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8 JUNE 1972

SUMMARY OF TEST RESULTS FOR ALUMINUM ALLOY
BOX BEAM FATIGUE PROGRAM, TEST PHASES
I-IV

FINAL REPORT
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ABSTRACT

The results of a four-phase fatigue program for bending tests of 7075-T6 aluminum alloy box beams for positive loads only, and for positive and negative loads for both constant and variable load amplitudes are presented. The relative damaging effect of four airplane flight-maneuver loads spectra was determined, and the effects on fatigue life for variations in spectrum block size, stress level, stress direction, and load sequence were established and the results reported on.

When compared to full-scale aircraft structures of like material under constant-amplitude unidirectional loading on a percent of ultimate strength basis the beams represented the upper bound of those data for full-scale structures and exhibited similar fatigue characteristics. The beams were thus established as a suitable idealized structure for the investigation of those parameters which affect the structural fatigue life.

The smallest feasible block size should be used for the tests of full-scale structures. The 20-hour block size under fixed-sequence loading was found to most closely simulate random-sequence loading, which approximates in flight loading.

Qualitatively, the significant effects of the parameter variations on fatigue life can be attributed to the compressive residual stresses produced at the edges of the fastener holes by the application of the highest spectrum loads and the subsequent changes that occur in these residual stresses.

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INTRODUCTION

An initial fatigue investigation by the National Bureau of Standards (NBS), reference 1, resulted in the design of a simple box beam structure of 7075-T6 aluminum alloy. The load-lifetime results obtained in bending for this beam specimen fell within the scatter band of full-scale structures data available at that time. A second fatigue investigation performed by the NBS, reference 2, using box beams of identical design further established that the bending fatigue characteristics were similar to those of typical full-scale aircraft structures of the same material.

Because of the relative economy in fabrication, the speed in testing, and the apparent similarity in characteristics between the beam structure and practical full-scale 7075-T6 aluminum alloy structures, an extensive study of the fatigue characteristics of the NBS designed 7075-T6 aluminum-alloy box beams was undertaken in late 1960 by the Aero Structures Department. This unit is now the Aero Structures Division of the Air Vehicle Technology Department (AVTD). The proper definition of parameters affecting the life of a structure is essential to the attainment of structural reliability, the primary goal in the design and analysis of aircraft structures.

It is impractical to test full-scale structures in sufficient quantity to obtain statistically valid data for parametric definitions; therefore, the establishment of the box beam program fulfilled this need.

The overall objective of this investigation was to provide structural fatigue data that could be used in the design, analysis, and test of complete aircraft to obtain more assurance of structural reliability. Constant and variable-amplitude fatigue tests were performed to determine the following:

1. The shape of the load-lifetime curve at the extremely short life end.
2. The relative damaging effects of the maneuver loads spectra specified as spectra A, B, and C in reference 3 (MIL-A-8866).
3. The effects of the test spectrum block size.
4. The effect of stress level.
5. The effect of load sequence within each block.
6. The effect of stress reversals

7. The validity of various cumulative damage hypotheses for predicting the lives of structures.

The experimental work for the program was divided into four phases.

Phase I--Determination of constant-and variable-load-amplitude fatigue test data for unidirectional loading. Lo-hi fixed-sequence loading was used for load spectrum tests.

Phase II--Determination of effects on life due to randomization of loads within the loading blocks for unidirectional loading. Load spectrum tests were identical to those of Phase I except that the load sequence within the loading blocks was randomized on a cycle by cycle basis.

Phase III--Determination of effects on life of combined positive and negative loading for constant-and variable-load-amplitude fatigue tests. Lo-hi and hi-lo fixed-sequence loading was used for the load spectrum tests. Randomization of loads on a cycle by cycle basis within the loading blocks was also investigated.

Phase IV--The determination of the effects on life of extended block size and limit-load-stress level ranges for Spectrum A under lo-hi, fixed-sequence unidirectional loading.

The Phases III and IV data are to be considered preliminary in nature until final review and analysis is completed. A final report will be issued subsequent to this report which will contain the analyses of data for Phases III and IV and the entire program.

TEST SPECIMENS

The beams used in this program, as stated previously, were designed by the NBS. The design of the test specimen is shown in figure 1. Design details of the beam are given in reference 4. The beam specimen represented a typical airframe structure with regard to material, fabrication process, and the presence of stress concentrations resulting from conventional riveted construction.

The beams were fabricated from three separate lots of material, which was purchased from two different producers. Presumably, each lot of material was from one batch and run of the alloy. All of the beams were fabricated at the AVTD using conventional aircraft manufacturing procedures; they were not handled or finished with the care and precision of material specimens. External defects in the material, such as nicks or scratches, were not removed.

The mechanical properties of the material of each lot were determined by performing static tensile tests on at least three standard material coupons cut from the beam cover plate material. Table 1 gives a comparison of typical properties obtained experimentally for material lot 2, reference 5, with the standard handbook values of reference 6. The beam sectional properties from reference 4 are also given in table 1.

The static strength for the batch of specimens fabricated from each material lot was determined by testing to static failure at least two beams from each batch.

TEST PROGRAM

The overall box beam program consisted of four test phases. The experimental work under Phases I and III was divided into three categories: static-strength tests, constant-load-amplitude fatigue tests, and variable-load-amplitude fatigue tests. Phases II and IV consisted only of variable-load-amplitude fatigue tests. The flight maneuver loads spectra used in the program are shown in tables 2a and 2b. The breakdown of these spectra into the load frequencies for a given block size and the manner of spacing the infrequently applied high loads within the spectra are detailed in references 4 and 7. Details of the test program for Phase I are contained in reference 3.

Statistically designed factorial experiments were used for performing the variable-load-amplitude fatigue tests. The same factorial design was used for performing the variable-load-amplitude fatigue tests of Phases I and II; a lo-hi fixed-sequence loading was used for the Phase I tests and a cycle by cycle randomization of loads within the blocks was used for the Phase II tests. A schematic depicting the fixed-and random-sequences is shown in figure 2. Details for the Phase I experiment are contained in reference 3 and for the Phase II experiment in reference 8.

The details of the test program for the constant-load-amplitude fatigue tests of Phase III are contained in reference 5. A 3 x 3 x 3 factorial experiment was used for the Phase III variable-load-amplitude fatigue tests for the full spectrum of positive and negative loads. The factors of block size (20, 60, and 100 equivalent flight hours), load sequence (lo-hi and hi-lo fixed-sequence and random-sequence), and load spectrum (Spectra A, B and C of MIL-A-8866) were investigated. Two replications were made for each test point, a total of 54 beams was used for this phase. Figure 3 shows the loading orders used for the fixed-sequence tests.

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A 4 x 3 factorial experiment was used for the variable-load-amplitude fatigue tests of Phase IV for Spectra A. The factors of block size (20, 100, 200, and 500 equivalent flight hours) and nominal limit load stress level (35, 45, and 54 KSI) were investigated. Two replications were made for each test point; a total of 24 beams was required for the experiment. However, lives of four beams were used from Phase I tests; therefore, only 20 beams were actually tested for the experiment. The nominal stress levels used in this phase were reduced to approach more closely those used in the design of aircraft structures.

The original test plan for this phase included tests for Spectra B and C, in addition to Spectrum A and for tests up to a 200 hour block size. However, these tests were eliminated due to funding limitations and long times required for tests. Since only four test points (eight beam tests) for the two spectra were completed, these data are not presented because they were not sufficient for statistical analysis.

A total of 256 beams were used for the entire program. These were allocated as follows: 7 for static-strength tests, 63 for constant-load-amplitude fatigue tests, and 186 for variable-load-amplitude fatigue tests (16 beams were included for retests). In addition, there were other beams that were used for special purposes such as for a local strain investigation for Phase I and some for comparative tests for lot 3 beams.

METHOD

The beams were simply supported at the ends and loaded at the midspan by means of a hydraulic actuator. The method of supporting the beams and reacting the beam loads at the ends of the beam were described in reference 4. The loading systems used for the Phase I tests were adequately described in this reference.

For the random-sequence tests of Phase II, a fully automatic fatigue-loading system, which was specifically designed and purchased for the program, was used. This was a four-channel electro-hydraulic servovalve-controlled closed-loop automatic control system, the details are found in references 7 and 8.

The tests to the full spectrum of positive and negative loads of Phase III, with the exception of Spectrum B fixed-sequence tests, were performed using the automatic fatigue loading system used for the Phase II tests. However, the beams were tested singly due to the nature of the loading. In the random-sequence tests the loads were randomized cycle

by cycle across the positive and negative load portions of each block. The load frequencies within blocks were maintained the same as for the fixed-sequence tests.

The fixed sequence tests for Spectrum B of Phase III were performed using an AVTD dynamometer-load-control system and an AVTD designed programmer for applying the positive loads of the spectrum in a parallel-beam arrangement. This system was the same as that used for the Phase I fixed-sequence tests and described in reference 4. The small number of infrequently occurring negative loads in the spectrum were applied by means of a hand-pump-operated hydraulic jack. For these tests only, the "0" spectrum load as applied was equivalent to approximately a -5% negative limit load due to a "0" load tare weight condition acting on the beams. The effects on life of this condition were considered negligible.

The beams for Phase III were fabricated of material from lots 2 and 3. At the start of the program for the Phase I tests, the basis for establishing the test loads for the variable-load-amplitude fatigue tests was the use of an average static failing load for all the beams tested to failure by the NBS and the AVTD. This value was 6,860#. (See reference 4). This value was only slightly changed by the addition of beams failed from lot 2 and the beam loads for Phase II tests were maintained the same as for Phase I. The addition of the failing loads of the beams from lot 3 to all previous failures reduced the average static failing load because the lot 3 values were the lowest in ranking order. However, again, to maintain consistency of loads throughout the program and because the change was not considered significant, the value of 6,860# for the average static failing load was maintained as the basis of determining the test loads for the variable-load-amplitude fatigue tests of Phase III for lot 3 beams.

For the variable-load-amplitude fatigue tests of Phase III (except for Spectrum B fixed-sequence tests) the loading rates for each level of the full spectrum of positive and negative loads were established to give a maximum strain rate during the load cycle of 10,000 in./in./sec. This same basis was used for the Phase II tests and is further explained in reference 8. However, due to difficulty with the response time of load recording equipment, most tests were performed at one-half the maximum rate and some at less than one-half of maximum.

