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A note on the loads imposed on fixed-wing light aircraft during agricultural operations

Sewell, Richard

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PAGES _____

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A NOTE ON THE LOADS IMPOSED ON
FIXED-WING LIGHT AIRCRAFT DURING
AGRICULTURAL OPERATIONS

SUBMITTED BY A. H. Hall
PRÉSENTÉ PAR _____
SECTION HEAD
CHEF DE SECTION

AUTHOR Richard Sewell
AUTEUR _____

APPROVED F. R. Thurston
APPROUVÉ _____
DIRECTOR
DIRECTEUR

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A NOTE ON THE LOADS IMPOSED ON FIXED-WING
LIGHT AIRCRAFT DURING AGRICULTURAL OPERATIONS

SUMMARY

This note summarizes the available published information on the flight and ground loads to which fixed-wing light aircraft are subjected during agricultural operations.

Mathematical formulae are developed which may be used to obtain estimates of the total fatigue damage resulting from any combinations of mean stress, stress increment per "g", number of flight hours, and frequency of ground-air-ground cycles per flight hour.

It is shown that the fatigue damage resulting from the loads imposed during taxiing on rough surfaces may be two orders of magnitude greater than that resulting from the average-case flight loads experience.

A NOTE ON THE LOADS IMPOSED ON FIXED-WING
LIGHT AIRCRAFT DURING AGRICULTURAL OPERATIONS

1.0 INTRODUCTION

This note summarizes the available published information on the flight and ground loads to which fixed-wing light aircraft are subjected during agricultural operations.

Estimates of fatigue damage have been obtained for various assumed stress conditions, based on the average flight loads distribution, the measured take-off and landing loads for two different surfaces, and measured rough-surface taxiing loads.

2.0 FLIGHT LOADS

2.1 Available Data

The data summarized are from 706 hours recording, all except 10 hours from counting accelerometer records (peak-count method). The remaining 10 hours data were reduced from oscillograph records.

The aircraft types were:

De Havilland Beaver
Cessna 180
Prospector
Stearman

The first three aircraft were of Australian registry, and were employed on crop-spraying, crop-dusting, and fertilizer spreading. These operations totalled 645 hours. The remaining 61 hours data from the Stearman aircraft were obtained during forest-spraying operations in Eastern Canada. Details of all operations are given in References 1 to 5.

2.2 Combined Gust and Manoeuvre Loads

The results are presented in Figure 1 in terms of the cumulative exceedances per flight hour at various acceleration levels. The distribution given by the solid lines represents the average case given by Payne in Reference 6, and it was from this that the block loading program used in the Cessna wing fatigue tests was derived (Reference 7).

The dashed lines represent the distribution derived by De Havilland of Canada, and used in the fatigue analysis and tests of the Beaver wing strut (Reference 8). The increased frequency of positive loads exceeding 1.75g results from drawing an envelope to include the maximum loads recorded during operations in New Zealand (not referenced in this note), and is termed by De Havilland as representing the worst case. This distribution was also used by Wiebe in fractography research (Reference 9).

The chain-dotted line (positive accelerations only) is that derived from the Canadian operations (Reference 5). In this case, the distribution is limited by the fact that the lowest counting level was set at 2.0g.

In Figure 2, the average-case distribution given by Figure 2 (solid lines) is compared with the average and most severe distributions derived from aerial pipeline patrol operations in Canada (Reference 10).

2.3 Gust Loads

In References 2 and 3, loads due to gusts only were separated from those due to manoeuvres on the basis of analyzing only those portions of the oscillograph records obtained while the aircraft was in straight and level flight.

Equivalent gust velocities were derived from the acceleration records using the discrete-gust method of analysis. The resulting distributions are shown in Figure 3 in terms of the cumulative number of exceedances per flight hour of a given gust velocity.

3.0 GROUND LOADS

A limited amount of ground loads data was obtained during operations with the Prospector aircraft (Reference 3). A total of 15 flights was analyzed - 12 on dusting work with the aircraft operating from an unprepared field, and the remainder on spraying work with the aircraft operating from a prepared grass surface.

