NBS TECHNICAL NOTE 863

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Fatigue Tests of Bituminous Membrane Roofing Specimens

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Fatigue Tests of Bituminous Membrane Roofing Specimens

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BITUMINOUS MEMBRANE ROOFING SPECIMENS

by

George F. Sushinsky and
Robert G. Mathey

ABSTRACT

Tensile and flexural fatigue tests were performed on built-up roof membrane specimens (ASTM Designation: D2523-70) fabricated from four different material systems. The tensile fatigue tests were run under cyclic load control conditions while specimens tested in flexural fatigue were run under cyclic midspan displacement control. Tests were run at ambient laboratory conditions, generally 70 ± 2°F (21 ± 1°C), and at 0 ± 2°F (-18 ± 1°C). Curves based on the experimental results are plotted relating the peak load or displacement to the median fatigue lifetimes for specimens fabricated from each material. Performance criteria for roof membranes subject to fatigue loading are recommended.

Key Words: Bituminous roof membranes; fatigue testing; flexural fatigue; performance criteria; roofing; temperature effects; tensile fatigue; test methods.

1. INTRODUCTION

In 1972 over 3.5 billion square feet ($3.x \times 10^8$ m^2)[1] of bituminous built-up roof membranes were applied to buildings in the United States. While the membrane represents only one component in a roof system[2], it is the membrane that provides protection to a building's contents and occupants from the weather. Traditionally, roof membranes have been described by prescriptive-type specifications for the materials

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[1]The units used for physical quantities in this paper are given in both the U. S. Customary Units and in the International System of Units (SI). Conversion factors can be found in ASTM Standard Metric Practice Guide, ASTM Designation E-380-72.

[2]Bituminous built-up roof system is a term used to describe roofs in which the waterproofing membrane is composed of layers of reinforcing felts adhered together with a bituminous material. The membrane is generally installed over insulation but is sometimes applied directly to the roof deck.

comprising the membranes. The use of prescriptive-type specifications tends to hinder innovation in systems design and the implementation of new materials in built-up roof systems.

The performance of the bituminous membrane has been considered for many years only from a practical viewpoint, that is, observation of its durability under in-service conditions. Only recently have some of the properties and characteristics of bituminous built-up roofs been described quantitatively [1][3]. Prior to this, a few quantitative guidelines have been available to predict the performance of built-up roof membranes. The lack of performance criteria probably represents the largest single constraint to the introduction of new and innovative systems into the roofing industry.

In an attempt to develop the "art" of roofing into more of a science, research was conducted at the National Bureau of Standards to develop performance criteria which would contain quantitative definitions on a roof membrane's overall ability to perform under in-service conditions. An important intent in the performance approach is to provide a basis for evaluating roofing membranes with reasonable assurance that the membrane will perform satisfactorily over its intended period of use. As part of the research program, preliminary performance criteria were recommended for bituminous membrane roofing [1]. These criteria recommend levels of performance for nine of the twenty attributes that were identified for laboratory study as affecting the performance of roof membranes under service conditions. Two of the attributes which were identified for laboratory study were tensile fatigue strength and flexural fatigue strength.

This report describes the development of performance criteria based on the fatigue behavior of conventional types of roof membranes. The objectives of this study were to measure the tensile and flexural fatigue strengths of conventional roofing membranes, to develop methods of tests for measuring these engineering properties and to recommend the levels of performance included in the performance criteria.

2. TEST SPECIMENS

The specimens tested in this investigation were die cut from four-ply membranes and conformed to standard size specimens such as those described in ASTM D-2523 [2]. The specimen geometry is shown in Figure 1. The specimens represented four different types of four-ply membranes. Four types of roofing felts and two types of bitumen were used in the fabrication of the test specimens[4]. The four types of roof membranes

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[3] Figures in brackets refer to literature references given in Section 8.

[4] Details of specimen fabrication will be given in a report, "Tensile Properties of Built-Up Roof Membranes" by Robert G. Mathey to be published.

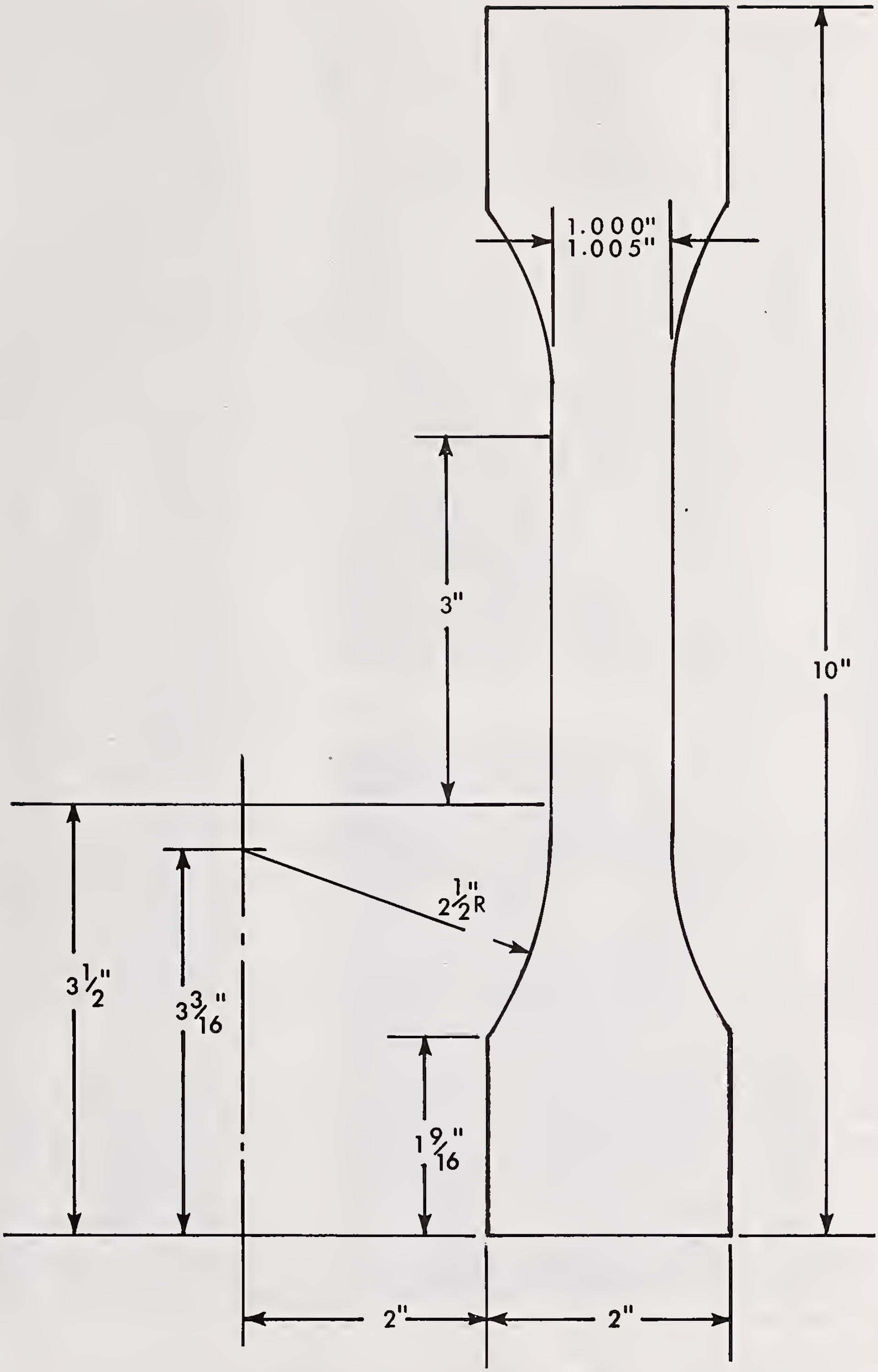


Figure 1 - Built-up roof membrane specimen geometry (ASTM Designation: D2523-70).

are given in Table 1. Specimens are identified using the appropriate

Table 1 - Roof Membrane Material Combinations and Membrane Designation

Felt	ASTM Designation	Matrix	ASTM Designation	Membrane Designation
Organic	D227	Coal-tar pitch	D450, Type A	A
Organic	D226, 15 lb type	Asphalt	D312, Type I	B
Asbestos	D250, 15 lb type	Asphalt	D312, Type I	C
Glass	D2178, Type I	Asphalt	D312, Type I	D

membrane designation letter code followed by a 2 digit number. The specimens tested were fabricated with the across machine (transverse) direction of the felts oriented in the direction along the longitudinal axis of the specimens[5]. All specimens were fabricated in an identical manner except the specimens to be tested in flexural fatigue. These specimens contained a 0.010-in (0.03-cm) diameter copper wire at midsection that spanned the length of the specimen.

3. TEST EQUIPMENT

3.1 Fatigue Equipment

The test program was conducted using the fatigue equipment available at the National Bureau of Standards' Engineering Mechanics Laboratory [3].

3.1.1 Tensile Fatigue

Tensile fatigue tests were run with the actuator from the 10,000 lbf (44,500 N) capacity fatigue machine mounted in a test stand (Figure 2). These tests were conducted under load control conditions with the span adjusted to a 5,000 lbf (22,200 N) maximum load. In order to further reduce the maximum load capacity of the fatigue test set-up, while attempting to maintain the accuracy of the applied load, the actuator was connected to a ten-to-one lever arm. This provided for a possible maximum load of 500 lbf (2,200 N) to the specimens.

The specimens were clamped in 2-in (5.1-cm) wide tension grips, so that the length of the specimen between grips was 7.0-in (17.8-cm). The upper grip was attached to the end of the lever arm through a steel

[5] Roofing felts are made on a moving belt and formed in rolls generally 36-in (91-cm) wide and of various lengths. The across machine (transverse) direction is the direction across the width of the felt. The strength of a felt oriented in the across machine direction is generally weaker than in its machine (longitudinal) direction. This is a result of the preferred orientation of the fibers of the felt in the direction along the material's length.