All of the tests for Phase IV of the program were performed using the automatic fatigue loading system and the two beam test setup for each test point in a parallel-beam arrangement. The beams for these

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tests were from lot 3 material and, as discussed previously, for Phase IV loads were based on an average static failing load of 6,860#. Test limit loads were based on a ratio of limit load stresses to the 0% M.S. limit load stress of Phase I as loads were proportional to stresses throughout the stress range covered.

The objective was to use the same loading rate for all spectrum tests. Thus, the loading rates for the tests were established on developing the same maximum strain rate during the load cycle (10,000 in./in./Sec.) as was used for the tests of Phases II and III. A bar graph visual load indicator system was developed during this test phase which enabled some tests to be performed developing the full strain rate. Other tests were performed at reduced rates.

RESULTS

The results of all static failing-load tests for beams from the various beam lots performed both by the NBS and the AVTD are given in table 3. The three last values in the table are for beams that were fabricated from lot 3 material.

Three types of load-lifetime curves were developed during the program; one for loading from (+lg to P), reference 4, one for loading from (-lg to P) and one for a lg mean load (lg $\frac{1}{2}P$), reference 5. These data which are presented as a family of curves in reference 5, are also reproduced in figure 4. At the extreme short life end, (low cycle region) the curves tend to become asymptotic to the line representing the static-strength of the structure. From a family of load-lifetime curves based on stresses in reference 5, a constant-life diagram based on outer fiber nominal stress was developed and is shown in figure 5. A comparison of the (+lg to P) load-lifetime curve for the beam structure with that for full-scale aircraft structures, made of 7075-T6 aluminum alloy and tested at the AVTD on the common basis of percent of static strength is presented in reference 4. This comparison shows that the curve for the beam structure is the outermost curve when compared to curves for full-scale structures; that is, the beam fatigue lives are greater because it is an idealized structure.

The results, in equivalent flight hours to failure for the fixed-sequence, variable-load-amplitude fatigue tests of Phase I from reference 4, are given in table 4. Detail results for each beam are also given in this reference. A pictorial presentation of these average life data showing the effects of the parameters investigated is shown in figure 6.

The BUAER spectrum was insensitive to the variations of both block size and stress level; therefore, it was not included in figure 6. A statistical analysis of the factorial experiment of Phase I, by means of the analysis-of-variance method, is given in appendix C of reference 4. A discussion of the effects of the various parameters on the fatigue life is also found in this reference. Qualitatively, the changes in fatigue life due to variations in block size and nominal stress level can be attributed to the compressive residual stresses developed at the edges of the fastener holes and the redistributions of these stresses. A detailed discussion of this is also contained in the reference.

The results for the random-sequence fatigue tests of Phase II from reference 8 are summarized in table 5. A comparison of the average fatigue lives for both the random-and fixed-sequence (lo-hi) fatigue tests is given in table 6. A pictorial presentation showing a superposition of the random-sequence data on the fixed-sequence data is shown in figure 7. for all of the test spectra. Reference 8 contains the statistical analyses of the factorial experiment for the random-sequence tests by the analysis-of-variance method. Data from the Phase I fixed-sequence tests were combined with the random-sequence data of Phase II to study the effects of load sequence. A discussion of the comparison of random-and fixed-sequence loading is given in the reference.

The results of the Phase III fatigue tests for the positive and negative loads of the MIL-A-8866 spectra are given in table 7. It is noted that for the hi-lo fixed-sequence tests, final failure occurred in all cases on the application of the 1st high load cycle (initial cycle of block) in the block where failure occurred. The specific loads in the spectrum at which beam failure occurred for the 54 beams tested were as follows: 40 at 125% L.L., 10 at 115% L.L., 1 at 105% L.L., 1 at 95% L.L. and 2 at 85% L.L. One of the 85% L.L. failures, was, however, due to an inadvertent overload to 125% L.L. while loading to the 85% L.L. level.

The individual lives to failure and the average life for each test point for the Phase III tests are given in table 8. The table shows that a much shorter life is obtained for the fighter spectrum (Spectrum A) under a lo-hi than for a hi-lo order of loading for the fixed-sequence tests. Tables 9a and 9b show comparisons between the average fatigue lives for the full spectrum loads under fixed-and random-sequence loading with the positive loads only results from Phase I (reference 4) for fixed-sequence loading, and with the positive loads only results for random-sequence loading from Phase II (reference 8). These comparisons

show that significant reductions in the fatigue lives occur for Spectra A and C when the negative loads are introduced into the load spectrum. For fixed-sequence loading and Spectrum A, an approximate 4 to 1 reduction in the fatigue life is obtained as a minimum. A graphic presentation of these comparison data is shown in figure 8 and 9, which readily show the large reduction in life in going from positive loads only to the full spectrum of positive and negative loads. For Spectrum B, the reductions in life are not as large nor as consistent, probably because there are only 8.25 negative load cycles per 1,000 hours for this spectrum as compared to 1,003 negative load cycles per 1,000 hours for Spectra A and C.

The results of the Phase IV fatigue tests for extended stress-level and block-size ranges for Spectrum A are presented in table 10. The beam failures, which took place at or near the end of a loading block under the application of the highest loads in the spectrum, occurred as follows for the 20 beams: 10 failed at 125% L.L., 5 at 115% L.L., 3 at 105% L.L., and one each at 95% L.L. and 85% L.L. The fatigue lives to failure and the average life for each test point is given in table 11.

A graphical comparison of these data, showing the effect of block size variation on life for a given limit load nominal stress is shown in figure 10. A pictorial presentation of these life data, showing the effects of the parameters investigated, is shown in figure 11.

Figure 10 shows an increase in life when the block size increases from 20 to 100 hours; a similar relationship was found in the first phase of the program and was reported in reference 4. However, when the block size increases from 100 hours to 500 hours there occurs a drop-off in life. This substantiates that the highest spectrum load is beneficial only when applied successively up to some optimum number of cycles after which the load becomes more damaging than beneficial for a given structure. Discussion pertaining to the build up of the beneficial compressive residual stresses at the edges of the fastener holes and supporting evidence to this fact are contained in reference 4.

It should be noted from figure 11 the increase in life that occurs with a decrease in the nominal limit load stress for a given block size and, in particular, the large increase in life when decreasing the stress level from 45 KSI to 35 KSI. This figure also shows the effect of block size variation on fatigue life for a given limit load stress condition, this effect having been discussed in the preceding paragraph.

CONCLUDING REMARKS

Constant-and variable-load-amplitude fatigue tests were performed in unidirectional and partially reversed bending on built-up box beams fabricated of 7075-T6 aluminum alloy structural elements. When compared to full-scale aircraft structures of like material under constant-amplitude unidirectional loading on a percent of ultimate strength basis the beams represented the upper bound of those data for full scale structures and exhibited similar fatigue characteristics. The beams were thus established as suitable idealized structure for the investigation of those parameters which affect the structural fatigue life.

The data presented herein and the final reports previously issued and referenced support the following concluding remarks: The results from the constant-load-amplitude tests for both unidirectional and partially reversed loading support the following:

1. The most severe loading conditions was that for lg^+P (complete load reversal about a lg mean load) which resulted in the shortest fatigue lives, the only exception was at the lowest load levels where the $-lg$ to P loading became more severe.

2. The effective stress-concentration factor K_t increased with a reduction in load (or increase in fatigue life) for both the lg to P and lg^+P loading conditions. This was attributed to a reduction in plastic deformation of the material around the fastener holes and to the deleterious effects of fretting.

3. A direct relationship between fretting and fatigue life and an inverse relationship between fretting and load were found for the two partially reversed loading conditions; i.e., the fretting increased with increased life and an accompanying reduction in the maximum load.

A series of factorial experiments were performed to develop the variable-load-amplitude fatigue data for the BUAER spectrum and Spectra A, B, and C of MIL-A-8866. These test results support the following:

1. Under fixed-sequence loading for positive loads only, there was a statistically significant increase in fatigue life for an 11% increase in the static margin of safety and for an increase in block size from 20 to 100 equivalent flight hours for Spectra A, B and C of MIL-A-8866.

2. The various test spectra were found to have a statistically significant effect on fatigue life under fixed-sequence loading for positive loads only. The relative order of severity, in decreasing order, were:

Spectrum A
BUAER Spectrum
Spectrum B
Spectrum C

3. The random-sequence application of loads on a cycle by cycle basis within the loading blocks produced a shorter fatigue life than that obtained under lo-hi fixed-sequence loading for positive loads only. A maximum reduction in average fatigue life of approximately 50 percent occurred.

4. The smallest feasible block size should be used for the tests of full-scale structures. The 20-hour block size under fixed-sequence loading was found to most closely simulate random-sequence loading, which approximates in flight loading.

5. Qualitatively, the significant effects of the parameter variations on fatigue life can be attributed to the compressive residual stresses produced at the edges of the fastener holes by the application of the highest spectrum loads and the subsequent changes that occur in these residual stresses.

6. The introduction of the negative loads into the test spectrum produced significant reductions in the fatigue lives, especially for Spectra A and C. For Spectrum A under fixed-sequence loading there is a minimum reduction in the life of approximately 4 to 1.

7. A much shorter fatigue life is obtained for a lo-hi order of loading than for a hi-lo order for Spectrum A under fixed-sequence loading.

8. An increase in life occurs with an increase in the block size from 20 to 100 equivalent flight hours for Spectrum A with nominal limit load stress levels in the range of 60 KSI down to 35 KSI. However, increasing the block size from 100 to 500 equivalent flight hours causes a decrease in life. This is attributed to there being an optimum number of high loads causing beneficial effects in a spectrum of about 100 hour block size. For higher block sizes the application of high loads in the spectrum are more damaging than beneficial.

9. For Spectrum A loads, there is a marked increase in the fatigue life with reduction in nominal limit load stress level, the largest increase taking place in reducing from 45 KSI to 35 KSI.

RECOMMENDATIONS

It was previously recommended in the final reports released at the completion of the fixed-sequence tests and the random-sequence tests for positive loads only that the block size requirement of 100 equivalent flight hours in specification MIL-A-8867 for the lo-hi fixed-sequence fatigue tests of aircraft wings be reduced to 20 equivalent flight hours. The results obtained from tests for the full spectrum of positive and negative loads for the spectra of MIL-A-8866 and those for extended nominal limit load stress level and block size ranges reported herein further substantiate this recommendation.

