI M50 dogbone splines, the lower dogbone spline fractured at or near the pivot point. It is believed that the through-hardened AISI M50 material (with the wear step on the forward loading side of the teeth) could not withstand the high tooth loading and imposed misalignment, thus resulting in a fatigue failure.

5.0 in. Dogbone Spline Tests. The four tests performed with the 5.0 in. dogbones resulted in a longer life. The AISI 4130 dogbone spline exhibited wear lives of 217 and 205 hr and 334 and 305 hr for the forward and reverse loading tests, respectively. Good test repeatability was attained with no spline breakage. The longer life of the 5.0 in. dogbone vs. the 2.5 in. dogbone was a direct result of reducing the spline misalignment within the spline connection.

The tests performed with the AISI M50 dogbone material resulted in somewhat longer spline lives of 262 and 255 hr for the forward loading tests with some inner spline breakage. One reverse loading test could not be performed since the AISI M50 dogbone fractured by fatigue during the forward loading test. The forward loading spline test having a wear life of 255 hr was operated for only 0.012 in. of total spline wear in an effort to provide a stronger or thicker tooth for the reverse test to follow. When the reverse test was performed (368 hr), the AISI M50 dogbone fractured even with the additional available tooth thickness.

3. Spline Wear Rate

The initial and final wear rates of the dogbone spline connections evaluated are presented in Table 8. The initial wear rates for all the tests varied from 0.000000 to 0.000009 in./hr with most of the initial wear rate taking place with the 5.0 in. dogbone. The final wear rates ranged from 0.000600 to 0.001000 in./hr and 0.000100 to 0.000220 in./hr for the 2.5 in. and 5.0 in. dogbones, respectively. The higher wear rates experienced in the shorter 2.5 in. dogbone spline tests were due to the greater misalignment imparted to the dogbone.

4. Spline Weight Loss

The effect of weight loss on the dogbone splines investigated is presented in Figure 13. The results have been

TABLE 8. INITIAL AND FINAL WEAR RATE OF DOGBONE SPLINE CONNECTIONS FOR DIFFERENT MATERIAL AND DESIGN COMBINATIONS

	Spline Material			Wear Rate, in./hr			
				Forward Loading		Reverse Loading	
Design Length, in.	Upper Outer	Dogbone	Lower Outer	Initial	Final	Initial	Final
2.5	9310	4130	9310	0.000000	0.000860	0.000006	0.000860
				0.000000	0.001000	0.000006	0.000600
	9310	M50	9310	0.000000	0.000760	0.000000	0.000680
				0.000000	0.000910	0.000000	0.000610
5.0	9310	4130	9310	0.000009	0.000150	0.000005	0.000220
				0.000003	0.000160	0.000007	0.000160
	9310	M50	9310	0.000004	0.000100	-	-
				0.000002	0.000100	0.000001	0.000100