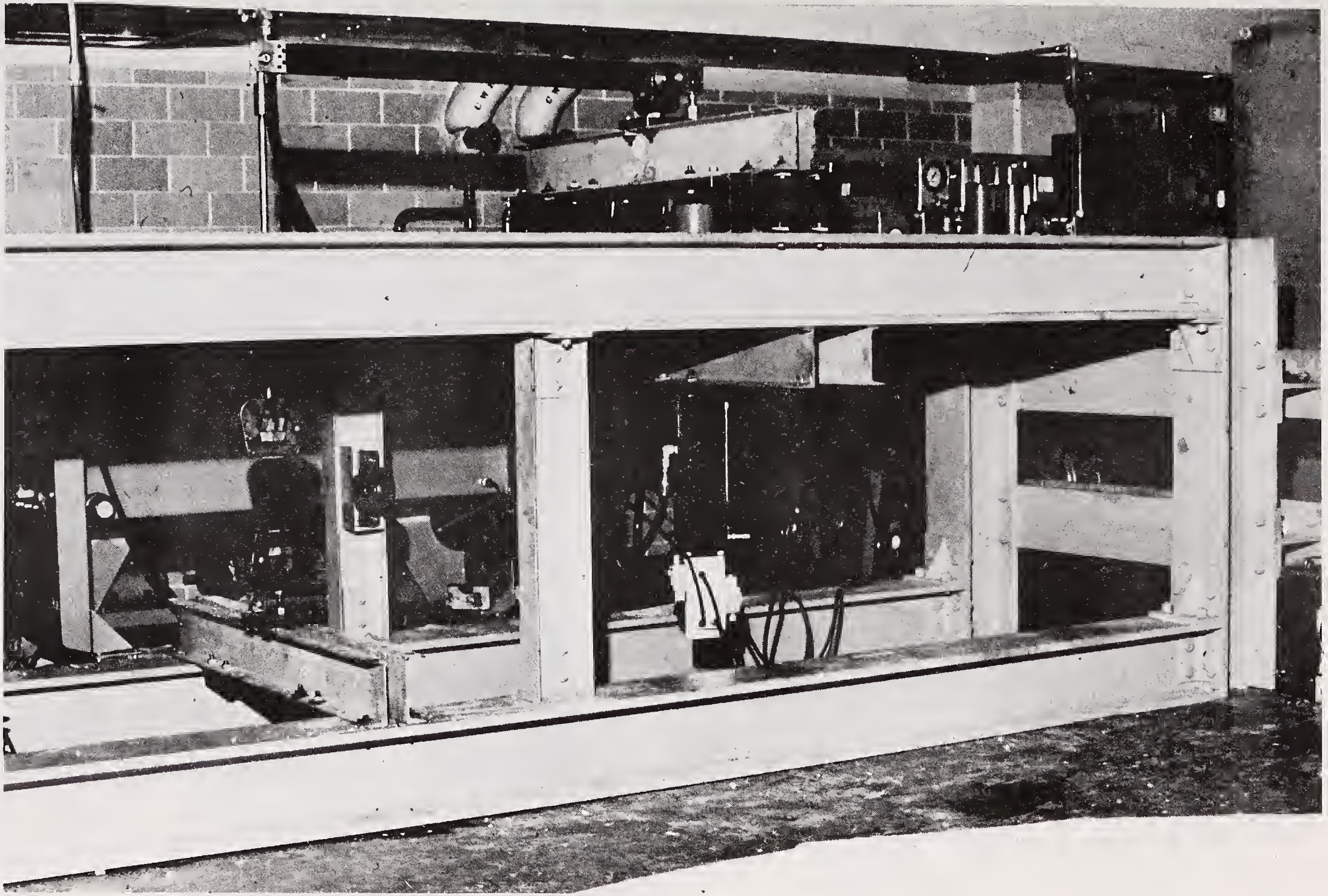


Figure 2 - Tensile fatigue test set-up for roof membrane specimens.

pull rod which swivelled on a ball and socket joint. The lower grip was rigidly attached to the test frame. The test set-up is shown in Figure 2.

An aluminum tensile coupon with physical dimensions similar to the specimens was instrumented with resistance strain gages to check the amount of in-plane and out-of-plane bending introduced by the test system. Adjustments were made to the test system so that the bending strain in each direction was less than 5% of axial strain under static loading conditions.

The test system was calibrated to determine the correspondence between the machine set point dial setting and applied static loads to 400 lbf (1,800 N). A 500 lbf (2,200 N) capacity load cell was used for this purpose. The uncertainty of the static loads applied to the specimen was less than 1 percent of the prescribed load. Using techniques described by Robinson [4], the inertial effects of the lever arm on the applied waveform amplitude and shape were checked at frequencies up to 15 Hz. No qualitative distortional effects on the waveform were noted.

3.1.2 Flexural Fatigue

Three point bending (flexural) fatigue tests were run under controlled displacement conditions in a 50,000 lbf capacity (222,000 N) fatigue machine for tests at ambient conditions and a 2,000 lbf (9,900 N) capacity fatigue machine for tests at 0 ± 2°F (18 ± 1°C) (Figures 3a and 3b respectively). Applied displacements of each machine were checked quasistatically against readings from a dial gage graduated in 0.001 in (0.003 cm) increments. The differences between these readings and the prescribed deflections were less than 1 percent of the prescribed deflections.

3.2 Flexure Fixture

Flexural fatigue tests were performed in the fixture shown in Figure 4. The loading member and the end supports were made from 1.5-in (3.8-cm) diameter aluminum rod. The span length of the fixture was 7.0-in (17.8-cm). The specimens were restrained from slipping at the support by clamping pressure applied at the supports and by plates 0.094-in (0.02-cm) thick clamped to the ends of the specimen and wedged against the supports of the fixture. The ends of the specimen were allowed to rotate at the supports.

3.3 Environmental Chamber

Two test chambers were used for the tests at 0°F (-18°C). One chamber was made with a wood shell insulated internally and externally with 2-in (5-cm) thick insulating foam plastic; the other chamber was made from an insulating foam plastic. In both chambers all joints and edges were sealed to minimize leakage. Each chamber was conditioned

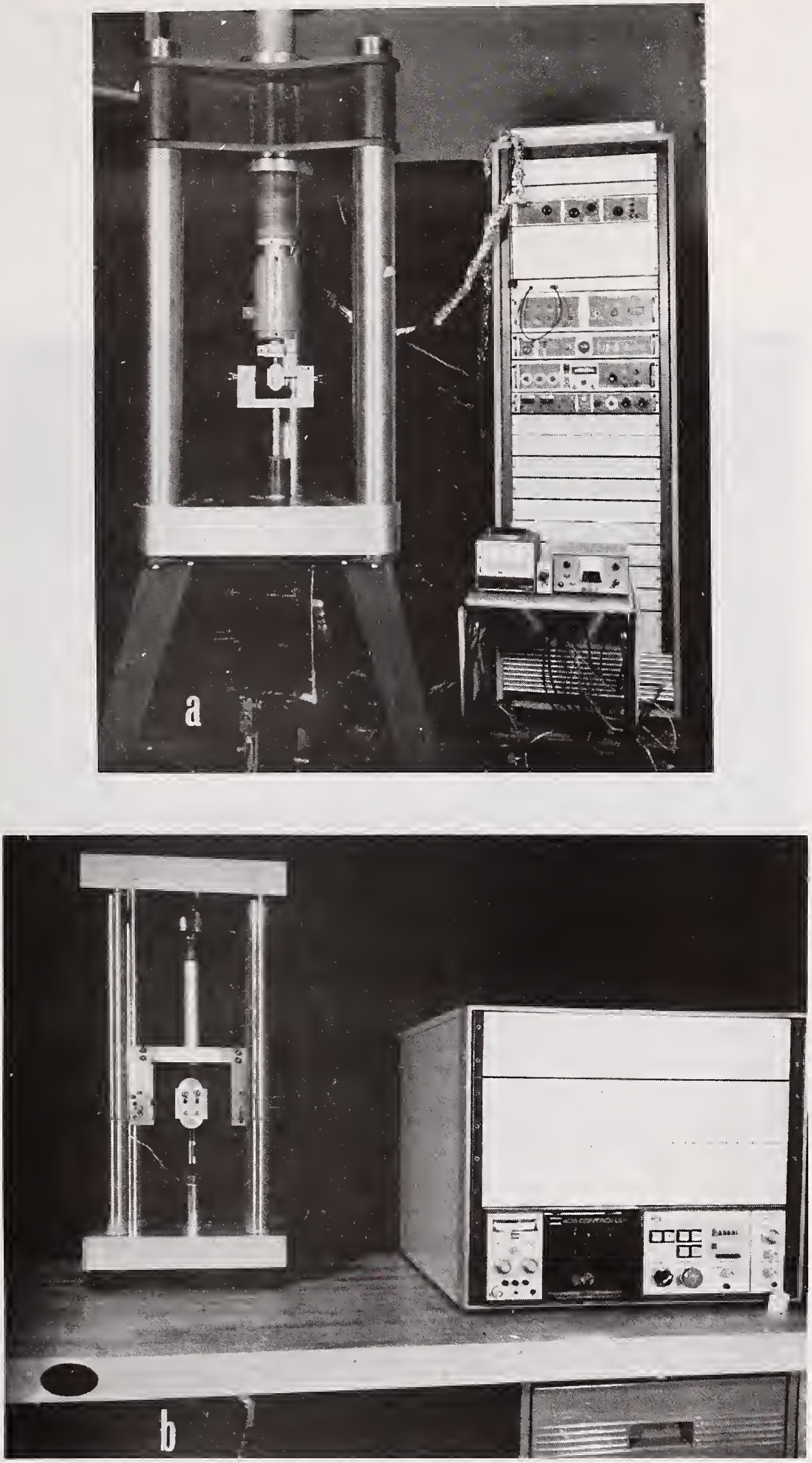


Figure 3 - Flexural fatigue test set-ups for roof membrane specimens.