The results for the tests which included the negative loads portion of the flight maneuver loads test spectra have shown significant reduction in the fatigue lives with the introduction of the negative loads into the test spectra. It is, therefore, recommended that the negative loads be included in the test spectra for the fatigue tests of aircraft wings in the laboratory. The use of the smaller block size and the inclusion of negative loads in the test spectra should produce fatigue lives which would be a more realistic interpretation of the flight loads environment. Hopefully, the laboratory fatigue lives obtained would be more representative of the useful service life of the aircraft.

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TABLE 1--PROPERTIES OF MATERIAL AND BEAM SPECIMENS

Tensile Properties of Beam Cover-Plate Material (Reference 5)

(7075-T6 bare extruded aluminum-alloy bar, lot 2)

Property	Handbook values, psi, from reference 6	Experimental values, psi
F_{t_u} -- ultimate stress	81,000	89,400
F_{t_y} -- yield stress	73,000	81,500
E -- modulus of elasticity	10.3×10^6	10.3×10^6

Calculated Sectional Properties (reference 4)

\bar{y} distance from outer compression fiber (bottom of beam) to centroid = 0.926 in.

c distance from \bar{y} to outer fiber of beam, in.

c_t (to outer tension fiber) = 1.074

c_c (to outer compression fiber) = 0.926

I moment of inertia about \bar{y} -axis at the midpoint location = 0.836 in.⁴
(calculated assuming aluminum equivalent for steel bar, net area on tension portion, and plugged holes on compression portion)

I/c section modulus at beam midpoint, in.³

I/c_t (to outer tension fiber) = 0.825

I/c_c (to outer compression fiber) = 0.957

Cross-sectional areas, in.²

Gross area = 2.093

Net area at beam midpoint through rivet and bolt holes = 1.413

Net area through rivet holes only = 1.811

Weight of Beams

Nominal beam weight = 15 lbs.

TABLE 2--FLIGHT LOADS MANEUVER SPECTRA FOR 1,000 HOURS

a. Discrete positive loads of spectra

BUAER spectrum		Specification MIL-A-8866 spectra ¹			
Max. load in % limit load	Occurrences ²	Max. load in % limit load	Occurrences ²		
			Spectrum A	Spectrum B	Spectrum C
	14,150	35	17,000	25,000	
		45	9,500	10,000	10,000
55	8,600	55	6,500	3,500	3,000
		65	4,500	1,000	1,000
70	3,250	75	2,500	500	300
		85	1,500	200	100
85	850	95	300	75	50
100	150	105	150	25	10
		115	40	10	3
		125	16	3	2
$\Sigma \dots$	27,000	$\Sigma \dots$	42,006	40,313	14,445

¹ Reference 3.² Each occurrence is one load cycle.

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TABLE 2--FLIGHT LOADS MANEUVER SPECTRA FOR 1,000 HOURS- CONCLUDED

b. Discrete negative loads of spectra

Max. load in % limit load ¹	Specification MIL A-8866 spectra ²	
	Occurrences ³	
	A&C ⁴	B
0	500	5
10	200	2
20	100	1
30	60	0.25
40	35	
50	30	
60	25	
70	20	
80	15	
90	10	
100	5	
110	3	
	1,003	8.25

¹ The negative limit load factor is -3.00.

² Reference 3.

³ Each occurrence is one load cycle; all occurrences start from unity (1g), to the specified load factor and back to unity.

⁴ Spectrum C for Phase III tests was that corresponding to a trainer (VT) type aircraft for which MIL-A-8866 specifies that the Spectrum A negative flight maneuver spectrum shall apply.

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TABLE 3--RESULTS OF STATIC FAILING-LOAD TESTS^{1,2}

Ranking order	Specimen No.	Static strength, lb.	Test performed at	Reference source
1	103	7,319	NBS ³	2
2	102	6,996	NBS	2
3	202	6,976	NBS	2
4	201	6,936	NBS	2
5	303	6,767	NBS	2
6	302	6,746	NBS	2
7	1	6,740	NBS	1
8	3-2-1	6,715	AVTD	5
9	3-2-2	6,700	AVTD	5
10	1	6,615	AVTD	4
11	2	6,615	AVTD	4
12	3-3-3	6,418	AVTD	-
13	3-3-1	6,218	AVTD	-
14	3-3-2	6,218	AVTD	-
$\Sigma P = 93,979$				

¹ Arithmetic mean = $\frac{\Sigma P}{N} = \frac{93,979}{14} = 6,713\#$

² In order to maintain consistence of loads throughout the entire program for the various phases, an average failing load of 6,860 pounds was used as a basis for establishing loads for the spectra. This was the average failing load determined at the start of the program based on nine specimens. It was felt necessary to maintain this basis for spectrum test load determination, the change in mean by the addition of other values later in the program being considered not significant.

³ National Bureau of Standards, Washington, D.C.

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TABLE 4--FATIGUE LIVES IN EQUIVALENT FLIGHT HOURS¹ FOR LO-HI
FIXED-SEQUENCE POSITIVE LOADS FATIGUE TESTS, PHASE I

Spectrum block size, hours	BUAER		Specification MIL-A-8866					
	spectrum		Spectrum A		Spectrum B		Spectrum C	
	11%	0%	11%	0%	11%	0%	11%	0%
	M.S.	M.S.	M.S.	M.S.	M.S.	M.S.	M.S.	M.S.
20	4859	3819	3299	1359	12,299	9,499	22,899	11,899
	5019	4679	3359	1399	13,299	10,299	22,899	12,299
Av life	4939	4249	3329	1379	12,799	9,899	22,899	12,099
60	4199	4019	4259	1499	15,959	6,659	33,899	16,619
	5579	4499	4439	1619	18,839	7,019	35,133	17,579
Av life	4889	4259	4349	1559	17,399	6,839	34,516	17,099
100	3297	3797	7099	3499	21,299	7,899	31,299	18,899
	3499	4299	7099	3899	22,599	8,299	50,899	25,899
Av life	3398	4048	7099	3699	21,949	8,099	41,099	22,399

¹ The two values at each test point are equivalent flight hours to failure for two replications. Values are given to the closest number of hours actually sustained.

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TABLE 5---FATIGUE LIVES IN EQUIVALENT FLIGHT HOURS FOR RANDOM-SEQUENCE FATIGUE TESTS¹, POSITIVE LOADS, PHASE II

Spectrum block size, hours	BUAER		Specification MIL-A-2866					
	spectrum		Spectrum A		Spectrum B		Spectrum C	
	11%	0%	11%	0%	11%	0%	11%	0%
	M.S.	M.S.	M.S.	M.S.	M.S.	M.S.	M.S.	M.S.
20	4,568	1,917	3,238	1,776	7,587	8,587	27,288	6,888
	5,346	2,121	3,265	1,825	8,531	10,899	27,896	8,888
Av life	4,957	2,019	3,251	1,800	8,059	9,743	27,532	7,888
60	2,665	1,888	3,108	2,170	7,781	7,936	21,381	9,861
	4,424	2,458	3,414	2,260	28,393	8,261	26,790	12,048
Av life	3,544	2,173	3,261	2,215	18,087	8,098	24,085	11,134
100	2,396	1,934	3,004	2,191	11,888	6,888	37,265	16,265
	2,891	2,106	4,253	2,821	18,556	7,556	48,265	16,390
Av life	2,643	2,020	3,629	2,506	15,222	7,222	42,765	16,532

¹ The two values at each test point are equivalent flight hours failure for two replications. Values are given to the closest number of hours actually sustained.

TABLE 6--COMPARISON OF AVERAGE FATIGUE LIVES¹ IN EQUIVALENT FLIGHT HOURS FOR RANDOM- AND FIXED-SEQUENCE (LO-HI) FATIGUE TESTS, POSITIVE LOADS ONLY

Spectrum block size, hours	Load Sequence	Specification MIL-A-8866										
		BUAER spectrum			Spectrum A			Spectrum B			Spectrum C	
		11% M.S.	0% M.S.	11% M.S.	0% M.S.	11% M.S.	0% M.S.	11% M.S.	0% M.S.	11% M.S.	0% M.S.	
20	Fixed Random	4,939	4,249	3,329	1,379	12,799	9,899	22,899	12,099			
		4,957	2,019	3,251	1,800	8,059	9,743	27,592	7,888			
60	Fixed Random	4,689	4,259	4,349	1,559	17,399	6,839	34,516	17,099			
		3,544	2,173	3,261	2,215	18,087	8,098	24,085	11,134			
100	Fixed Random	3,398	4,048	7,099	3,699	21,949	8,099	41,099	22,399			
		2,643	2,020	3,629	2,506	15,222	7,222	42,765	16,532			

¹ Data from tables 4 and 5

TABLE 7--RESULTS OF FATIGUE TESTS FOR POSITIVE AND NEGATIVE LOADS OF MIL-A-8866
SPECTRA, PHASE III, 11% MARGIN OF SAFETY

Specimen No.	Test point ident.	Load spectrum	Order of loading	Spectrum block size, equiv. flt. hr.	Life to failure, equiv. flt. hr.	Block of failure	Cycle of failure within block	Failure load, 1 % L.L.	Location of tension failure of coverplate
2	1-4	A	Lo-hi	20	899	45	837	105	A
15	1-4	A	Lo-hi	20	719	39	841	125	B
31	2-14	A	Lo-hi	60	898	15	2,518	115	B
48	2-14	A	Lo-hi	60	718	12	2,520	125	A
35	3-5	A	Lo-hi	100	1,197	12	4,196	115	C
24	3-5	A	Lo-hi	100	1,897	19	4,196	115	B
25	4-8	A	Hi-lo	20	1,380	95	1st	125	A
59	4-8	A	Hi-lo	20	2,660	134	1st	115	B
37	5-17	A	Hi-lo	60	2,820	48	1st	125	B
6	5-17	A	Hi-lo	60	3,000	51	1st	125	B
36	6-12	A	Hi-lo	100	3,700	38	1st	125	B
38	6-12	A	Hi-lo	100	2,800	29	1st	125	B
17	10-26	A	Random	20	1,095	55	673	125	A
11	10-26	A	Random	20	900	46	4	85 ³	A
43	11-24	A	Random	60	753	13	1,457	125	A
19	11-24	A	Random	60	1,392	24	554	125	B
4	12-19	A	Random	100	849	9	2,122	125	A
14	12-19	A	Random	100	849	9	2,122	125	A
7	13-1	B	Lo-hi	20	2,592	480	808	125	B
40	13-1	B	Lo-hi	20	12,199	610	807	115	A
59	14-10	B	Lo-hi	60	14,219	237	2,419	115	C
33	14-10	B	Lo-hi	60	14,999	250	2,420	125	B