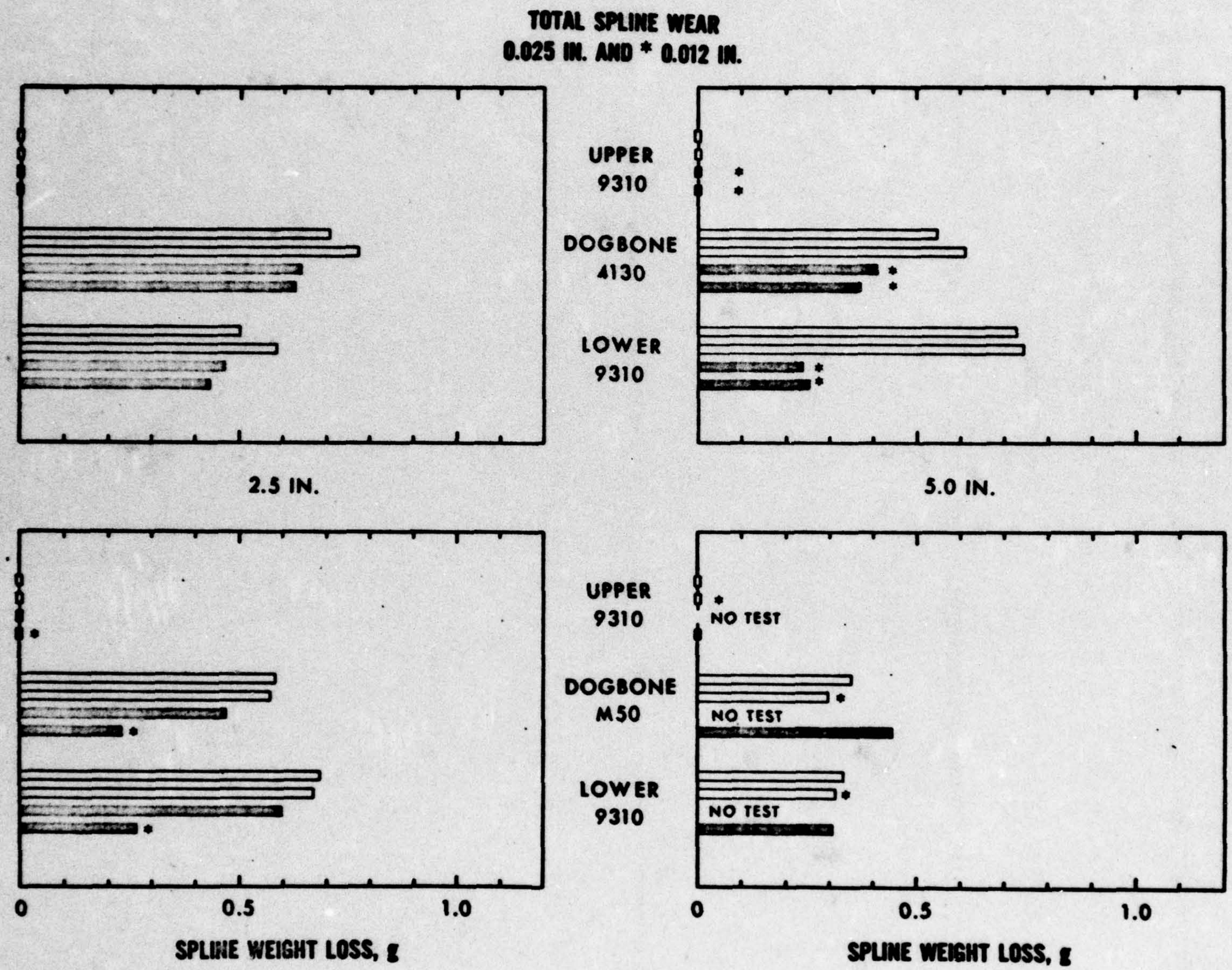


FIGURE 13. EFFECT OF WEIGHT LOSS ON DOGBONE SPLINES FOR DIFFERENT MATERIAL AND DESIGN COMBINATIONS

summarized in four bar charts with the charts on the left for the 2.5 in. dogbone tests and the ones on the right for the 5.0 in. dogbone tests. The upper charts contain the weight loss results for the AISI 4130 dogbones with the lower two charts for the AISI M50 dogbones. Most tests were operated for a total of 0.025 in. of total spline wear except for those noted by asterisks which were operated for 0.012 in. In all of the charts, the clear bars represent the forward loading tests, while the shaded bars represent the reverse loading tests.

In virtually all of the tests performed, the upper outer spline (refer to Fig. 3 for a pictorial representation) did not exhibit any spline wear. The mating inner dogbone operating against the upper outer spline also did not exhibit any detectable wear. It is not known at this time why the upper interface did not wear since they were subjected to the same torque, speed, and imposed misalignment conditions as the lower interface. Apparently, the upper interface was not subjected to some of the imposed spline misalignment and all or most of the misalignment was imparted to the lower interface.

Since the upper dogbone end did not wear, the weight loss for the dogbone represents the weight loss for the lower dogbone end. In virtually all of the tests performed, the weight loss of the lower dogbone end was essentially the same as the mating lower outer spline, whether the splines were operated for 0.012 in. or 0.025 in. of total spline wear.

D. Investigation of Muff Splines

An initial investigation was performed using muff spline test specimens similar to the ones shown in Figure 14. The test plan was devised to study the effects of two muff spline materials having different mating spline fits. All of the forward loading tests were operated to 0.025 in. of total spline wear, while the reverse loading tests were operated to 0.012 in. of total spline wear.

1. Typical Wear Behavior

The typical wear behavior of muff splines operating with the MIL-G-81322B grease in dry air in the forward and reverse loading directions is shown in Figure 15. In these tests, the standard inner spline made of AISI 9310 steel was operated against a muff of AISI 4130 steel which also operated against an outer spline made of AISI 9310 steel.

The forward and reverse loading tests followed the same general trend as the standard and dogbone spline tests, in that the reverse loading tests operated for a longer period of time.