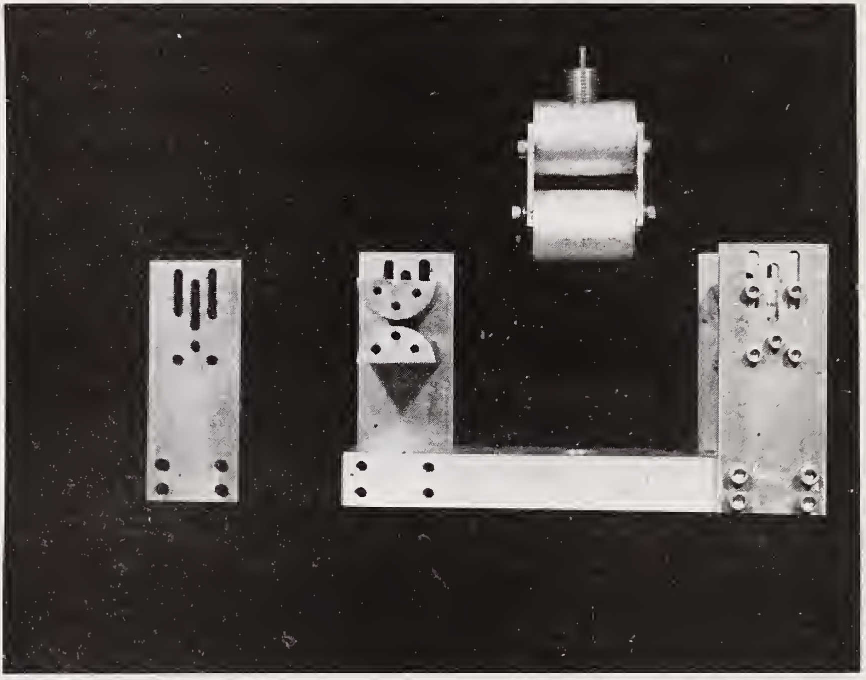


Figure 4 - Fixture used in testing roof membrane specimens in flexure.

using a commercial refrigeration unit and circulating fan. Temperature was measured with a thermocouple taped to the gage section of the specimen. Temperature was controlled and recorded by a time-proportioning, recording controller. An initial temperature between 0°F (-18°C) and -2°F (-19°C) with a time variation of 1°F (0.6°C) was used in each test. Temperatures were maintained within these limits for the duration of each test.

4. TEST PROCEDURES

Tensile fatigue tests and flexural fatigue tests were performed on four types of four ply built-up roof membranes. These tests were run at ambient laboratory conditions, generally 70 ± 2°F (21 ± 1°C), and at 0 ± 2°F (-18 ± 1°C). Triplicate tests were run at each of three load levels and at two temperatures on the four different types of membrane specimens. Specimens tested under ambient laboratory conditions were stored prior to testing at 42°F (6°C) while those tested at the lower temperature were stored at -6°F (-21°C) prior to testing. These storage conditions facilitated handling of the specimens and the environmental conditioning of the specimens to be tested at the cold environment.

4.1 Tensile Fatigue

All tensile fatigue tests were run under load control in the set-up shown in Figure 2. A specimen was placed in the grips and a small tensile load, 5 lbf (22 N), was applied. The specimen was held at this load level until it attained the desired test temperature. It was maintained under these conditions for an additional period of at least 30 minutes prior to the start of fatigue testing.

Fatigue loads were based on the average static strengths of similar specimens [1]. The peak fatigue loads were approximately 80, 60, and 40 percent of the average static strengths of specimens of each material type. The minimum load in the fatigue cycle was 10 percent of the maximum applied fatigue load. The cyclic load waveform was a haversine. Tests were run at frequencies of 10 Hz for tests at ambient laboratory conditions and 15 Hz for tests at 0°F (-18°C). Failure was defined as separation of the specimen into two pieces.

4.2 Flexural Fatigue

Roof membranes have very little flexural stiffness, which resulted in large deflections in the static flexural tests [1] at low loads. Therefore, it was decided to conduct the flexural fatigue tests under center-span displacement control. Test set-ups for flexural fatigue tests at ambient laboratory temperatures and 0 ± 2°F (-18 ± 1°C) are shown in Figures 3a and 3b respectively. Specimens were first clamped in the test fixture. The 0.010-in (0.03-cm) diameter copper wire, placed in the specimen during fabrication, was connected to the machine interlock completing an electrical circuit. Each specimen was held at zero displacement until it attained the desired test temperature, and then maintained at this temperature for 30 minutes prior to the start of the fatigue test.

Tests were run with positive and negative peak center-span displacements of 0.20, 0.15 and 0.125-in (0.51, 0.38 and 0.32-cm). These displacements were chosen to produce failures at about 5,000, 50,000 and 500,000 cycles respectively as based on preliminary test results using specimens fabricated from material B.

Test frequency was dictated by the available equipment. For tests at ambient laboratory temperatures, the test frequency was limited to 2, 3, and 4 Hz for positive and negative peak center-span displacements of 0.20, 0.15, and 0.125-in (0.51, 0.38, and 0.32-cm) respectively by the displacement-frequency characteristics of the 50,000 lbf (222,000 N) fatigue machine. At 0°F (-18°C), for tests in the 2,000 lbf (8,900 N) fatigue machine, frequency was not a limiting constraint. For these tests, restraint was imposed by the environmental chamber which could maintain temperature for only about 18 hours. For positive and negative peak center-span displacements of 0.20, 0.15, and 0.125-in (0.51, 0.38 and 0.32-cm) the low temperature tests were run at 7.5 Hz.

The cyclic waveform for all the flexure tests was a full sine wave cycled between the positive and negative peak displacement values. Specimens were cycled until failure. This occurred when the wire in the center of the specimen broke, interrupting the circuit to the machine interlock. Wire breakage occurred as damage propagated through the thickness of the specimen from the two outer felt plies to the two inner felt plies. Complete physical separation of the specimens into two parts did not necessarily result at this point, but irreparable damage was always evident and separation did occur within minimal additional effort.

A limited amount of data relating the static load at the peak displacement versus the number of fatigue cycles was taken for specimens being tested at ambient temperatures. These data were taken by intermittently stopping the flexural fatigue tests and recording static loads using a 75 lbf (330 N) load cell and associated instrumentation.

5. EXPERIMENTAL RESULTS

5.1 Tensile Fatigue

Specimen designations, test conditions and fatigue lifetimes for specimens run under load controlled tensile fatigue are given in Tables 2 and 3. Replicate specimens are grouped as indicated by a single digit appended to the specimen number. The median fatigue lifetime of each group of replicate specimens is indicated in the last column of each table. Graphical data based on the median fatigue lifetimes of these specimens are presented in Figures 5 through 8. Figures 5 and 6 represent

Table 2 - Results of Tensile Fatigue Tests on Roof Membrane Specimens

Specimen number	Percent of average static failure load	Cyclic load limits		Frequency	Temperature		Cycles to failure		
		lbf	N	Hz	°F	°C		median	
A-51-1	81	5.0-50.0	22-220	10	70	21	63900		
A-52-1	81	5.0-50.0	22-220	10	70	21	70600	70600	
A-53-1	81	5.0-50.0	22-220	10	72	22	71600		
A-57-2	57	3.5-35.0	16-160	10	72	22	252000	252000	
A-58-2	57	3.5-35.0	16-160	10	72	22	290000		
A-60-2	57	3.5-35.0	16-160	10	72	22	153000		
A-61-3	41	2.5-25.0	11-110	10	68	20	2540000		(1)
A-63-3	41	2.5-25.0	11-110	10	68	20	4220000	4220000	(1)
A-64-3	41	2.5-25.0	11-110	10	72	22	4250000		(1)
B-90-1	83	5.0-50.0	22-220	10	70	21	11200		
B-91-1	83	5.0-50.0	22-220	10	70	21	10700	10700	
B-93-1	83	5.0-50.0	22-220	10	70	21	6850		
B-86-2	58	3.5-35.0	16-160	10	70	21	64600		
B-94-2	58	3.5-35.0	16-160	10	70	21	80400	80400	
B-96-2	58	3.5-35.0	16-160	10	68	20	137000		
B-95-3	42	2.5-25.0	11-110	10	72	22	975000		
B-97-3	42	2.5-25.0	11-110	10	68	20	1110000	1110000	
B-98-3	42	2.5-25.0	11-110	10	68	20	1280000		
B-92-4	33	2.0-20.0	9-90	10	70	21	1150000	1150000	(1)
C-80-1	83	3.0-30.0	13-130	10	68	20	16300		
C-82-1	83	3.0-30.0	13-130	10	68	20	8420		
C-84-1	83	3.0-30.0	13-130	10	68	20	13200	13200	
C-85-2	55	2.0-20.0	9-90	10	68	20	101000		
C-86-2	55	2.0-20.0	9-90	10	68	20	103000	103000	
C-89-2	55	2.0-20.0	9-90	10	72	22	174000		
C-91-3	41	1.5-15.0	7-70	10	72	22	284000		
C-95-3	41	1.5-15.0	7-70	10	72	22	420000		
C-98-3	41	1.5-15.0	7-70	10	72	22	161000		
C-100-3	41	1.5-15.0	7-70	10	73	23	236000	236000	
C-90-3	41	1.5-15.0	7-70	10	72	22	142000		
D-92-1	86	6.0-60.0	27-270	10	70	21	1240	1240	
D-96-1	86	6.0-60.0	27-270	10	68	20	1000		
D-97-1	86	6.0-60.0	27-270	10	68	20	3930		
D-93-2	57	4.0-40.0	18-180	10	70	21	18200		
D-94-2	57	4.0-40.0	18-180	10	70	21	41200		
D-98-2	57	4.0-40.0	18-180	10	68	20	32900	32900	
D-95-3	43	3.0-30.0	13-130	10	72	22	157000		
D-99-3	43	3.0-30.0	13-130	10	68	20	708000		
D-100-3	43	3.0-30.0	13-130	10	68	20	267000	267000	
D-91-4	80	5.5-55.0	24-240	10	70	21	8440	8440	

(1) No visible evidence of specimen damage.