TABLE 7--RESULTS OF FATIGUE TESTS FOR POSITIVE AND NEGATIVE LOADS OF MIL-A-8866
SPECTRA, PHASE III, 11% MARGIN OF SAFETY--CONTINUED

Specimen No.	Test point ident.	Load spectrum	Order of Loading	Spectrum block size equiv. flt. hr.	Life to failure equiv. flt. hr.	Block of failure	Cycle of failure within block	Failure load, 1 % L.L.	Location of tension failure of coverplate ²
18	15-2	B	Lo-hi	100	6,599	68	4,032	125	A
63	15-2	B	Lo-hi	100	6,899	69	4,032	125	A
72	16-3	B	Hi-lo	20	8,880	445	1st	125	A
60	16-3	B	Hi-lo	20	10,880	543	1st	125	B
13	17-11	B	Hi-lo	60	14,520	243	1st	115	B
23	17-11	B	Hi-lo	60	17,160	287	1st	125	B
12	18-9	B	Hi-lo	100	14,500	146	1st	125	A
27	18-9	B	Hi-lo	100	17,200	173	1st	125	A
34	22-22	B	Random	20	12,581	630	42	125	B
41	22-22	B	Random	20	16,581	830	42	125	D
29	23-25	B	Random	60	14,909 ⁴	262	1,994	125	A
30	23-25	B	Random	60	13,367	223	1,908	125	A
8	24-21	B	Random	100	9,207	93	322	125	A
22	24-21	B	Random	100	7,892	79	3,732	125	A
57	25-6	C	Lo-hi	20	3,898	195	291	115	A
21	25-6	C	Lo-hi	20	9,178	459	289	95	B
42	26-16	C	Lo-hi	60	4,735	79	869	125	C
32	26-16	C	Lo-hi	60	3,175	53	869	125	B
20	27-7	C	Lo-hi	100	14,593 ⁴	146	1,445	115	D
26	27-7	C	Lo-hi	100	16,293	163	1,446	125	E
45	28-13	C	Hi-lo	20	4,880	245	1st	125	A
47	28-13	C	Hi-lo	20	8,880	445	1st	125	B
10	29-18	C	Hi-lo	60	7,560	127	1st	125	B
62	29-18	C	Hi-lo	60	9,840	165	1st	125	C
39	30-15	C	Hi-lo	100	15,800	159	1st	125	B

TABLE 7--RESULTS OF FATIGUE TESTS FOR POSITIVE AND NEGATIVE LOADS OF MIL-A-8866
SPECTRA, PHASE III, 11% MARGIN OF SAFETY--CONCLUDED

Specimen No.	Test point ident.	Load spectrum	Order of loading	Spectrum block size, equiv. flt. hr.	Life to failure, equiv. flt. hr.	Block of failure	Cycle of failure within block	Failure load, 1 % L.L.	Location of tension failure of coverplate ²
44	30-15	C	Hi-Lo	100	11,200	113	1st	125	B
9	34-20	C	Random	20	4,887	245	123	125	C
46	34-20	C	Random	20	3,281	165	24	115	A
1	35-27	C	Random	60	4,583	77	340	5th of 85	A
3	35-27	C	Random	60	4,725	79	710	125	A
16	36-23	C	Random	100	4,892	49	1,424	125	A
5	36-23	C	Random	100	4,203	43	140	125	A

1 Failures occurred at single application of load shown where only one cycle occurred in the block or on application of first cycle of load level. Where this did not occur, cycle of failure at load level is also given.

2 A - across rivet holes at beam midspan

B - across rivet holes 1 inch from beam midspan

C - across rivet holes 2 inches from beam midspan

D - across rivet holes 3 inches from beam midspan

E - across rivet holes 4 inches from beam midspan

3 Failure was caused by the inadvertent application of an overload (125% L.L.). Although failure was premature, the beam already contained fatigue cracks at the beam midspan rivet holes.

4 Failure was caused by application of high load at end of block because it had been inadvertently skipped during the block. Life to failure is given to point where this load should have been applied during the block, assumption being made that failure would have occurred there with its application.

TABLE 8--FATIGUE LIVES IN EQUIVALENT FLIGHT HOURS¹ FOR POSITIVE AND NEGATIVE
LOAD (FULL SPECTRUM) FATIGUE TESTS, PHASE III, 11% MARGIN OF SAFETY

Spectrum block size, hours	Specification MIL-A-8866									
	Spectrum A					Spectrum B				
	Load sequence					Load sequence				
	Lo-hi, fixed	Hi-lo, fixed	Random	Lo-hi, fixed	Hi-lo, fixed	Random	Lo-hi, fixed	Hi-lo, fixed	Random	Lo-hi, fixed
20	779	1,880	900 ²	9,599	8,880	12,581	3,898 ³	4,880	3,281	4,880
Av life	899	2,660	1,095	12,199	10,880	16,581	9,178	8,880	4,887	8,880
	839	2,270	997	10,899	9,880	14,581	6,538	6,880	4,084	6,880
60	718	2,820	753	14,219 ³	14,520	13,367	3,175	7,560	4,583	7,560
Av life	898	3,000	1,392	14,999 ³	17,160	16,909	4,736	9,840	4,725	9,840
	808	2,910	1,072	14,609	15,840	15,138	3,955	8,700	4,654	8,700
100	1,197 ³	2,800	849	6,599	14,500 ³	7,892	14,593	11,200	4,203	14,593
Av life	1,897	3,700	849	6,899	17,200	9,207	16,293	15,800	4,892	16,293
	1,547	3,250	849	6,749	15,580	8,549	15,443	13,500	4,547	15,443

¹ The two values at each test point are equivalent flight hours to failure for two replications. Values are given to the closest number of hours actually sustained.

² The beam for this point was failed inadvertently by an overload at this life. Although failure was premature, the beam already contained fatigue cracks at the beam midspan rivet holes.

³ The specimen lives for these points were probably adversely affected to an unknown degree by the metal conditioner used for installation of -S/N fatigue life gages.

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TABLE 9--COMPARISON OF AVERAGE FATIGUE LIVES IN EQUIVALENT FLIGHT HOURS FOR POSITIVE LOADS ONLY AND FOR FULL SPECTRUM LOADS, 11% MARGIN OF SAFETY

a. Fixed-sequence loading (lo-hi)

Spectrum block size, hours	Type of loads	MIL-A-8866 test spectra		
		Spectrum A	Spectrum B	Spectrum C
20	Pos. only	3,329 ¹	12,799	22,899
	Pos. & neg.	839 ²	10,899	6,538
60	Pos. only	4,349	17,399	34,516
	Pos. & neg.	808	14,609	3,955
100	Pos. only	7,099	21,949	41,099
	Pos. & neg.	1,547	6,749	15,443

b. Random-sequence loading

Spectrum block size, hours	Type of loads	MIL-A-8866 test spectra		
		Spectrum A	Spectrum B	Spectrum C
20	Pos. only	3,251 ³	8,059	27,592
	Pos. & neg.	997 ²	14,581	4,084
60	Pos. only	3,281	18,087	24,085
	Pos. & neg.	1,072	15,138	4,654
100	Pos. only	3,622	15,222	42,765
	Pos. & neg.	849	8,549	4,547

¹ From Phase I tests, reference 4.

² From Phase III tests

³ From Phase II tests, reference 8

TABLE 10--RESULTS OF FATIGUE TESTS FOR EXTENDED STRESS-LEVEL AND BLOCK-SIZE RANGES, PHASE IV, POSITIVE LOADS ONLY, LO-III FIXED-SEQUENCE LOADING

Specimen No.	Test point ident.	Spectrum block size, equiv. ft. hr.	Nominal L.L. Stress, KSI	Life to failure, equiv. ft. hr.	Block of failure	Failure load, % L.L., & cycle no.	Location of tension failure of coverplate ¹
30	1-4	20	35	11,859	593	115	A
28	1-4	20	35	13,839	692	125	A
14	2-1	100	35	16,399	164	125	B
7	2-1	100	35	24,999	250	125	C
24	3-3	200	35	18,799	94	125	A
1	3-3	200	35	12,199	61	115	A
3	4-5	500	35	21,498	43	13th of 105	A
26	4-5	500	35	8,498	17	11th of 105	D
21	5-7	20	45	9,539	477	125	A
22	5-7	20	45	6,959	348	125	B
19	6-9	100	45	6,199	62	125	A
31	6-9	100	45	7,399	74	125	D
17	7-6	200	45	6,199	31	105	B
20	7-6	200	45	5,799	29	2nd of 115	A
6	8-10	500	45	1,490	3	631th of 85	C
11	8-10	500	45	1,499	3	125	A
27	11-2	200	54	3,399	17	2nd of 125	A
18	11-2	200	54	2,999	15	115	A
2	12-8	500	54	1,499	3	14th of 115	E
10	12-8	500	54	997	2	139th of 95	A

- ¹ A - across rivet holes at beam midspan.
 B - across rivet holes 1 inch from beam midspan.
 C - across rivet holes 2 inches from beam midspan.
 D - across rivet holes 3 inches from beam midspan.
 E - across rivet holes 4 inches from beam midspan.