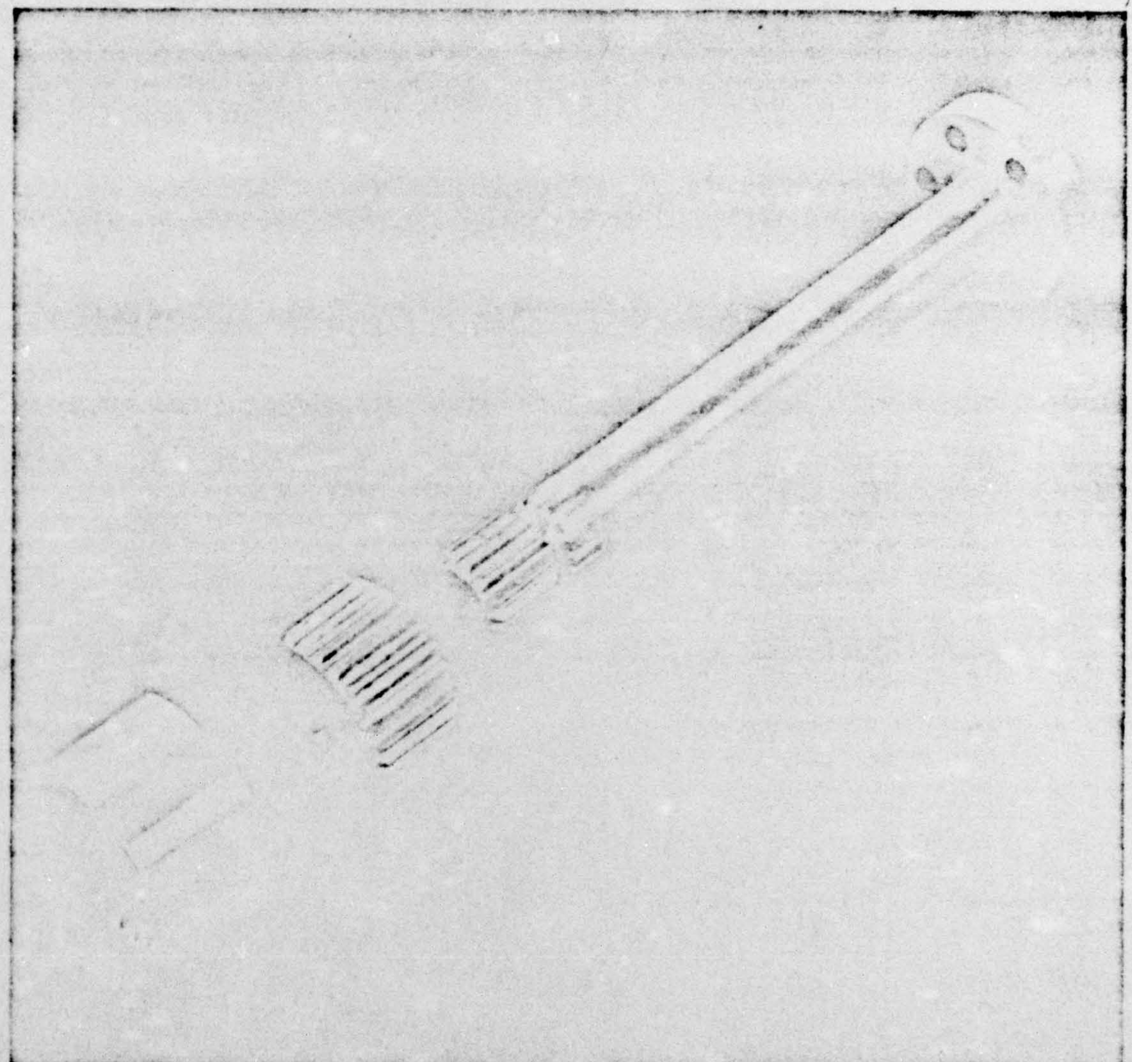


FIGURE 14. APPEARANCE OF MUFF SPLINE TEST SPECIMENS AFTER TEST

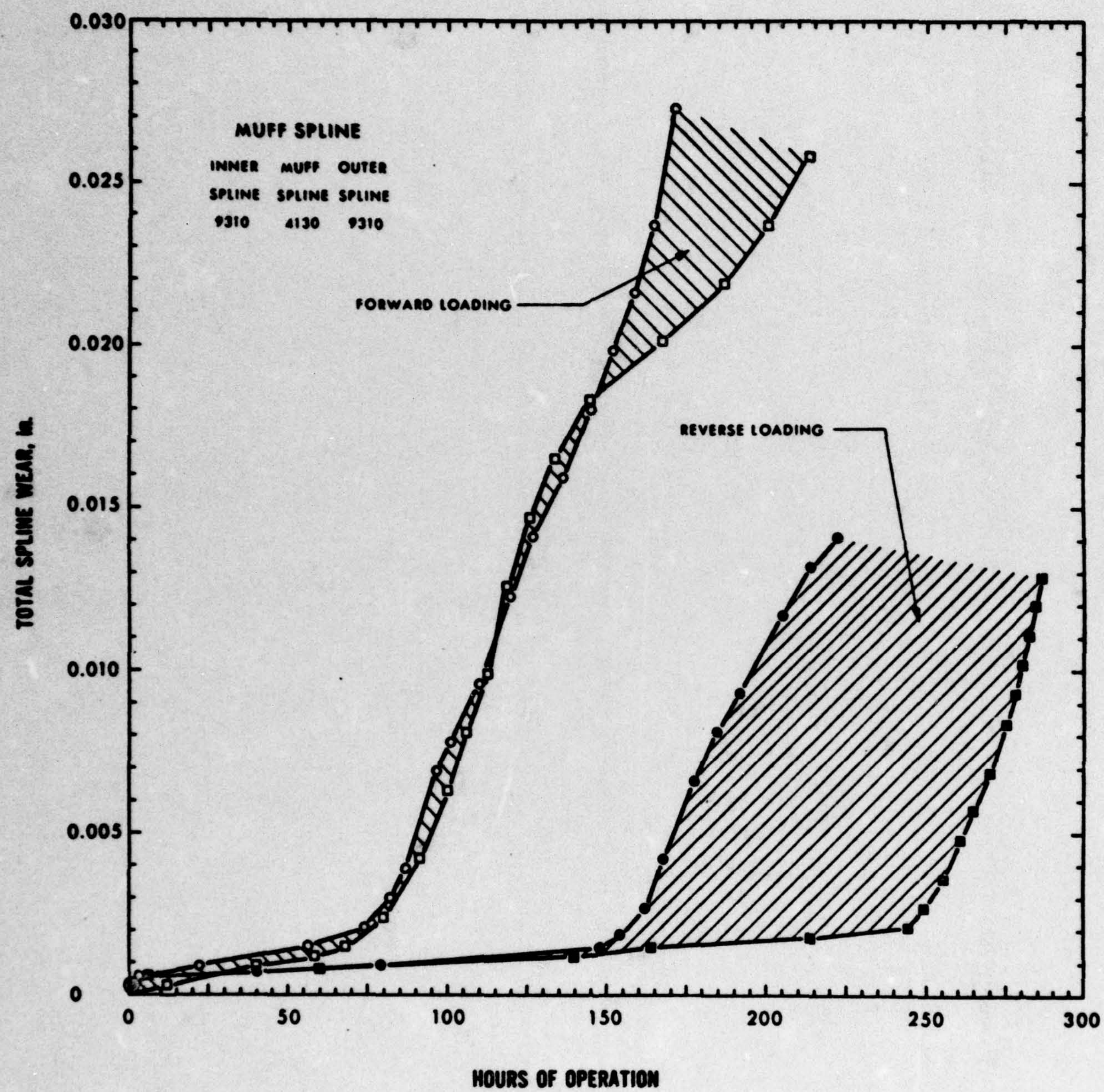


FIGURE 15. TYPICAL WEAR BEHAVIOR OF MUFF SPLINES FOR DIFFERENT MATERIAL COMBINATIONS

In all of the muff tests, the splines began to wear immediately at a low rate of wear and continued to the end of the induction period, after which the wear rate increased rapidly. The transition between the low and high wear rates (end of the induction period) was gradual.

In the muff spline tests, the muff had a tendency to move up within the outer spline (similar to the dogbone) due to the imposed spline misalignment. An O-ring was used on the inner spline (between the inner spline and the spline shank) to prevent the muff from rising.

2. Spline Wear Life

Table 9 contains a summary of the wear life data for the muff spline tests performed.

"Medium-Medium" Fit. The spline wear tests performed with the "medium-medium'" fit (medium fit between the standard inner spline and the muff and a medium fit between the muff and the outer spline) resulted in some differences in wear life. The wear life in the forward loading direction was 118 hr and 203 to 166 hr for the AISI 4130 muff and AISI M50 muff materials, respectively.

In these forward loading medium-medium fit tests, the AISI M50 muff material proved to be superior to the AISI 4130 muff material. The reverse loading tests lasted longer, in most cases, than the forward loading tests as before. All of the reverse loading spline tests were performed without any spline breakage.