Table 3 - Results of Tensile Fatigue Tests on Roof Membrane Specimens

Specimen number	Percent of average static failure load	Cyclic load limits		Frequency	Temperature		Cycles to failure		
		lbf	N	Hz	°F	°C		median	
A-82-1	83	22-220	98-980	15	-1	-18	23		
A-81-1	83	22-220	98-980	15	-1	-18	230	126	
A-80-1	83	22-220	98-980	15	-1	-18	13		
A-92-1	83	22-220	98-980	15	0	-18	280		
A-79-2	59	15.5-155	69-690	15	-1	-18	396000		
A-87-2	59	15.5-155	69-690	15	-2	-19	1270000		
A-93-2	59	15.5-155	69-690	15	-2	-19	409000	409000	
A-90-3	42	11-110	49-490	15	-1	-18	2920000		(1)
A-94-3	42	11-110	49-490	15	-2	-19	3330000	3330000	(1)
A-91-3	42	11-110	49-490	15	-2	-19	5950000		(1)
B-56-1	82	22-220	98-980	15	-1	-18	1150	1150	
B-67-1	82	22-220	98-980	15	-2	-19	650		
B-69-1	82	22-220	98-980	15	-2	-19	1170		
B-68-2	58	15.5-155	69-690	15	-2	-19	212000		
B-55-2	58	15.5-155	69-690	15	-1	-18	98200		
B-61-2	58	15.5-155	69-690	15	-2	-19	197000	197000	
B-65-3	41	11-110	49-490	15	-3	-19	2060000		(1)
B-57-3	41	11-110	49-490	15	-2	-18	4540000		(1)
B-58-3	41	11-110	49-490	15	-3	-19	4530000	4530000	(1)
C-73-1	82	15-150	67-670	15	-1	-18	110		
C-102-1	82	15-150	67-670	15	-1	-18	2000		
C-65-1	82	15-150	67-670	15	-1	-18	1000	550	
C-60-1	82	15-150	67-670	15	-1	-18	55		
C-61-2	58	10.5-105	47-470	15	-1	-18	180000	199000	
C-62-2	58	10.5-105	47-470	15	-1	-18	174000		
C-63-2	58	10.5-105	47-470	15	-1	-18	218000		
C-64-2	58	10.5-105	47-470	15	-1	-18	499000		
C-69-2	41	7.5-75	33-330	15	-1	-18	2480000		(1)
C-66-3	41	7.5-75	33-330	15	-1	-18	4820000		(1)
C-67-3	41	7.5-75	33-330	15	-2	-19	3550000	3550000	(1)
D-81-1	80	11.5-115	51-510	15	-1	-18	15		
D-65-1	80	11.5-115	51-510	15	-1	-18	140		
D-67-1	80	11.5-115	51-510	15	-1	-18	28	28	
D-72-1	80	11.5-115	51-510	15	-1	-18	7		
D-77-1	80	11.5-115	51-510	15	-1	-18	370		
D-82-2	56	8-80	36-360	15	-1	-18	26800		
D-66-2	56	8-80	36-360	15	-1	-18	34600	58800	
D-64-2	56	8-80	36-360	15	-1	-18	126000		
D-63-2	56	8-80	36-360	15	0	-18	82000		
D-68-3	38	5.5-55	24-240	15	-1	-18	1230000		(1)
D-70-3	38	5.5-55	24-240	15	-2	-19	4460000		(1)
D-73-3	38	5.5-55	24-240	15	-2	-19	3290000	3290000	(1)

(1) No visible evidence of specimen damage.

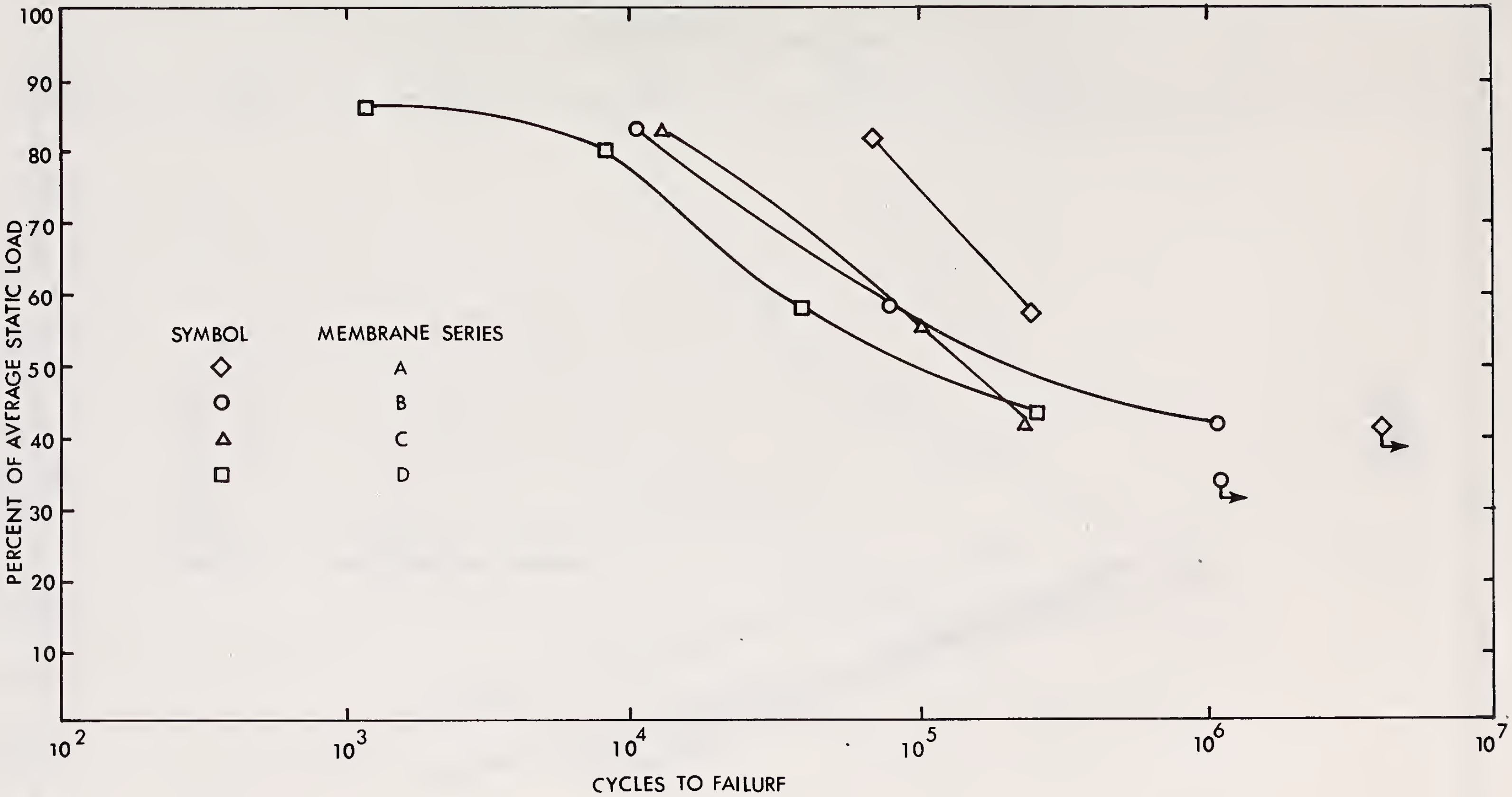


Figure 5 - Median fatigue lifetime of specimens versus percent of the average static failure load at 70 °F (21 °C).

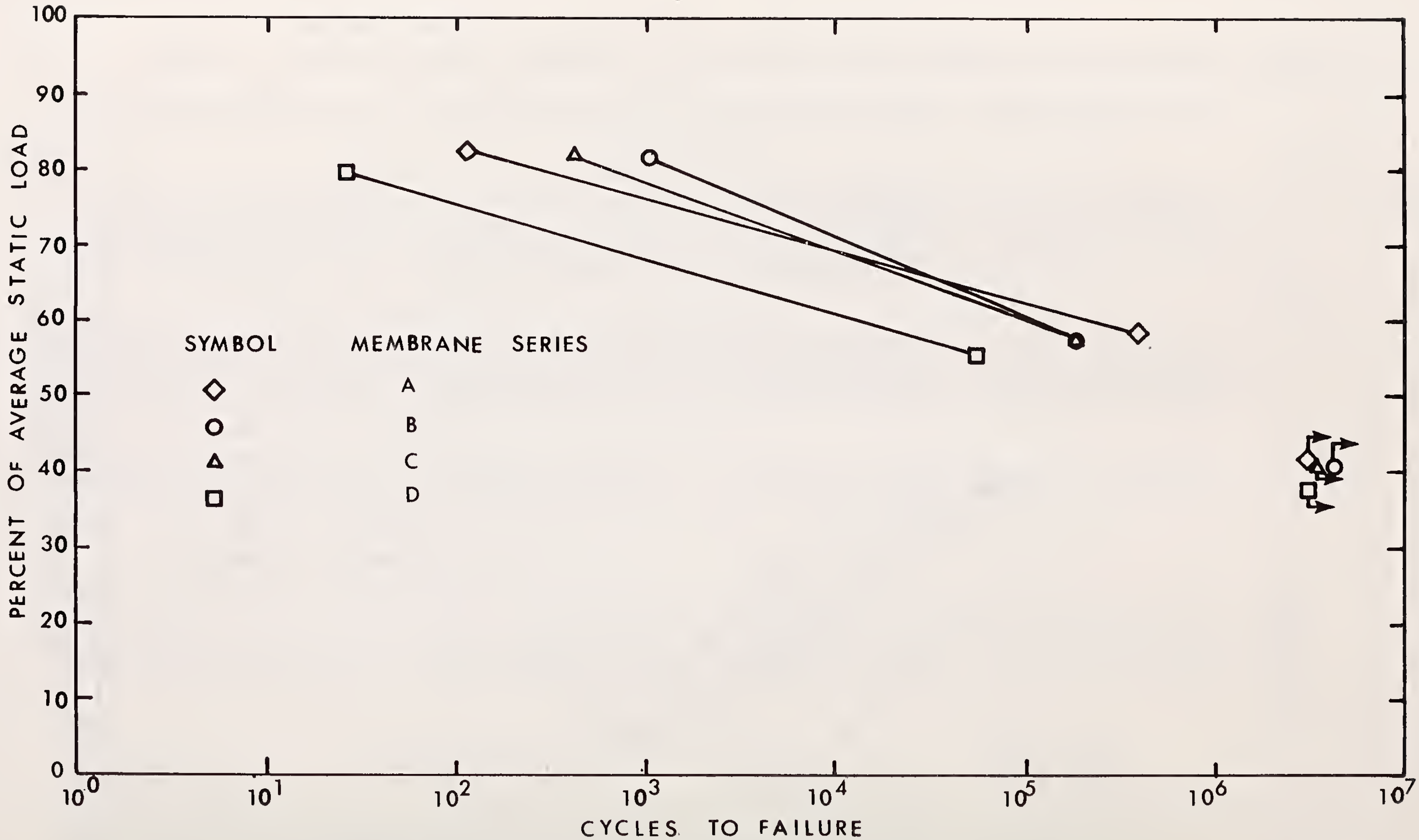


Figure 6 - Median fatigue lifetime of specimens versus percent of the average static failure loads at 0 °F (-18 °C).