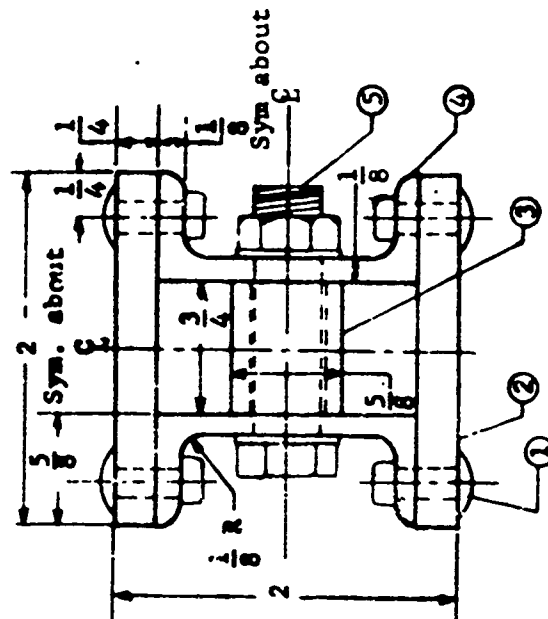
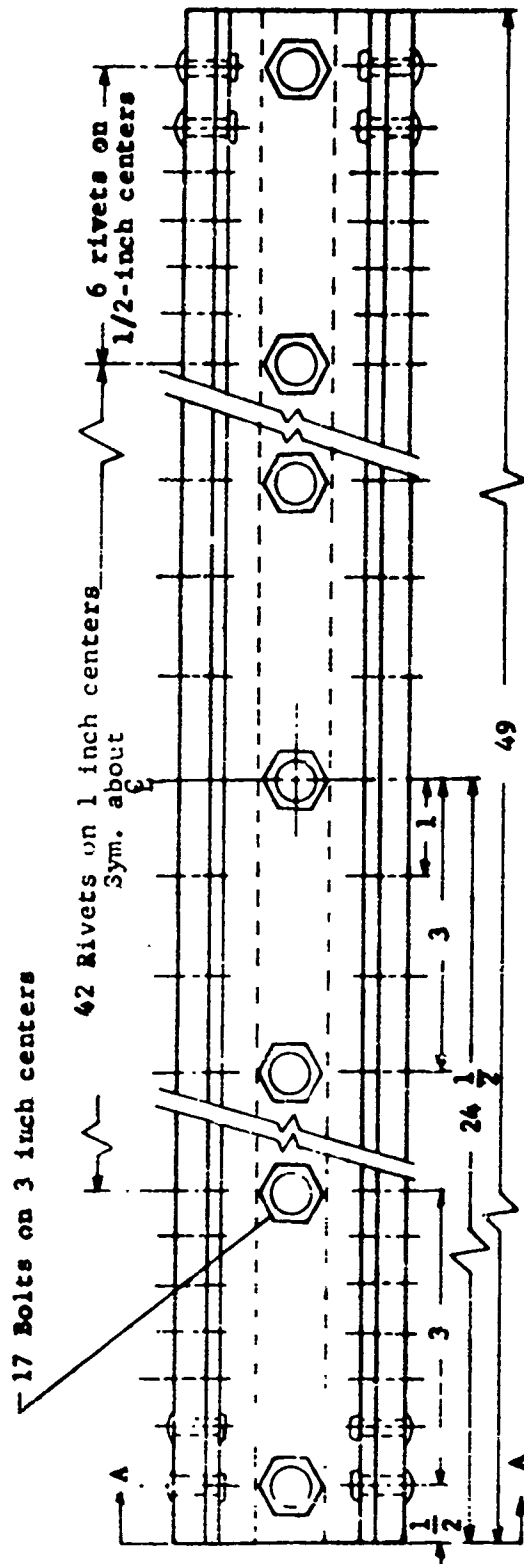
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TABLE 11--FATIGUE LIVES IN EQUIVALENT FLIGHT HOURS¹ FOR EXTENDED STRESS-LEVEL AND BLOCK-SIZE RANGES, PHASE IV, POSITIVE LOADS ONLY, LO-HI FIXED-SEQUENCE LOADING

Spectrum A Specification MIL-A-8866			
Spectrum block size, hours	Nominal L.L. stress,		
	35	45	54
20	11,859	6,959	3,299 ²
	13,839	9,539	3,359
Av life	12,849	8,249	3,329
100	16,399	6,199	7,099 ²
	24,999	7,399	7,099
Av life	20,699	6,799	7,099
200	12,199	5,799	2,999
	18,799	6,199	3,399
Av life	15,499	5,999	3,199
500	8,498	1,490	997
	21,498	1,499	1,499
Av life	14,998	1,494	1,248

¹ The two values at each test point are equivalent flight hours to failure for two replications. Values are given to the closest number of hours actually sustained.

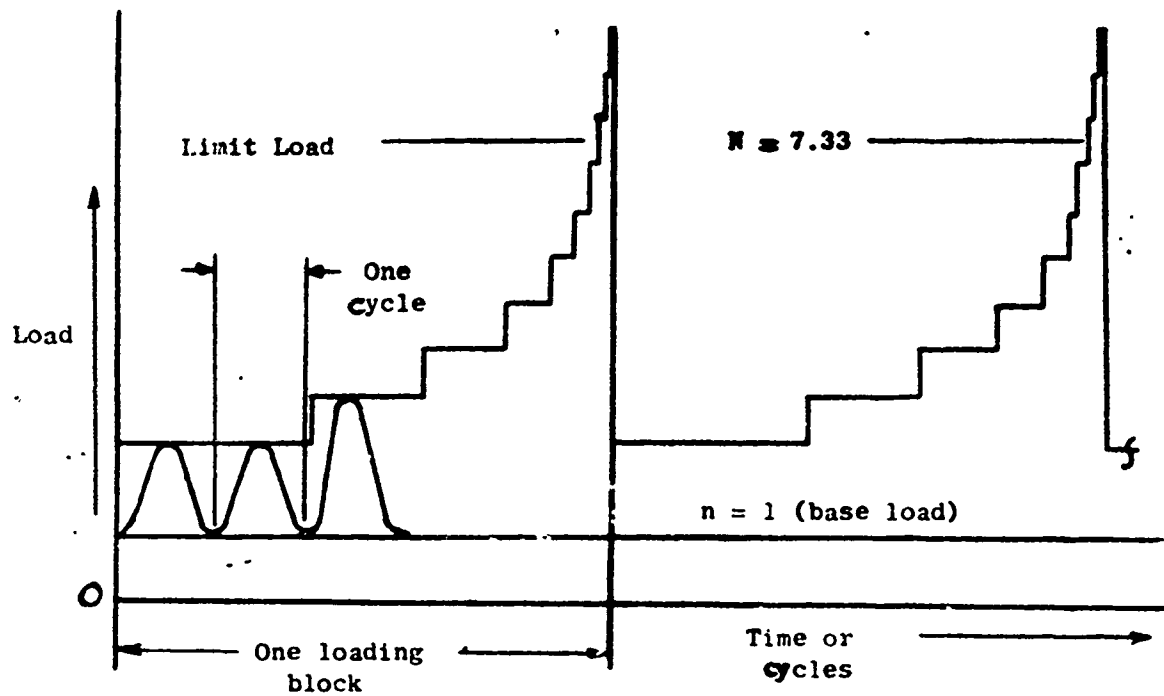
² These data points are from Phase I (reference 4) of the program.



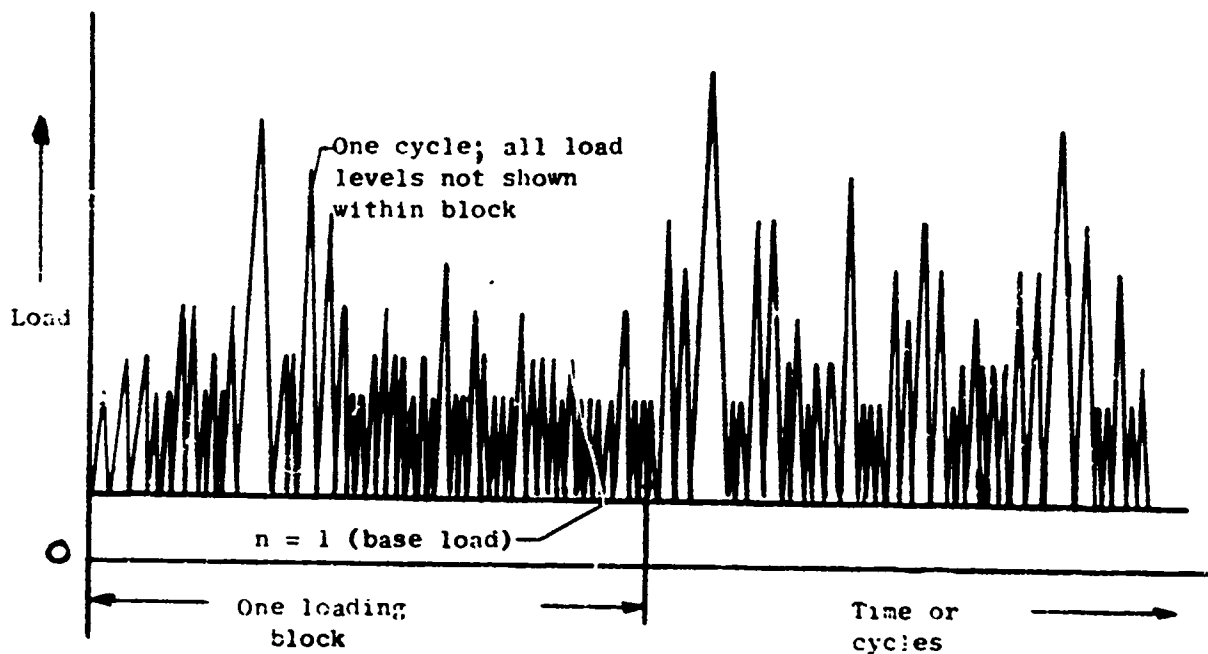
Sec. A-A

Part No.	Item	Material
1	Rivet, AM470-ND6-10	2024-T4 AL. Alloy
2	Plate	7075-T6 AL. Alloy
3	Bar	Steel
4	Channel	7075-T6 AL. Alloy
5a	Bolt, AM5-14A	Steel
5b	Nut, AM315-5R	Steel
5c	Washer, AM960-516	Steel

Figure 1 -- Box beam spec'n in design



Fixed-sequence, lo-hi, loading (reference 3)



Random-sequence loading

Figure 2-- Comparison of loading schematics for fixed-and random-sequence fatigue tests, MIL-A-8866 spectra, positive loads only