"Large-Small" Fit. The spline wear tests performed with the "large-small" fit (large fit between the standard inner spline and the muff and a small fit between the muff and the outer spline) resulted in some scatter in the test results. The spline wear life was 71 to 172 hr and 114 to 194 hr for the tests performed with the AISI 4130 and AISI M50 muff materials, respectively. In most cases, the reverse loading tests provided a longer wear life to the spline connections due to the added grease volume.

3. Spline Wear Rate

The initial and final wear rates of the muff spline connections evaluated are presented in Table 10. In most cases, the wear rate repeatability was good.

The initial wear rate for the medium-medium fit splines ranged from 0.000017 to 0.000170 in./hr which was considerably higher than the initial wear rate for the large-small fit splines exhibiting a wear rate of 0.000001 to 0.000015 in./hr.

TABLE 9. WEAR LIFE OF MUFF SPLINES FOR DIFFERENT MATERIAL AND DESIGN COMBINATIONS*

	Muff Spline Material			Wear Life, hr Spline Loading	
Design	Inner	Muff	Outer	Forward	Reverse
Medium Medium Fit	9310	4130	9310	118	207
				118	284
	9310	M50	9310	203	174
				166	202
Large Small Fit	9310	4130	9310	71	155
				172	160
	9310	M50	9310	114	250
				194	278

* Wear life, hr, is herein defined as that for 0.012 in. of total spline wear.