The distributions are shown in Figure 4. These are for take-off and landing runs only - taxiing loads are not included.

4.0 TYPICAL FLIGHT PROFILE

Details of a typical flight profile for a Beaver aircraft engaged on crop-dusting are given in Appendix A.

The turns performed at the end of each run are of a special nature, as given below:

At the end of the first run at a speed of approximately 100 knots (115 mph), the pilot breaks down-wind in a full aileron turn, at the same time pulling the nose up. As the speed falls off, approximately 15 degrees flap is selected and the aircraft enters a semi-stalled turn, pulling fairly constant "g" until lined up for the second run. Under normal conditions, the positive accelerations are of the order of 1.5g to 2.0g during the initial break and the turn. Aircraft weight at the end of the first run is approximately 5200 lb.

Flap is not normally used during the second and third turns, but in general, higher "g" loadings are experienced as the weight decreases. These loads go as high as 3.0g, and occasionally, to 3.5g. Entry speed into the second and third turns is of the order of 115 knots (132 mph).

The average altitude above ground is 20 feet during dusting operations and 100 feet during spraying operations.

5.0 FATIGUE LIFE ESTIMATES

For the purposes of fatigue life estimates, the average case distribution of Figure 1 and the ground loads distributions of Figure 4 were transformed to amplitude distributions. These are shown on Figures 5 and 6.

Each of the three load distributions is asymmetric to some degree. Figure 7 shows a plot of amplitude against mean load for the flight loads distribution - which is that having the greatest asymmetry.

In spite of this, it has been assumed that the amplitude distributions are symmetric about the 1.0g mean. The change in true mean load resulting from the maximum observed deviation of 0.115g from the 1.0g mean at an amplitude of approximately 0.75g is considered insignificant in its effect on the estimated fatigue damage at that level.

The average frequency of flights is given in Reference 1 as 11 per hour. This value has been assumed in deriving the ground loads frequencies per hour. (The distributions of Figure 6 are given in terms of cycles per event - that is, one landing or take-off).

Damage calculations were carried out using the Miner-Palmgren hypothesis of cumulative damage and the S-N curves of Reference 11 for typical wings and tailplanes of aluminum alloy construction. These calculations were performed for a number of assumed 1.0g mean stresses between 3 ksi and 15 ksi (stress increment per "g" assumed equal to the mean stress), for a bandwidth of 0.05g and for each of the following cases:

- (a) Flight loads only
- (b) Flight loads plus ground loads (unprepared surface)
- (c) Flight loads plus ground loads (grass surface)

The estimated unfactored fatigue lives for each of the above cases are plotted on Figure 8 against mean stress.

The cumulative damage per-flight hour or per take-off and landing can be expressed as a function of the assumed mean stress when the stress increment per "g" is equal to the mean stress. This relationship has been plotted on Figure 9 for flight loads only, and on Figure 10 for ground loads only.

The best-fit polynomials for these curves are:

- (a) Flight loads only:

$$\log_{10} D_1 = -7.316724 + 2.738329x + 3.482397x^2 - 1.507850x^3 \quad (1)$$

- (b) Ground loads only (unprepared field):

$$\log_{10} D_2 = -9.154891 + 2.557742x + 3.741288x^2 - 1.677830x^3 \quad (2)$$

(c) Ground loads only (grass surface):

$$\log_{10} D_3 = -9.746102 + 2.585780x + 3.701407x^2 - 1.651199x^3 \quad (3)$$

$$\begin{aligned} \text{where } x &= \log_{10} S_m \\ S_m &= \text{mean stress (ksi)} \end{aligned}$$

Further calculations were carried out for assumed constant mean stresses, but varying the stress increment per "g" within limits of ± 2 ksi from the mean.

It was found that irrespective of the distribution of flight or ground loads, a mathematical relationship could be established between the stress ratio and the corresponding cumulative damage ratio, these two parameters being defined as:

$$\text{Stress ratio} = S_r = \frac{S_g}{S_m} \quad (4)$$

$$\begin{aligned} \text{where } S_g &= \text{stress increment per "g"} \\ S_m &= \text{assumed mean stress} \end{aligned}$$

and the cumulative damage ratio is the ratio of the total damage at any value of S_g not equal to S_m to the total damage when the value of the stress ratio is equal to unity.