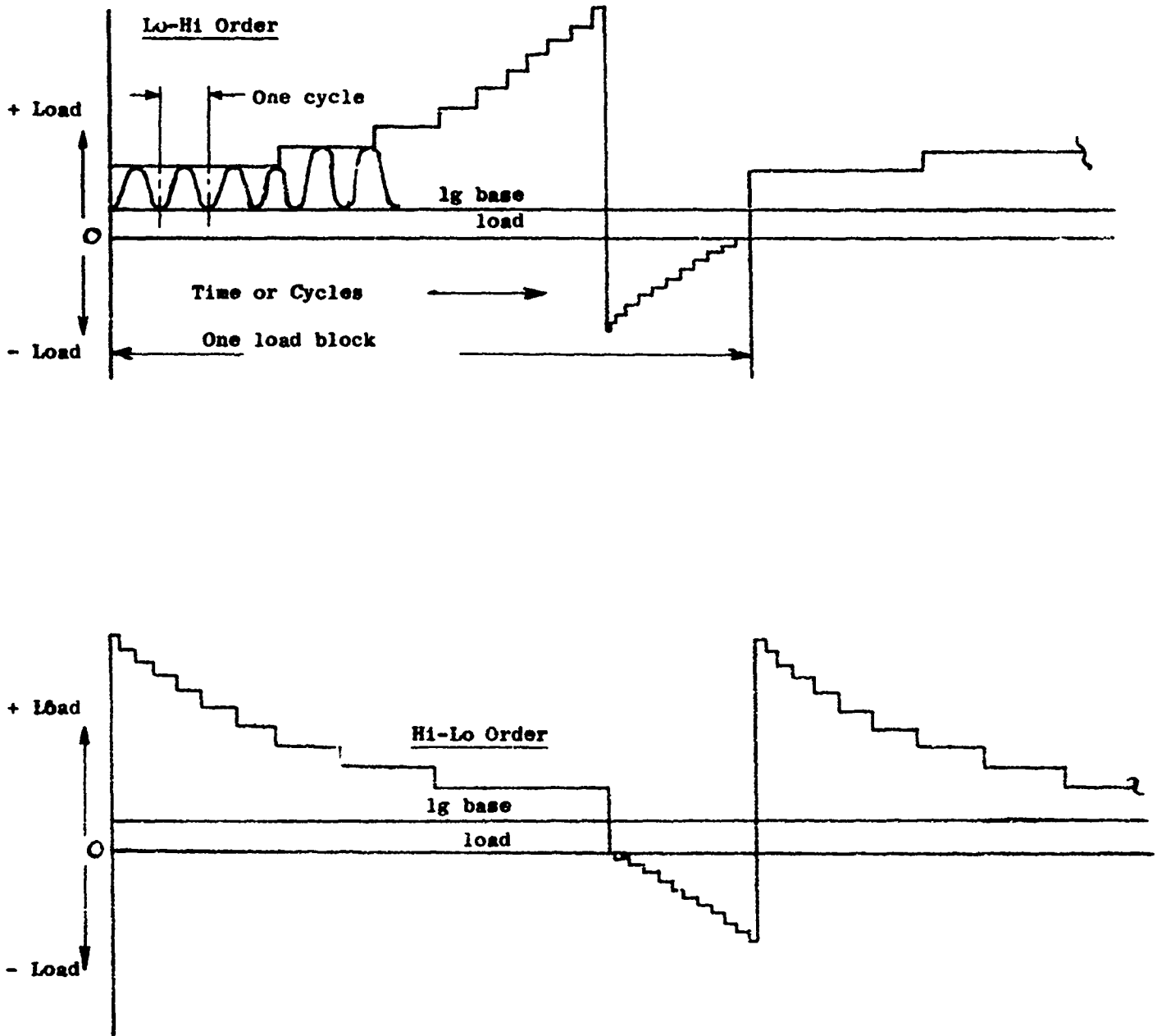
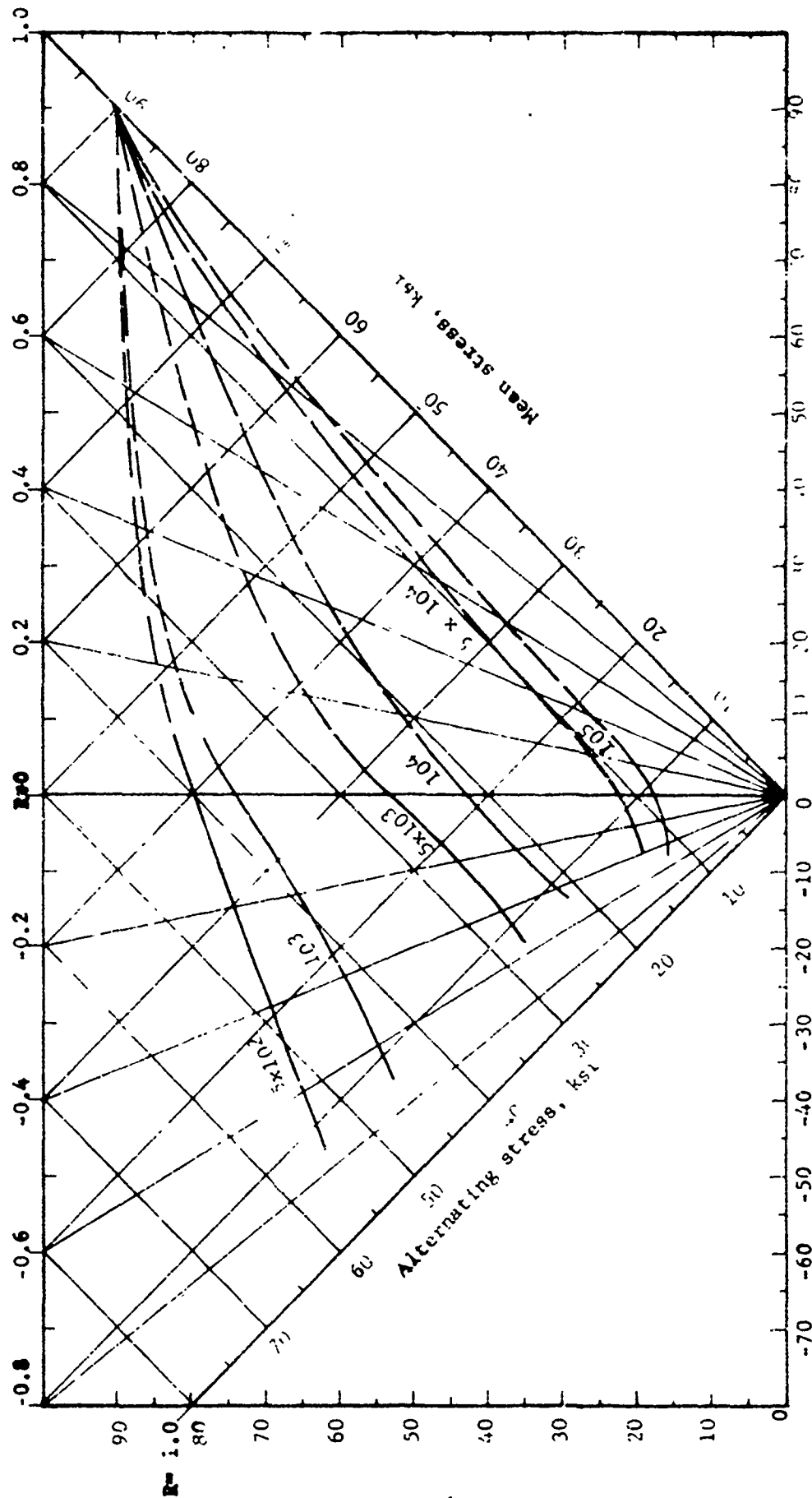


Figure 3--Schematic diagrams of fixed-sequence loading orders for positive and negative load fatigue tests

30



Figure 4 -- Load vs. Median-Life Curves, Log-Log Plots



Presented data are average life values from table 4

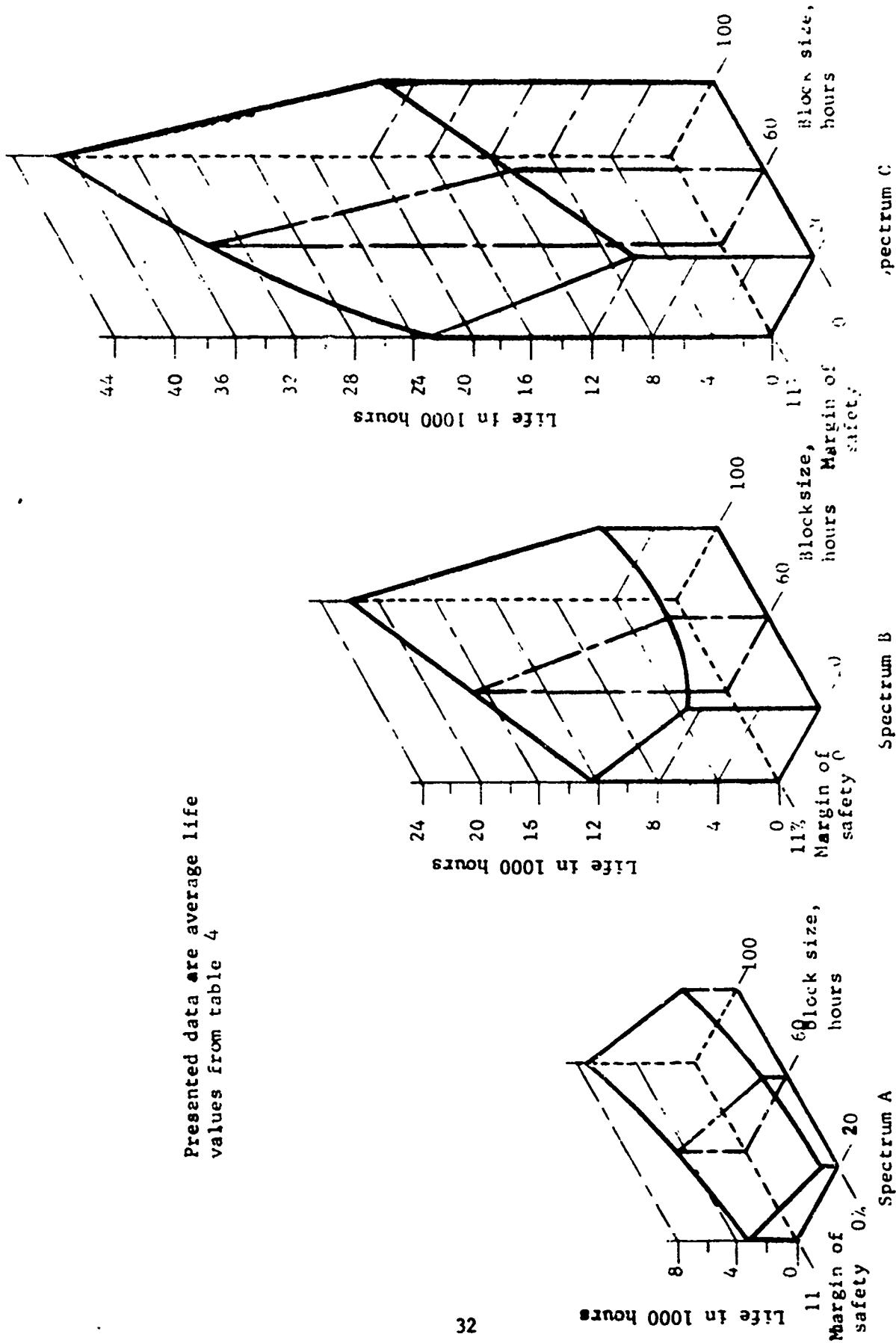


Figure 6 - Pictorial presentation of beam fatigue-life data for test spectra of MIL-A-8866, 10-hi fixed-sequence positive load tests of Phase I