TABLE 10. INITIAL AND FINAL WEAR RATE OF MUFF SPLINE CONNECTIONS FOR DIFFERENT MATERIAL AND DESIGN COMBINATIONS

	Muff Spline Material			Wear Rate, in./hr			
				Forward Loading		Reverse Loading	
Design	Inner	Muff	Outer	Initial	Final	Initial	Final
Medium Medium Fit	9310	4130	9310	0.000017	0.000240	0.000008	0.000191
				0.000018	0.000320	0.000005	0.000229
	9310	M50	9310	0.000170	0.000350	0.000007	0.000280
				0.000120	0.000300	0.000005	0.000330
Large Small Fit	9310	4130	9310	0.000006	0.000830	0.000001	0.000828
				0.000001	0.000600	0.000001	0.000750
	9310	M50	9310	0.000015	0.000630	0.000005	0.000570
				0.000003	0.000390	0.000009	0.000553

The final wear rates for the medium-medium fit splines were about half as great as the tests performed with the large-small fit splines.

The reverse loading tests exhibited somewhat lower initial wear rates and comparable final wear rates compared to the forward loading tests.

4. Spline Weight Loss

The effect of weight loss on the muff splines investigated is summarized in the charts in Figure 16. The two charts on the left illustrate the weight loss for the medium-medium fit splines, while the ones on the right show the weight loss for the large-small fit splines. In addition, the upper two charts are shown for the AISI 4130 muff with the results for the AISI M50 muff given in the two lower charts. In all of the charts, the clear bars represent the forward loading tests, while the shaded bars represent the reverse loading tests.

These charts illustrate the importance of spline fit and material selection in the design of the muff. In the upper left chart, an AISI 4130 muff with a medium-medium fit exhibited about 3 times the weight loss of the outer spline and about twice the weight loss of the inner spline. When a large-small fit (upper right chart) was used with the AISI 4130 muff, the outer spline weight loss was virtually eliminated. In this case, most of the weight loss was shared between the muff and the inner spline. The reason why no weight loss was encountered in the outer spline was due to the small fit between the outer 24-tooth spline and the 24-tooth muff. Virtually all of the misalignment was then directed to the 12-tooth spline connection having the large fit. Good repeatable weight loss data were obtained for the tests performed in the forward and reverse loading directions.

When AISI M50 steel was used as the muff material, the same general trend resulted for both the medium-medium and large-small fits used.