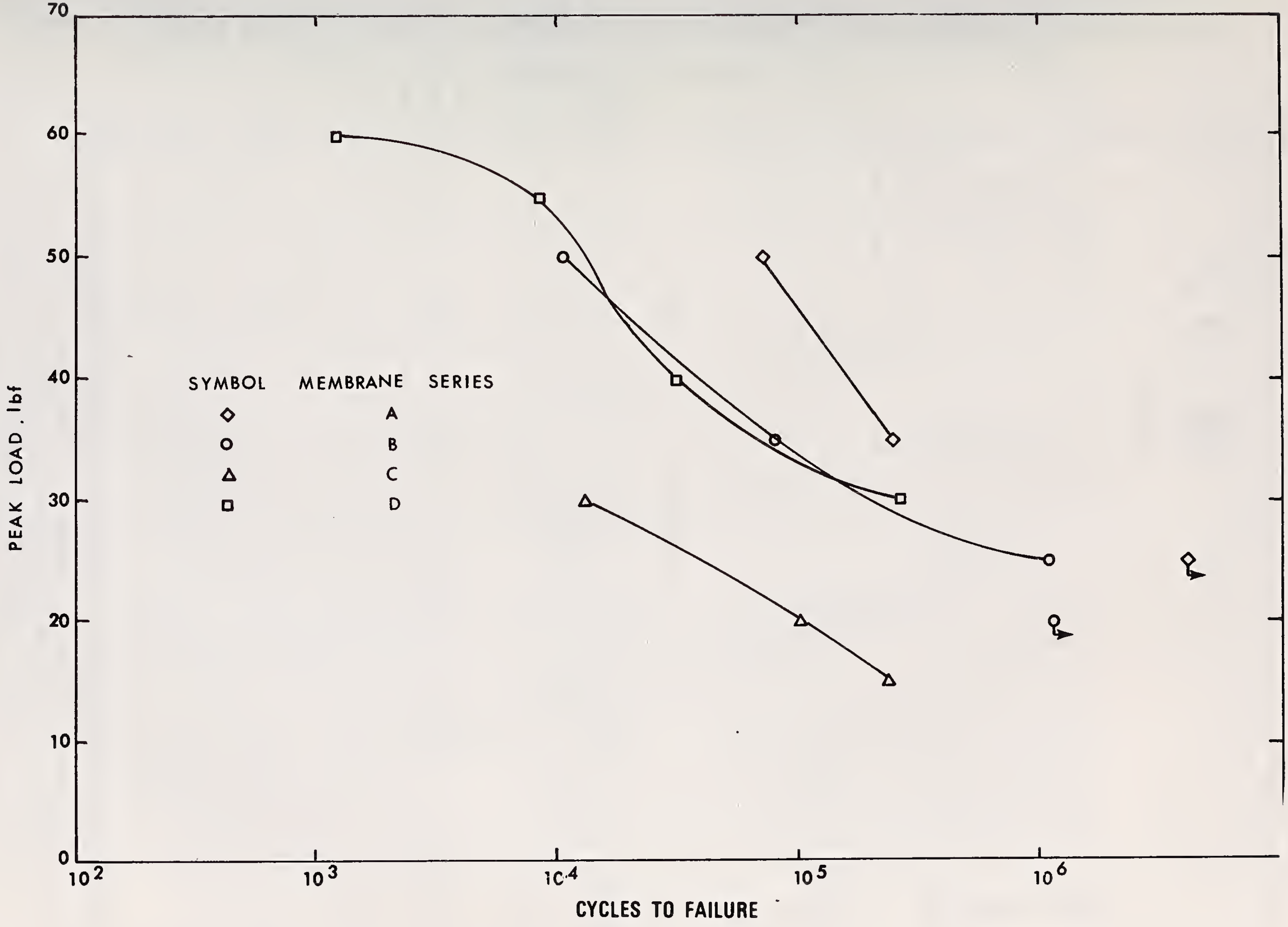


Figure 7 - Median fatigue lifetime of specimens versus applied peak fatigue load at 70 °F (21 °C).

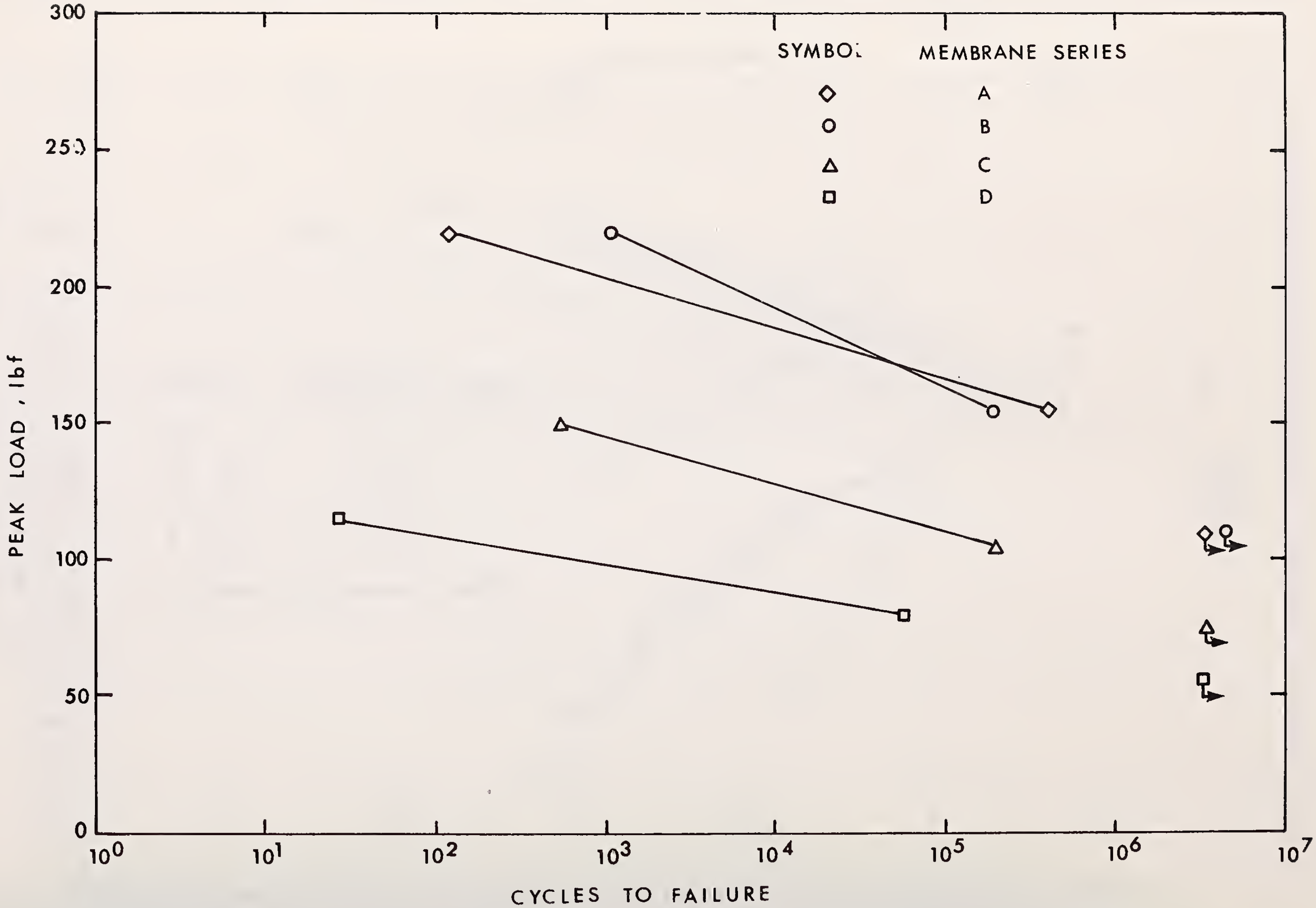


Figure 8 - Median fatigue lifetime of specimens versus applied peak fatigue load at -0 °F (-18 °C).

comparative data of the median fatigue lifetimes based on percentages of the average static strength for each membrane type, while Figures 7 and 8 represent comparative data of the median fatigue lifetimes based on the actual peak fatigue loads at ambient temperatures and 0°F (-18°C) respectively.

5.2 Flexural Fatigue

Specimen designations, test conditions, and fatigue lifetimes for specimens run under displacement controlled flexural fatigue are given in Tables 4 and 5. Replicate specimens are grouped as indicated by a single digit appended to the specimen number. The median fatigue lifetime of each group of replicate specimens is indicated in the last column of each table. Graphical data based on the median fatigue lifetimes of these specimens are presented in Figures 9 through 12. Figures 9 and 10 represent comparative data of the median fatigue lifetimes based on percentages of the maximum static midspan deflection for each membrane type [1], while Figures 11 and 12 represent comparative data of the median fatigue lifetimes based on the applied peak midspan deflections at ambient laboratory temperatures and 0°F (-18°C) respectively. Compliance data relating the static flexural loads to the number of fatigue cycles for a given displacement are given in Table 6.

6. DISCUSSION AND RECOMMENDATIONS

Fatigue loading in a roofing membrane encompasses the spectrum from low cycle, large amplitude fatigue caused by foot traffic to wind induced high frequency vibrations at small amplitudes as well as thermally induced load cycling. Therefore, performance guidelines for roof membranes should consider their fatigue properties.

Membrane material types A, B, C, and D were chosen to be evaluated since they represent commonly used roof membranes with known in-service performance histories. Generally, four-ply roof membranes similar to those designated as A, B, and C have demonstrated satisfactory performance in-service under varying climatic conditions and roof loadings. All of the membranes have experienced some degree of splitting in cold climates. However, splitting appears to have been more prevalent in membranes having low tensile strengths and large coefficients of thermal expansion such as some two-ply membranes and some of those similar to type D. A new type of glass felt having a higher tensile strength compared to the other roofing felts [1] has been developed recently. Although preliminary static tensile and flexural data have been favorable for membranes fabricated from this felt it has not been evaluated in fatigue.