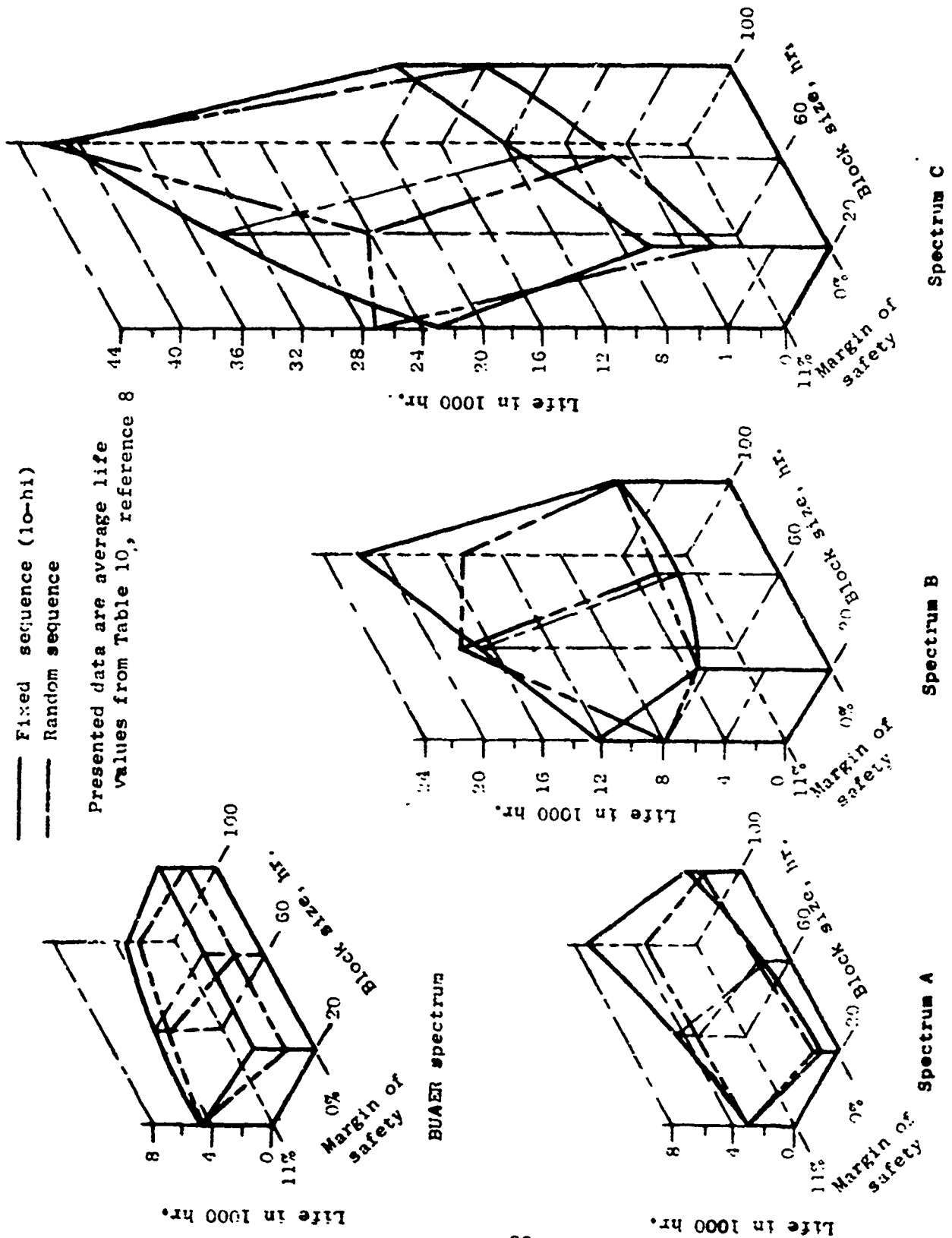


Figure 7--Pictorial presentation of beam fatigue-life data for random and fixed-sequence fatigue tests

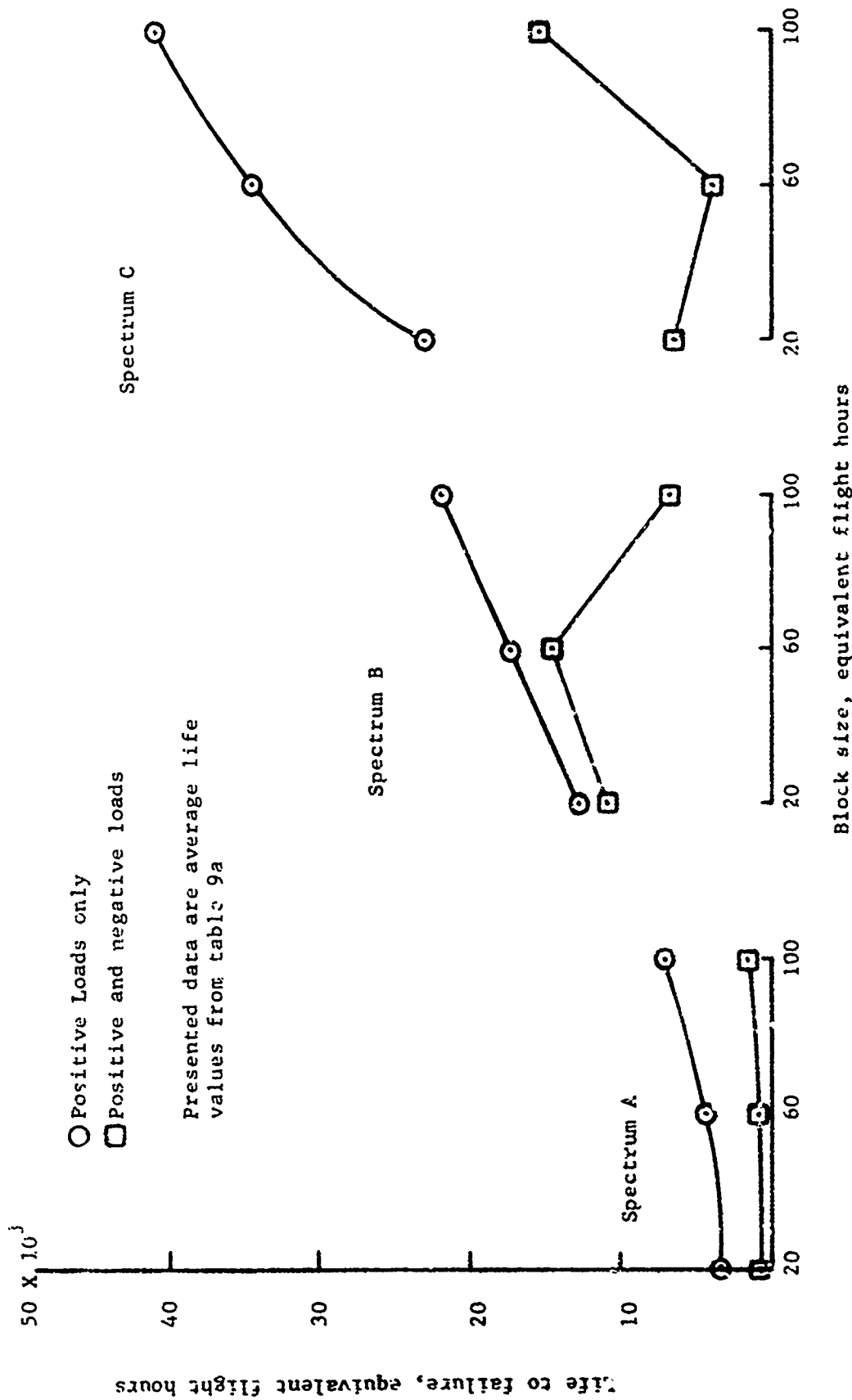


Figure 3--Comparison of average fatigue lives for positive only and positive and negative loads for MIL-A-8866 spectra, lo-hi fixed-sequence loading, 11% margin of safety