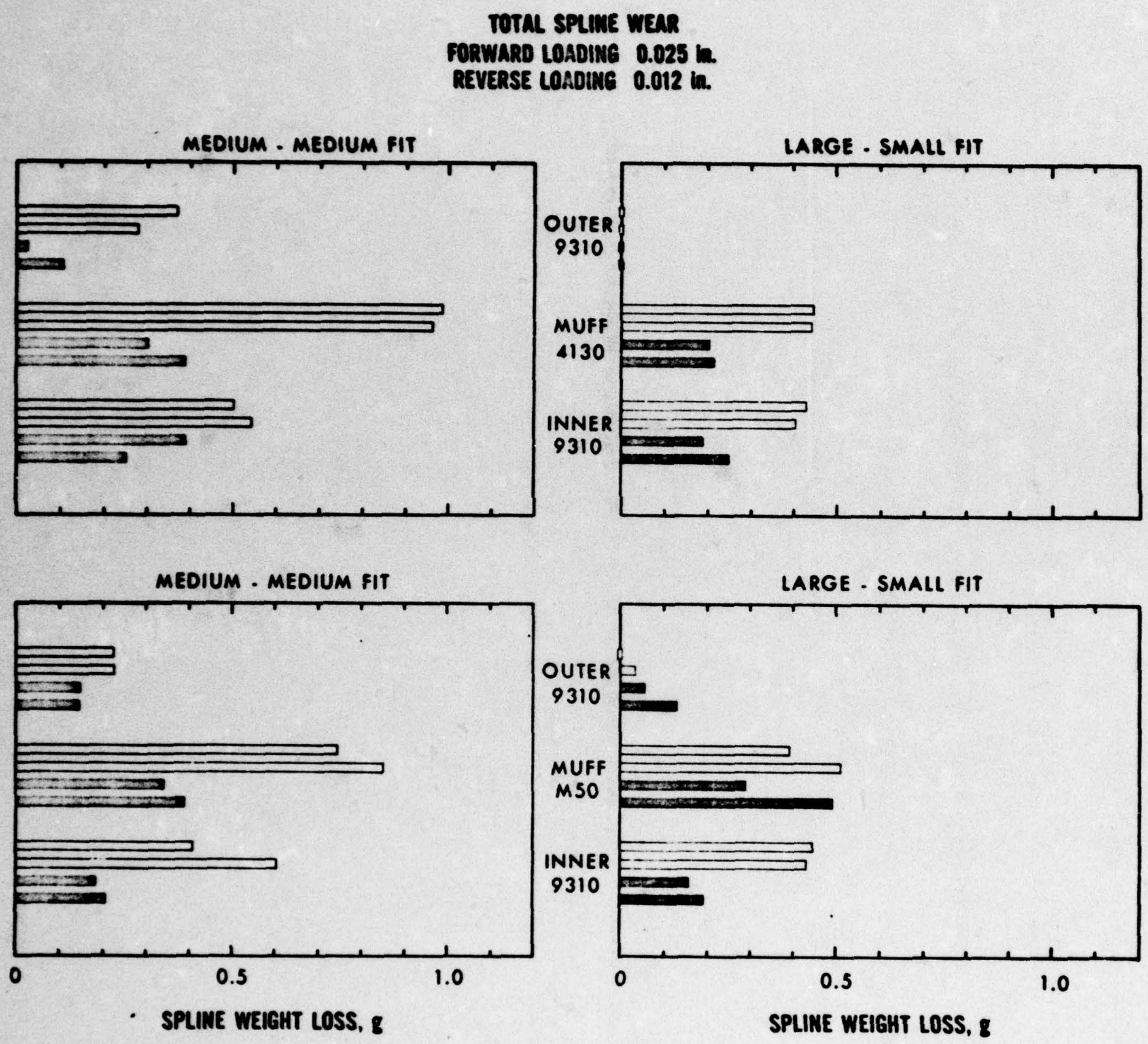


FIGURE 16. EFFECT OF WEIGHT LOSS ON MUFF SPLINES FOR DIFFERENT MATERIAL AND DESIGN COMBINATIONS

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Summary of Results

The performance summary of the forward loading tests for the standard, dogbone, and muff spline connections evaluated in dry air with a MIL-G-81322B grease is presented in Figure 17. This figure summarizes the spline wear life and weight loss data.

1. Standard Splines—No Coating

As noted in the upper left corner of Figure 17, standard outer splines made of AISI 9310, AMS 6475, AISI M50, and Vasco X2 steels were each operated against inner splines made of AISI 9310, AMS 6475, AISI M50, Vasco X2, and AISI 4130 steels, for 0.012 in. of total spline wear. These forward loading tests exhibited an average wear life of 51.6 hr.

The inner and outer spline weight loss was about the same for all of the material combinations investigated with the outer spline having more scatter in the weight loss data. A trend in weight loss (refer to Fig. 7) was apparent when inner splines of AMS 6475 steel were evaluated against AISI 9130, AMS 6475, AISI M50, and Vasco X2 outer spline materials. The trend was that the outer splines were protected more when an inner spline of AMS 6475 was used.

2. Standard Splines—With Coating

Similar Materials. Spline tests performed with standard inner and outer splines made of AISI 9310, AMS 6475, AISI M50, and Vasco X2 steels with metallic coatings on the outer splines resulted in an increase in wear life for all of the three coatings evaluated. The average wear life (irrespective of material combination) was 91.0, 70.3, and 63.0 hr for the Electrolize, electroless nickel II, and nickel boron coated splines, respectively.

The Electrolize coating provided a lower weight loss thereby protecting the outer splines. Tests performed with the electroless nickel II and nickel boron resulted in a more equal weight loss indicating little protection to the outer spline.

Dissimilar Materials. Two tests were performed (see asterisks in Fig. 17) with an inner spline of AISI 4130 steel and an outer spline of AISI 9310 steel, with Electrolize and electroless nickel II coatings. The splines were of equal hardness. A large fit was used. A near three-fold improvement in spline life was obtained. However, in both tests, the