The following recommendations present performance guidelines based on the data available at this point. Minimum levels of acceptable performance were selected such that membrane types A, B, and C satisfied the proposed performance criteria. Roof membranes made from other materials that equal or exceed these fatigue performance guidelines

Table 4 - Results of Flexure Fatigue Tests on Roof Membrane Specimens

Specimen number	Peak deflection		Percent of static deflection at maximum load	Frequency	Temperature		Cycles to failure	
	in	cm	percent	Hz	°F	°C		median
A-58W-1 (1)	0.20	0.51	18	2.0	72	22	1160	1160
A-65W-1	0.20	0.51	18	2.0	72	22	540	
A-64W-1	0.20	0.51	18	2.0	72	22	2620	
A-68W-2	0.15	0.38	14	3.0	73	23	8260	8260
A-69W-2	0.15	0.38	14	3.0	73	23	10900	
A-62W-2	0.15	0.38	14	3.0	72	22	6200	
A-70W-3	0.125	0.32	11	4.0	72	22	12800	12800
A-71W-3	0.125	0.32	11	4.0	72	22	14300	
A-72W-3	0.125	0.32	11	4.0	72	22	11200	
B-73W-1	0.25	0.64	31	2.0	72	22	1170	
B-72W-1	0.25	0.64	31	2.0	72	22	7730	
B-69W-1	0.25	0.64	31	2.0	72	22	2660	2660
B-70W-2	0.20	0.51	25	2.0	72	22	4880	
B-67W-2	0.20	0.51	25	2.0	72	22	7370	
B-66W-2	0.20	0.51	25	2.0	72	22	7260	7260
B-62W-3	0.15	0.38	19	3.0	72	22	60200	
B-63W-3	0.15	0.38	19	3.0	68	20	20600	
B-64W-3	0.15	0.38	19	3.0	70	21	51100	51100
B-59W-4	0.125	0.32	15	4.0	72	22	65000	
B-58W-4	0.125	0.32	15	4.0	68	20	80500	80500
B-54W-4	0.125	0.32	15	4.0	70	21	99400	
B-65W-5	0.10	0.25	12	4.0	72	22	703000	703000(2)
C-65W-1	0.20	0.51	25	2.0	72	22	1850	
C-64W-1	0.20	0.51	25	2.0	72	22	1580	
C-66W-1	0.20	0.51	25	2.0	72	22	1780	1780
C-69W-2	0.15	0.38	19	3.0	72	22	6340	
C-73W-2	0.15	0.38	19	3.0	72	22	13800	14100
C-71W-2	0.15	0.38	19	3.0	72	22	14400	
C-68W-2	0.15	0.38	19	3.0	66	19	5920	
C-70W-3	0.125	0.32	15	4.0	70	21	53700	
C-74W-3	0.125	0.32	15	4.0	72	22	16200	
C-61W-3	0.125	0.32	15	4.0	72	22	39900	39900
D-61W-1	0.20	0.51	33	2.0	72	22	12100	12100
D-60W-1	0.20	0.51	33	2.0	72	22	3880	
D-58W-1	0.20	0.51	33	2.0	70	21	14100	
D-57W-2	0.15	0.38	25	3.0	72	22	61100	
D-55W-2	0.15	0.38	25	3.0	72	22	34800	34800
D-53W-2	0.15	0.38	25	3.0	72	22	25900	
D-50W-3	0.125	0.32	20	4.0	72	22	669000	(2)
D-59W-3	0.125	0.32	20	4.0	70	21	653000	653000(2)
D-54W-3	0.125	0.32	20	4.0	72	22	590000	(2)

(1) W indicates specimens fabricated with copper wire inserted between the center plies.

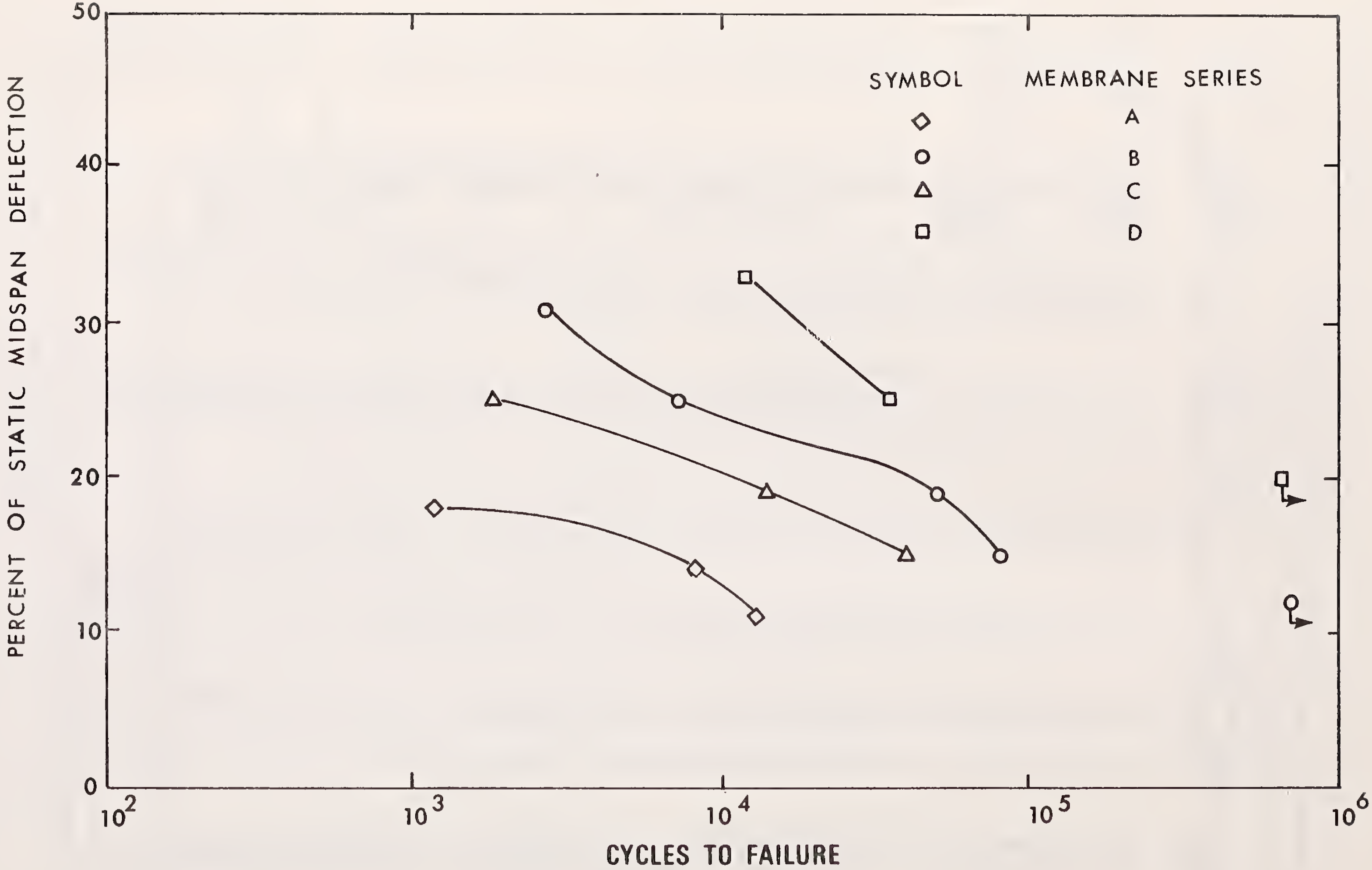
(2) No visible evidence of specimen damage.

Table 5 - Results of Flexure Fatigue Tests on Roof Membrane Specimens

Specimen number	Peak deflection		Percent of maximum static deflection	Frequency	Temperature		Cycles to failure		
	in	cm	percent	Hz	°F	°C		median	
A-56W-1[1]	0.20	0.51	50	7.5	0	-18	16000	16000	(2)
A-61W-1	0.20	0.51	50	7.5	0	-18	16100		
A-60W-1	0.20	0.51	50	7.5	0	-18	790		
A-73W-2	0.15	0.38	38	7.5	0	-18	60		
A-55W-2	0.15	0.38	38	7.5	-1	-18	60	60	
A-57W-2	0.15	0.38	38	7.5	-0.5	-18	80		
A-50W-3	0.125	0.32	30	7.5	-2	-19	146000	146000	(2)
A-53W-3	0.125	0.32	30	7.5	-2	-19	19400		
A-52W-3	0.125	0.32	30	7.5	-2	-19	194000		
B-51W-1	0.20	0.51	50	7.5	-1.5	-19	30		
B-76W-1	0.20	0.51	50	7.5	-1.5	-19	40	40	
B-77W-1	0.20	0.51	50	7.5	0	-18	190		
B-83W-2	0.15	0.38	38	7.5	-1.5	-19	70		
B-74W-2	0.15	0.38	38	7.5	-1	-18	21100		
B-82W-2	0.15	0.38	38	7.5	-1.5	-19	230	230	
B-78W-2	0.15	0.38	38	4.0	0	-18	13150		
B-85W-3	0.125	0.32	30	7.5	0	-18	35000		
B-81W-3	0.125	0.32	30	7.5	-1	-18	740		
B-79W-3	0.125	0.32	30	7.5	-1	-18	24200	24200	
C-57W-1	0.20	0.51	67	7.5	-1.5	-19	40		
C-74W-1	0.20	0.51	67	7.5	0	-18	10	25	
C-53W-2	0.15	0.38	50	7.5	-1.5	-19	20		
C-83W-2	0.15	0.38	50	7.5	0	-18	50	50	
C-80W-2	0.15	0.38	50	7.5	0	-18	50		
C-52W-3	0.125	0.32	40	7.5	-1	-18	70		
C-84W-3	0.125	0.32	40	7.5	-0.5	-18	4530		
C-81W-3	0.125	0.32	40	7.5	-0.5	-18	250	250	
D-75W-1	0.20	0.51	67	7.5	0	-18	90		
D-74W-1	0.20	0.51	67	7.5	-0.5	-18	1380		
D-82W-1	0.20	0.51	67	7.5	-1	-18	500	500	
D-72W-2	0.15	0.38	50	7.5	-2	-19	10600		
D-70W-2	0.15	0.38	50	7.5	-0.5	-18	16000	13000	
D-78W-2	0.15	0.38	50	7.5	0	-18	15500		
D-71W-2	0.15	0.38	50	7.5	-0.5	-18	9190		
D-76W-3	0.125	0.32	40	7.5	-1.5	-18	66800	66800	
D-79W-3	0.125	0.32	40	7.5	-1.5	-18	48900		
D-83W-3	0.125	0.32	40	7.5	-2	-19	222000		

(1) W indicates specimens fabricated with copper wire inserted between the center plies.