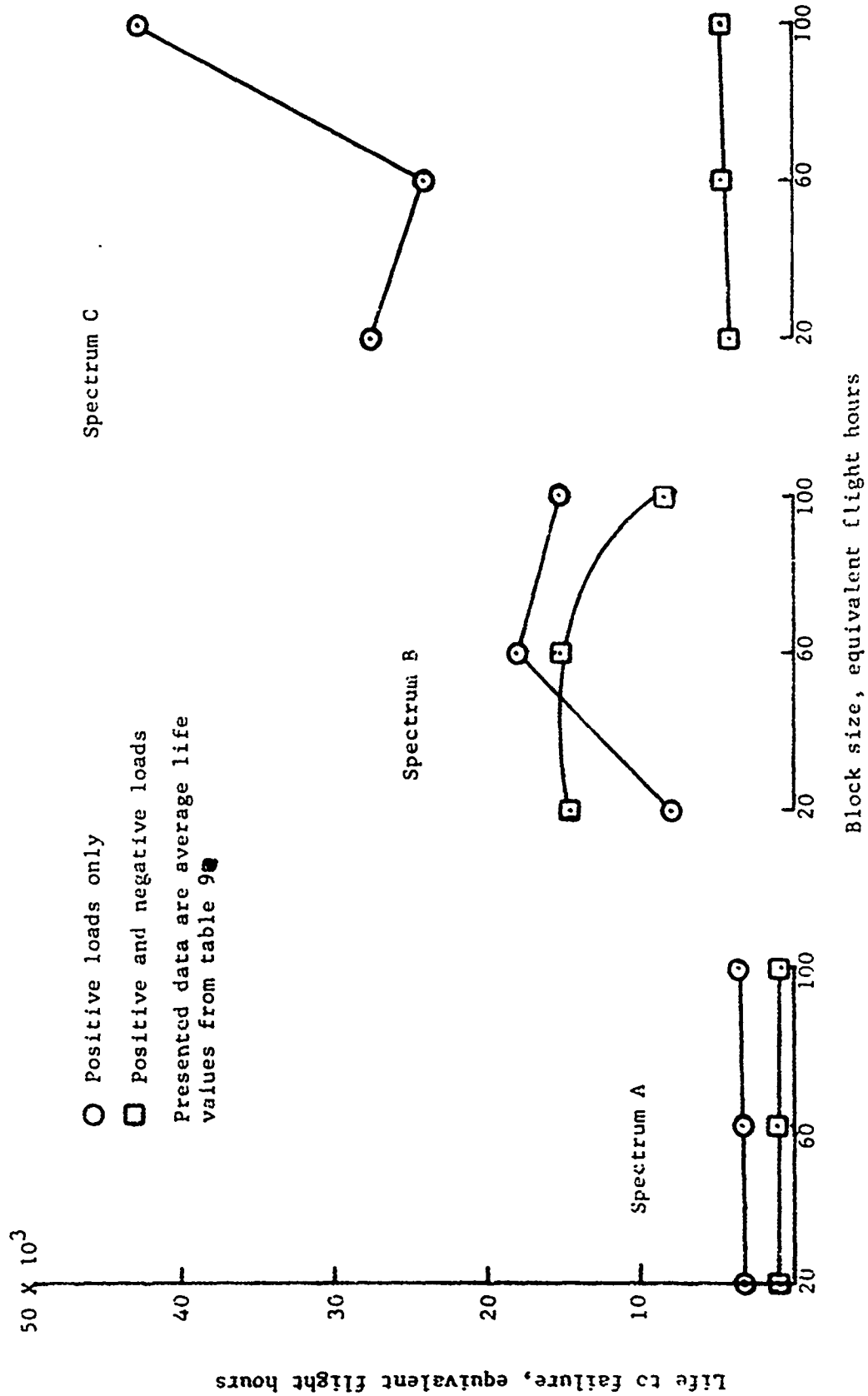


Figure 9--Comparison of average fatigue lives for positive only and positive and negative loads for MIL-A-8866 spectra, random-sequence loading, 11% margin of safety

Presented data are life values from table 11

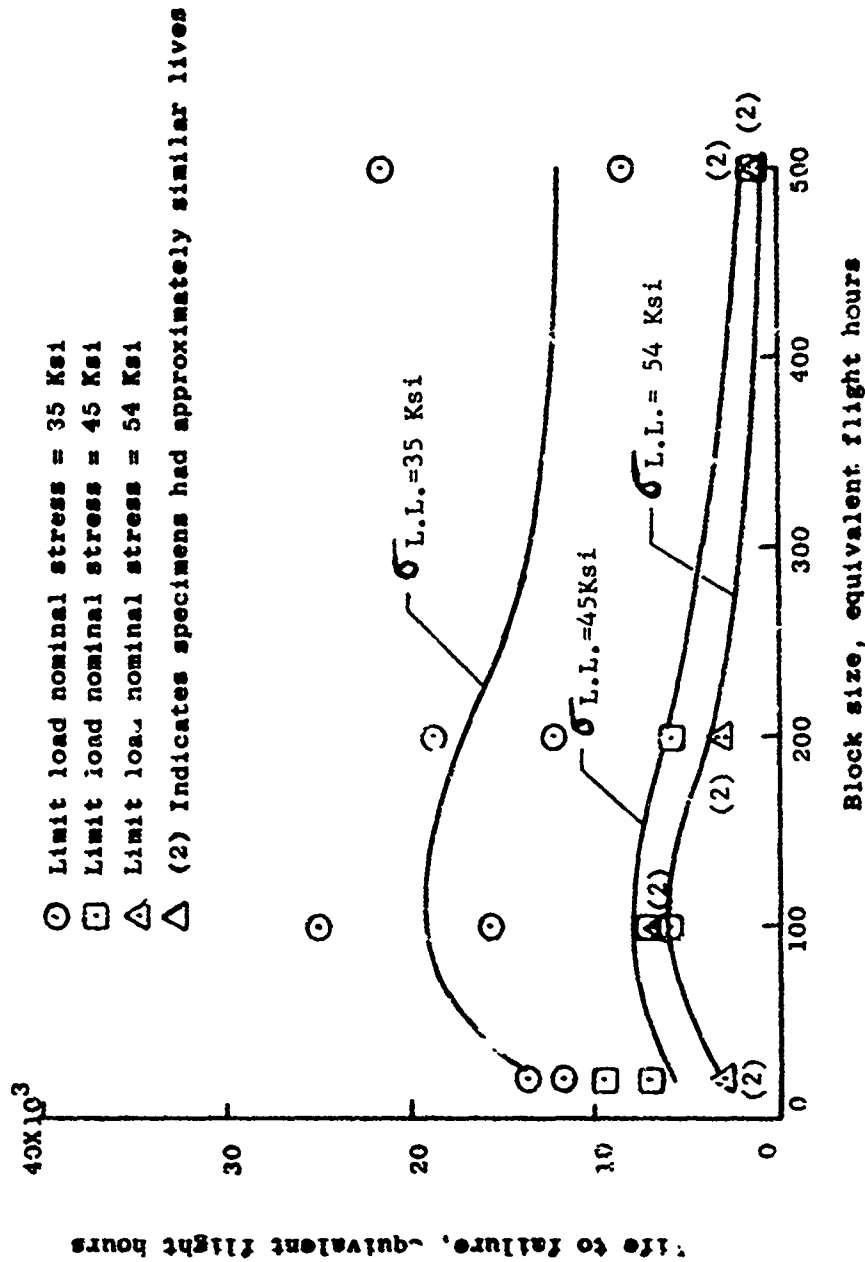
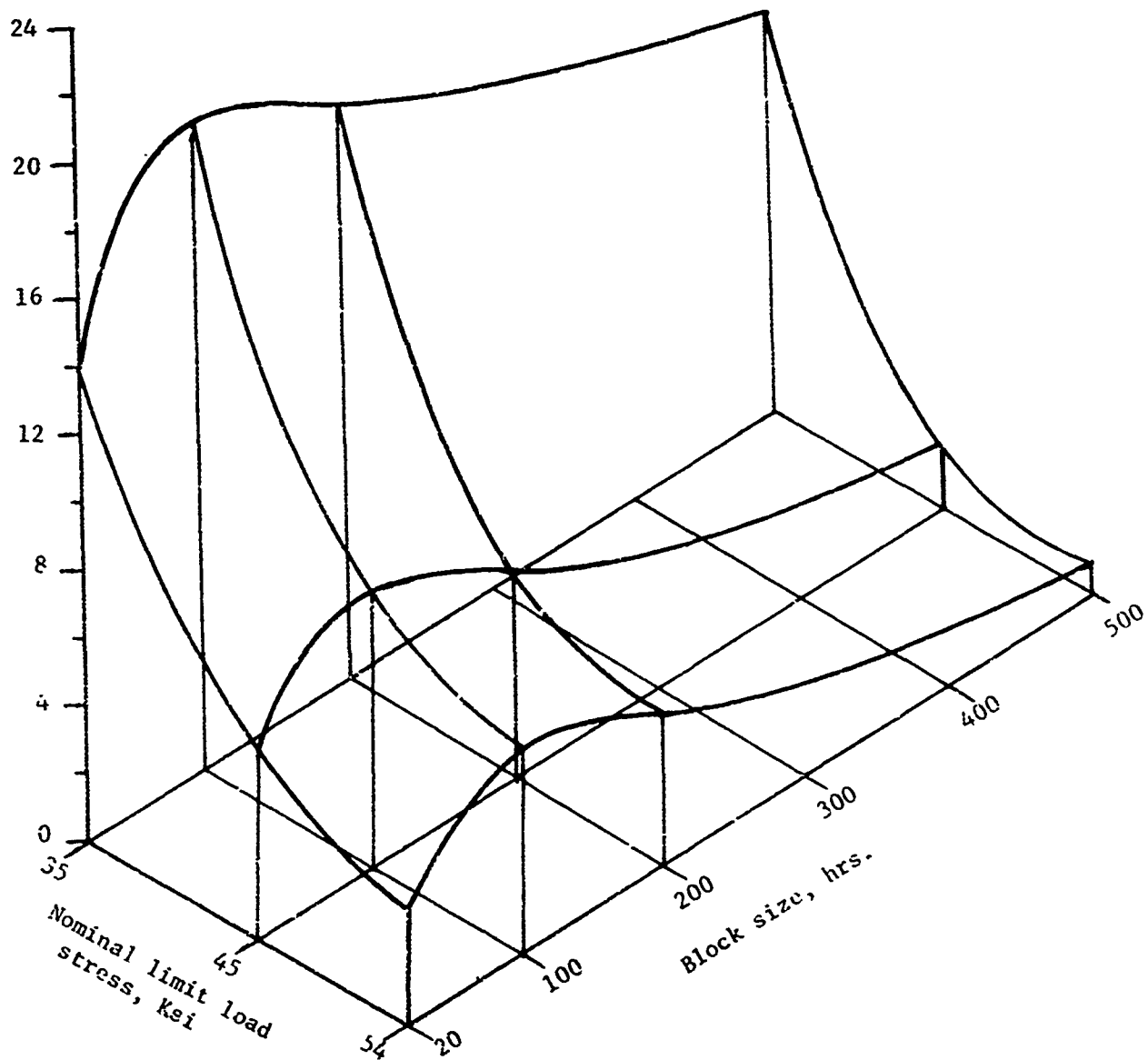


Figure 10--Effect of block size variation on life for limit load stress conditions, Spectrum A, positive loads only, 10-hi fixed-sequence loading

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Curves cross plotted from
Figure 10.

Figure 11--Pictorial presentation of Spectrum A beam fatigue-life data for extended stress-level and block-size ranges, Phase IV, positive loads only, lo-hi fixed-sequence loading