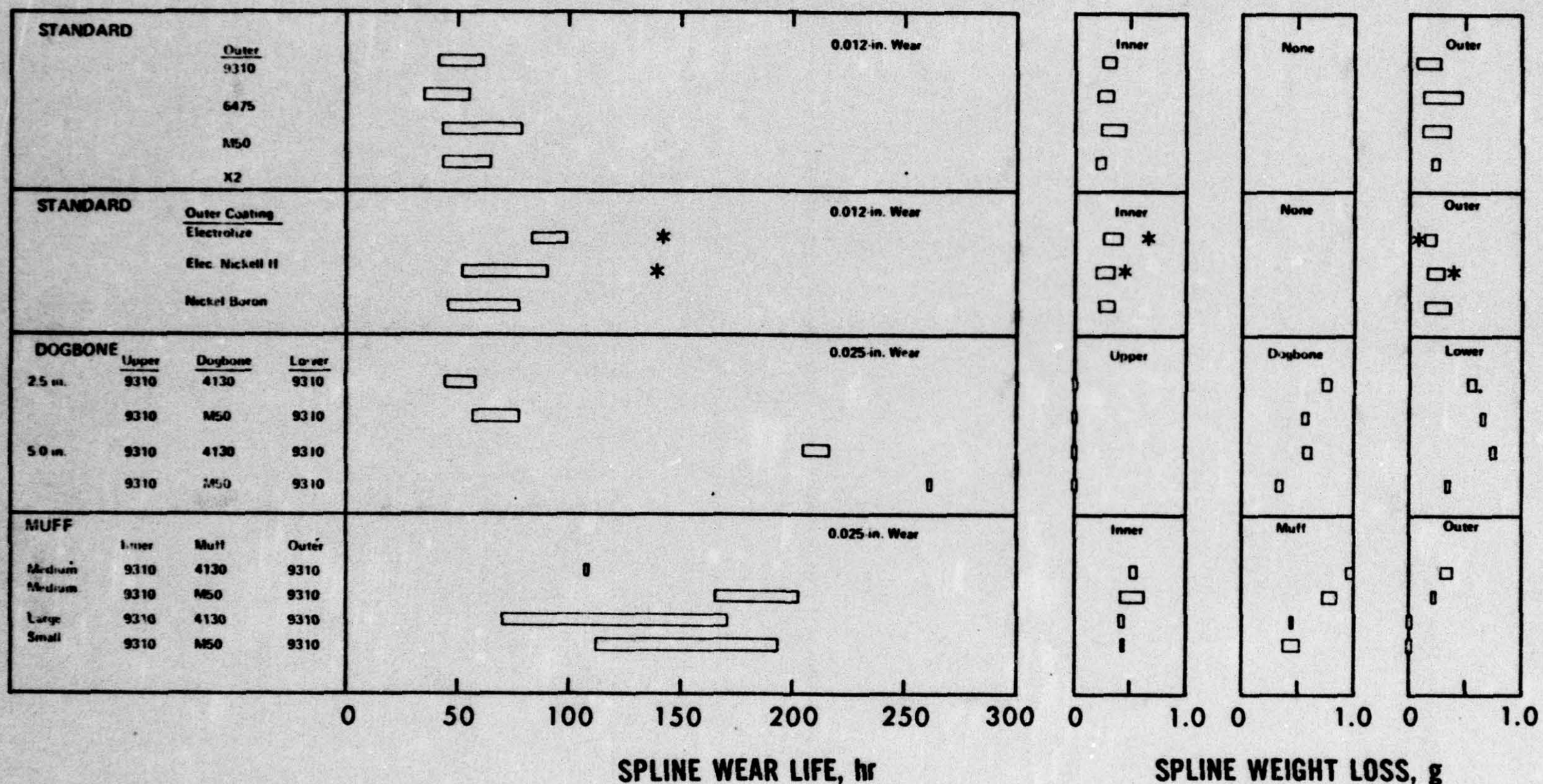


FIGURE 17. PERFORMANCE SUMMARY FOR STANDARD, DOGBONE, AND MUFF SPLINE CONNECTIONS

inner splines fractured.

3. Dogbone Splines

Tests were performed with the dogbone splines to investigate the effect of the length of the dogbone and the effect of two spline materials. Splines were allowed to operate for 0.025 in. of total spline wear.

2.5 in. Dogbone Splines. The tests performed with the AISI 4130 and AISI M50 dogbone materials resulted in an average wear life of 52.0 hr and 66.5 hr, respectively. Although the AISI M50 dogbone exhibited a slightly longer wear life, they were not reliable. Both AISI M50 splines fractured during the reverse loading tests.

The upper outer spline and mating end of the dogbone did not exhibit any weight loss. Most of the weight loss was shared between the lower end of the dogbone and the lower outer spline. No trends in weight loss were apparent due to the limited number of tests performed.

5.0 in. Dogbone Splines. The tests performed with the 5.0 in. dogbone resulted in longer spline life due to the decrease in imposed misalignment on the dogbone. As in the 2.5 in. dogbone tests, the AISI 4130 dogbone exhibited a lower average wear life than the AISI M50 dogbone. The AISI 4130 and AISI M50 dogbones resulted in an average wear life of 211 hr and 259 hr, respectively. Two of the AISI M50 dogbones fractured during the tests.

The upper outer spline and mating upper end of the dogbone did not exhibit any measurable wear. As in the 2.5 in. dogbone tests, no conclusion can be drawn from the limited weight loss data.

4. Muff Splines

Tests were performed to study the effects of muff spline materials and spline fits. Splines were allowed to operate for 0.025 in. of total spline wear.

Medium-Medium Fit. The duplicate tests performed with the AISI 4130 and AISI M50 muffs exhibited an average wear life of 118 hr and 185 hr, respectively. Good test repeatability and no spline breakage was obtained.

Tests performed with the AISI 4130 and AISI M50 muff splines exhibited most of the wear taking place within the muff. The inner spline did lose some wear, while the outer spline was reasonably well protected, losing only a small amount of wear.

Large-Small Fit. The muff splines with the large-small fit (large fit between the standard inner spline and the muff and a small fit between the muff and the outer spline) resulted in some scatter in the wear life. An average wear life of 122 hr and 154 hr was obtained for the AISI 4130 and AISI M50 muff splines, respectively. The AISI M50 muff was superior to the AISI 4130 muff, regardless of the spline fits investigated. The splines did not break.

Of significant importance is the fact that the outer splines exhibited virtually no weight loss. This was due to the small fit between the outer 24-tooth spline and the 24-tooth muff. Most of the misalignment was absorbed within the 12-tooth spline connection having the large fit. The muff and inner spline exhibited about the same amount of weight loss.

B. Conclusions

It has been shown that the basic objective of this program was has been accomplished, i.e., to show that the "expendable spline" concept can be used to advantage to extend the wear life of grease-lubricated steel interface spline connections.