(2) Delamination of felts on initial loadings.



Figue 9 - Median fatigue lifetime of specimens versus percent of maximum static deflection at 70 °F (21 °C).

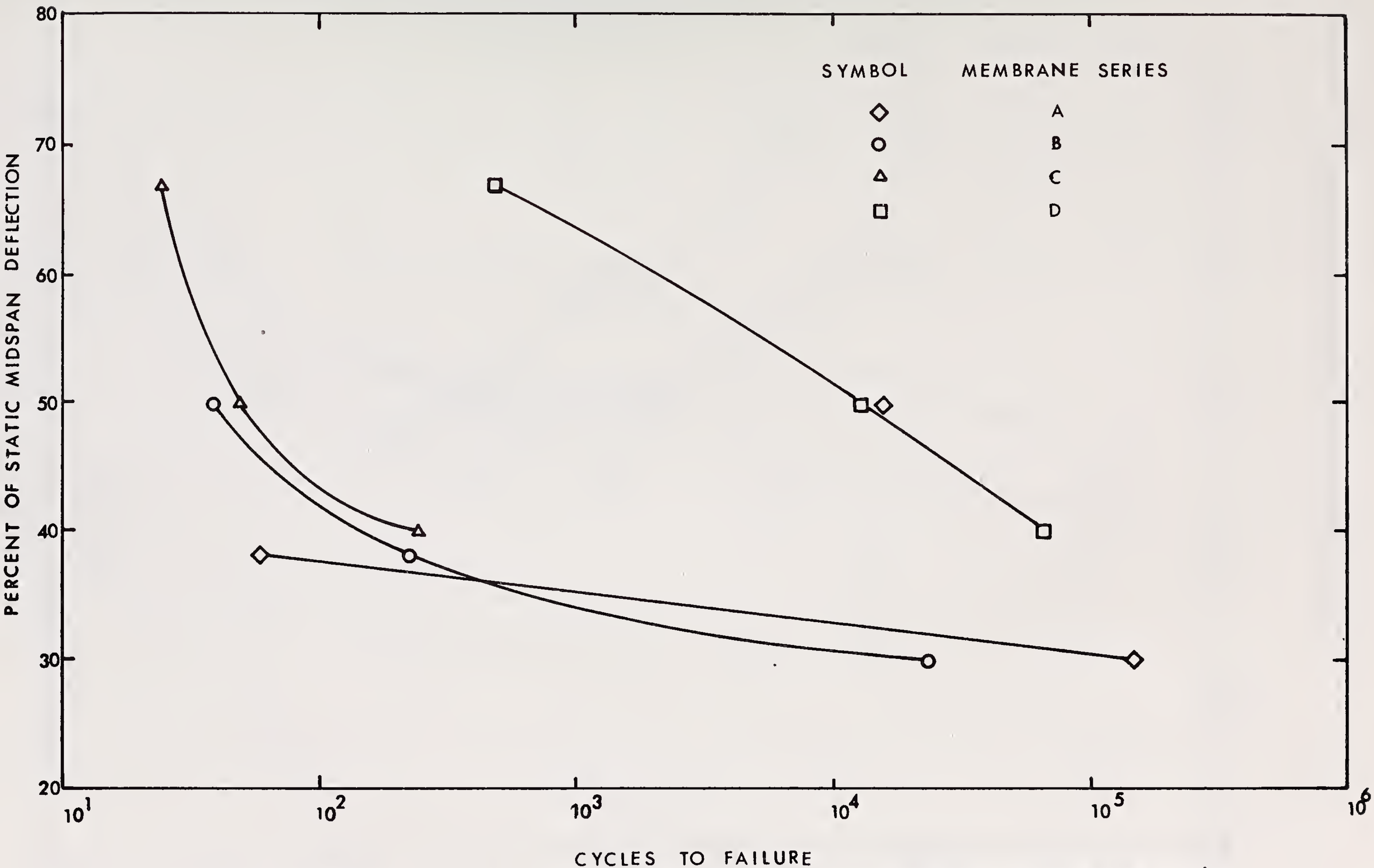


Figure 10 - Median fatigue lifetime of specimens versus percent of maximum static deflection at 0 °F (-18 °C).

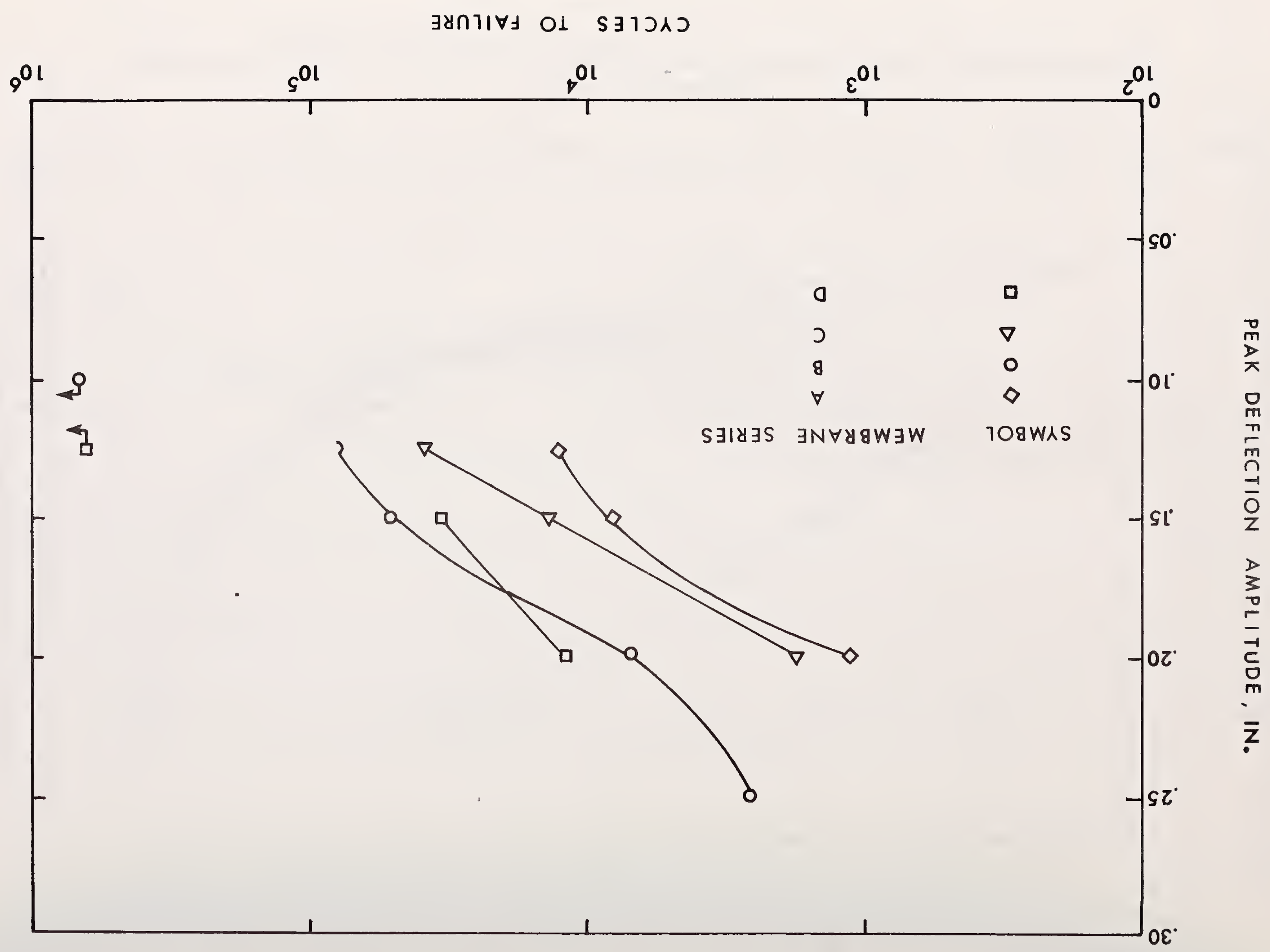


Figure 11 - Median fatigue lifetime of specimens versus applied deflection at 70 °F (21 °C).