The principal conclusions of this program are as follows:

1. The selection of mating standard spline materials for grease-lubricated splines is not the major consideration in extending spline life.

2. For standard splines, a hardness of R_c of 62-65 and R_c of 48-50 for the outer and inner splines, respectively, provides a reliable mating connection.

3. A metallic coating on a standard outer spline (operating against an inner spline of the same material) can increase spline life.

4. An effective metallic coating used on a standard outer spline can minimize the wear of that spline when operated against a noncoated inner spline. This makes the inner spline "expendable."

5. A dogbone spline can be used as an "expendable" member.

6. The design of dogbone spline appears to be more critical than the design of standard spline connections.

7. In the design of a dogbone, steps should be taken to contain the dogbone within the desired location to prevent axial movement.

8. Material selection appears to be more critical for dogbones. A dogbone made of through-hardened AISI M50 steel was unreliable because it fractured during testing.

9. The length of the dogbone can have a large effect on the life of the spline connection.

10. A muff can be used as an "expendable" member.

11. The wear on the outer spline in a muff connection can be minimized by providing a small fit between the muff and the outer spline.

12. The use of a medium fit (typical of current aircraft practice) on muff splines will create wear on the outer spline.

13. In the design of a muff connection, steps should be taken to contain the muff within the desired location to prevent axial movement.

C. Recommendations

The work performed in this program has answered many questions facing spline designers. However, there are still areas to pursue in order to provide more effective spline connections.

The AND and MS Design Standards, for example, provide general design information for the standard spline connections only. There are no provisions in the Standards for the designers to use in making dogbone and muff splines, which are used extensively in current aircraft to connect accessories to the gearbox. The work presented herein is believed to be the first systematic study performed with dogbone and muff spline connections. A more comprehensive research program is needed to obtain the needed design information. Based on these considerations, it is recommended that the following additional work be performed for direct comparison with the current program:

1. Additional work is needed using standard splines. Splines of equal hardness, such as R_C of 60-65, should be investigated with various spline fits and spline lengths. Additional metallic coatings should be investigated on outer and inner-outer splines fabricated from different spline materials of equal and unequal hardnesses having different spline fits. Protecting the outer spline should remain the basic objective.

2. Additional work is recommended to supplement the initial investigation performed on dogbone splines. Dogbones of different lengths, hardnesses, materials, and fits with and without metallic coatings should be considered. The purpose of

this work should be to minimize the wear on both outer splines. Efforts should be concentrated on making the dogbone the only expendable member.

3. Additional work is also recommended to supplement the initial work performed on the muff splines. Further verification is needed to strengthen the work reported herein. Consideration should be given to using other muff materials, other inner spline materials with different spline fits. Efforts should be made to protect both the inner and outer splines, allowing the muff to be the only "expendable" member.

REFERENCES

1. Valtierra, M. L., Brown, R. D., and Ku, P. M., "A Critical Survey and Analysis of Aircraft Spline Failures," SwRI Rept. RS-574 (Department of the Navy Contract N00156-70-C-2156), Aug. 1971.

2. Valtierra, M. L., "Spline Test Research," Proc. Maintenance Manager Review Conf., Warner Robins Air Materiel Area, pp. 121-127, Sept. 1973.

3. Valtierra, M. L., "Spline Wear," Proc. Wear Control in Naval Aircraft Conf., Naval Air Development Center, pp. F14, F17-F18, Dec. 1975.

4. Weatherford, W. D., Jr., Valtierra, M. L., and Ku, P. M., "Experimental Study of Spline Wear and Lubrication Effects," ASLE Trans., Vol. 9, pp. 171-178, 1966.

5. Weatherford, W. D., Jr., Valtierra, M. L., and Ku, P. M., "Mechanisms of Wear in Misaligned Splines," Trans. ASME, Jour. Lub. Tech., Vol. 90F, pp. 42-48, 1968.

6. Ku, P. M., "Tribology of Gears and Splines," Proc. Tribology Workshop, National Science Foundation, pp. 402-427, 1974.

7. Ku, P. M., "Design of Spline Couplings for Fretting Mitigation," Fretting in Aircraft Systems, NATO-AGARD Conf. Proc. CP-161, pp. 11.13-11.22, Jan. 1975.

8. Valtierra, M. L., and Ku, P. M., "Evaluation of Six Spline Surface Treatments on New and Used Spline Specimens," SwRI Rept. RS-620 (Department of the Navy Contract N62269-73-C-0359), Mar. 1975.

9. Valtierra, M. L., Pakvis, A., and Ku, P. M., "Spline Wear in Jet Fuel Environment," Lub. Eng., Vol. 31, pp. 136-142, 1975.

10. Ku, P. M., and Valtierra, M. L., "Spline Wear—Effects of Design and Lubrication," Trans. ASME, Jour. Eng. Ind., Vol. 97B, pp. 1257-1265, 1975.