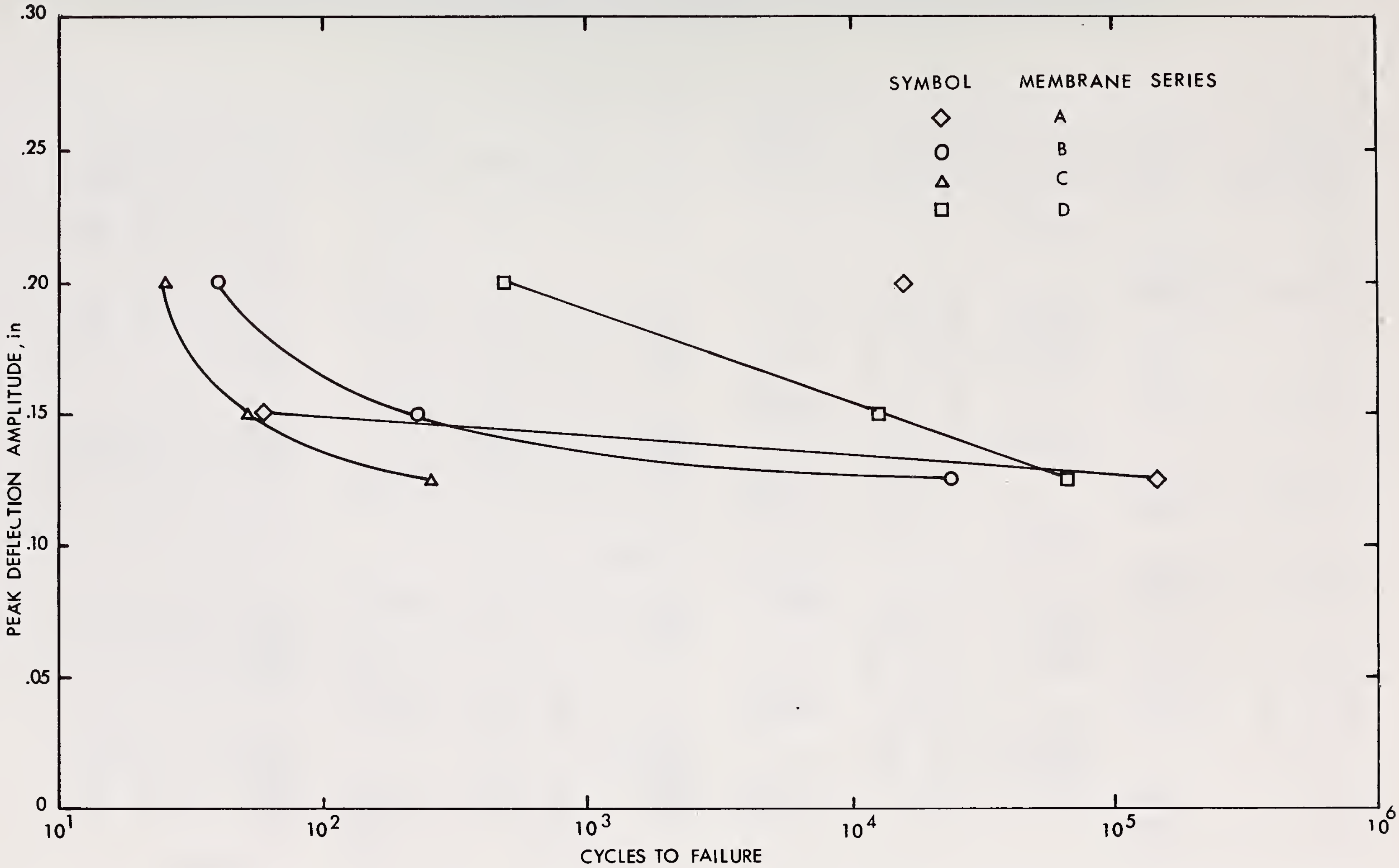


Figure 12 - Median fatigue lifetime of specimens versus applied peak deflection at 0 °F (-18 °C).

Table 6 - Data Relating Static Load to Peak Deflection After Fatigue Cycling at 70°F (21°C)

Peak deflection in	Peak deflection cm	Specimen number	Cycles	Static load lbf	Static load N	Specimen number	Cycles	Static load lbf	Static load N	Specimen number	Cycles	Static load lbf	Static load N
0.20	0.51	A-58W-1	1	24	107	A-65W-1	1	24	107	A-64W-1	1	20	89
			1163	0	0		500	13	58		1670	13	58
							540	0	0		2620	0	0
0.15	0.38	A-68W-2	1	12.5	56	A-69W-2	1	10	44	A-62W-2	1	19	84
			2000	10	44		3500	8	36		130	15	67
			7200	5	22		9500	3.5	16		2300	13	58
			8257	0	0		10900	0	0		6200	0	0
0.125	0.32	A-70W-3	1	12	53	A-71W-3	1	10	44	A-72W-3	1	12	53
			12800	0	0		8600	9	40		1600	10.5	47
							12000	4	18		5300	9	40
							14300	0	0		11200	0	0
0.20	0.51	B-66W-2	1	13	58								
			4000	6	27								
			7260	0	0								
0.15	0.38	B-62W-3	1	10	44	B-63W-3	1	12	53	B-64W-3	1	10	44
			16000	9	40		2000	5	22		11000	6.5	29
			40000	5.5	24		20600	0	0		22000	6	27
			60200	0	0						51100	0	0
0.125	0.32	B-59W-4	1	7.5	33	B-58W-4	1	8	36	B-54W-4	1	9	40
			14000	7	31		10000	8	36		2500	7.5	33
			26000	5	22		19400	7	31		18200	6.5	29
			52000	3	13		52000	4	18		45000	5.5	29
			65000	0	0		59700	3	13		59000	5.5	24
							80500	0	0		99400	0	0

Continued

Table 6 - Data Relating Static Load to Peak Deflection After Fatigue Cycling at 70°F (21°C)

Peak deflection		Specimen number	Cycles	Static load		Specimen number	Cycles	Static load		Specimen number	Cycles	Static load	
in	cm			lbf	N			lbf	N			lbf	N
0.20	0.51	C-65W-1	1	9	40	C-64W-1	1	9	40	C-66W-1	1	10	44
			1850	0	0		1580	0	0		600	5	22
											1780	0	0
0.15	0.38	C-69W-2	1	9	40	C-73W-2	1	8	36	C-71W-2	1	7	31
			6338	0	0		1300	5	22		1000	5	20
							2200	4	18		10000	3	13
							3280	3	13		14400	0	0
							13800	0	0				
0.125	0.32	C-74W-3	1	7.5	33	C-70W-3	1	6	27	C-61W-3	1	6	27
			5000	3.5	16		10000	3	13		11700	4	18
			16172	0	0		33500	3	13		31000	2.5	11
							53700	0	0		39900	0	0
0.20	0.51	D-61W-1	1	12	53	D-60W-1	1	12	53	D-58W-1	1	15	67
			4400	8.5	38		3900	0	0		3600	8	36
			12100	0	0						14100	0	0
0.15	0.38	D-57W-2	1	8	36	D-55W-2	1	10	44	D-53W-2	1	8	36
			8500	7	31		7000	8	36		6000	7	31
			16000	7	31		18600	6	27		20500	4	18
			61100	0	0		34755	0	0		25900	0	0
0.125	0.32	D-50W-3	1	6	27	D-59W-3	1	6	27	D-54W-3	1	6.5	29
			8000	5	22		58000	5	22		8900	6	27
			25600	5	22		30100	5	22		272000	5	22
			52000	5	22		336000	5	22		310000	4	18
			77000	4	18						364000	4	18

possess adequate material properties in fatigue to allow their consideration as suitable roof membrane materials. The fact that these guidelines may not represent the absolute minimum for membrane material properties in fatigue is a question that can be resolved only by further qualitative in-service testing.

The tensile fatigue properties of the roof membranes were closely related to the static tensile strength of the roof membrane. In-service the largest tensile forces on the roof membrane probably occur during the low cycle fatigue due to thermal cycling. Fortunately, the static tensile strengths of roof membranes A, B, and C at 0°F (-18°C) are more than three times their strengths at 70°F (21°C). This is probably due to the increased stiffness of the membrane matrix material at low temperatures. Thus, performance guidelines should be stated in terms of test results at 0°F (-18°C). Based on the available data, it is concluded that an adequate tensile fatigue performance criterion for roof membrane specimens requires a fatigue lifetime of at least 10^5 tension-tension cycles at a peak cyclic test load of 100 lbf (440 N) at 0°F (-18°C). Furthermore, this criterion should be augmented in terms of the load carrying capability of the felt material which is better reflected in the data at 70°F (21°C), at which temperature the matrix material has softened considerably. This data indicates an adequate lifetime performance criterion of 10^5 tension-tension cycles at a peak cyclic test load of 20 lbf (89 N).

The performance criteria for roof membranes subjected to flexural fatigue are not as clearly defined. Large amplitude deflections of some roof membranes at 0°F (-18°C) result in data scatter that is difficult to analyze. In particular, the brittle glassy nature of the coal tar matrix in membrane series A resulted in felt delamination at a peak deflection amplitude of 0.20-in (0.51-cm) with a simultaneous shattering and loss of the matrix material. This loss of material effectively relaxed the remaining felt plies thus lowering the applied loads to the specimens and affecting the amount of fatigue damage and the medium of damage propagation. This is shown by the high lifetime points in both Figures 10 and 12 for material A. In service, this matrix material remains in situ and reforms its adhesive bond with the felts as the temperature rises. This healing process is a desirable characteristic of the coal tar roofing membrane.

The trends of medium flexural fatigue lifetime data are presented in Figures 11 and 12. Based on these, the recommended performance criterion for the flexural fatigue properties of membrane specimens requires a fatigue lifetime of 10^4 cycles at an alternating positive and negative peak midspan deflection of 0.125-in (0.32-cm) at 70°F (21°C). At 0°F (-18°C) a fatigue lifetime of 250 cycles at an alternating positive and negative peak midspan deflection of 0.125-in (0.32-cm) represents a minimum criterion.

6.1 Proposed Performance Criteria

The minimum performance criteria for roof membrane specimens subjected to fatigue are summarized below.

6.1.1 Tensile Fatigue

Based on the available data, minimum tensile fatigue performance criteria for the membrane types tested require a fatigue lifetime of 10^5 tension-tension cycles at a peak cyclic test load of 100 lbf (440 N) at 0°F (-18°C) and 10^5 tension-tension cycles at a peak cyclic test load of 20 lbf (89 N) at 70°F (21°C).

6.1.2 Flexural Fatigue

Based on the available data, minimum flexural fatigue performance criteria for the membrane types tested require fatigue lifetimes of 10^4 and 250 cycles at an alternating positive and negative peak midspan deflection of 0.125-in (0.32-cm) for test temperatures of 70°F (21°C) and 0°F (-18°C) respectively.

The observations stated above and the recommended performance criteria are based on results of tests on four ply membrane specimens (ASTM Designation: D2523-70) with the longitudinal axis oriented in the across machine direction.

7. ACKNOWLEDGMENT

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Tensile and flexural fatigue tests were performed on built-up roof membrane specimens (ASTM Designation: D2523-70) fabricated from four different material systems. The tensile fatigue tests were run under cyclic load control conditions while specimens tested in flexural fatigue were run under cyclic midspan displacement control. Tests were run at ambient laboratory conditions, generally 70 ± 2°F (21 ± 1°C), and at 0 ± 2°F (-18 ± 1°C). Curves based on the experimental results are plotted relating the peak load or displacement to the median fatigue lifetimes for specimens fabricated from each material. Performance criteria for roof membranes subject to fatigue loading are recommended.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Bituminous roof membranes; fatigue testing; flexural fatigue; performance criteria; roofing; temperature effects; tensile fatigue; test methods.

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NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N. W., Wash. D. C. 20056.

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