This relationship is plotted on Figure 11. The best-fit polynomial is:

$$\log_{10} D_r = -0.000584 + 3.785878y + 0.157431y^2 + 0.878928y^3 \quad (5)$$

$$\text{where } y = \log_{10} S_r$$

Using equations (1), (2), (3) and (5), it is then possible to calculate the total damage for any combination of mean stress, stress increment per "g", number of flight hours, and number of ground-air-ground cycles per hour for either one or both of two surfaces.

For example, given that the number of flight hours is N_1 , the number of ground-air-ground cycles per hour is N_2 for the unprepared surface and N_3 for the grass surface, the unit cumulative damage in each case is D_1 , D_2 and D_3 , and the damage ratios corresponding to the stress ratio in each case are D_{r1} , D_{r2} and D_{r3} , the total damage is:

$$D_t = N_1(D_1 \cdot D_{r1} + N_2 \cdot D_2 \cdot D_{r2} + N_3 \cdot D_3 \cdot D_{r3}) \quad (6)$$

and the estimated unfactored fatigue life is:

$$L = \frac{N_1}{D_t} \quad (7)$$

Trial calculations using equation (6) show that the results obtained are within a maximum of 4 percent of those obtained by a step-by-step calculation for each condition. Greater accuracy could be obtained by increasing the number of coefficients in the calculation of D and D_r , but this is not considered to be necessary.

6.0 DISCUSSION

6.1 Flight Loads

The average-case distribution shown on Figure 1, based on a total of 706 hours recording, may be considered statistically significant and representative of the flight loads to which

light aircraft are subjected during agricultural operations of all types.

It is of interest to note that Reference 1 draws attention to the negative "g" manoeuvres performed with the Cessna aircraft in order to close the hopper doors at the end of each flight. The average acceleration increment associated with this manoeuvre is $-0.98g$, with a maximum value of $-1.27g$. For the stated average flight duration of 3.9 minutes, zero "g" conditions (weightlessness) should then occur approximately 15 times per hour. Since the average distribution gives the frequency of occurrence of this condition only once per hour, it would appear that the majority of operations would be spraying (which would not necessitate the manoeuvre), or that this particular type of manoeuvre is not necessary for all types of aircraft and hopper design.

Figure 2 shows that the average-case agricultural distribution is approximately equal in severity to the most-severe case derived from pipeline patrol operations. This is at first sight rather surprising in view of the fact that the pipeline patrol operations involve terrain-following in conditions of moderate-to-severe turbulence with wind speeds of the order of 20 mph. However, agricultural operations necessitate the performance of relatively high "g" manoeuvres at frequent intervals.

6.2 Ground Loads

The distributions shown on Figure 4 were derived from recordings taken on the Prospector aircraft (Reference 3). Twelve dusting flights from an unprepared field and three spraying flights from a grass surface airfield were analyzed.

Since the number of samples is so small, the results cannot be considered statistically significant. Nevertheless, they have been included in the calculations in order to obtain an approximate indication of the extent to which ground loads affect the total fatigue damage.

6.3 Gust Loads

The sampling times from which the gust distributions of Figure 3 were derived were so short that these distributions cannot be considered statistically significant. Moreover, an anomaly exists in that the Prospector distribution is markedly more severe than the Beaver distribution, yet the former aircraft was operating in dry, overcast conditions with light winds, and the latter in cold and wet conditions with gusty winds. References 2 and 3 do not comment on this anomaly.

Since no specific statements of exclusion have been made in any of the reports from which the overall flight loads distribution has been derived, it is to be presumed that this distribution includes loads resulting from gust encounters.

The commonly-held view that agricultural operations are carried out only in calm conditions does not appear to be correct in all circumstances. For example, the experiments with Cessna VH-PAV were carried out in very hot weather (temperature 98 deg.F) with strong gusting north winds, the aircraft being employed in aerial top-dressing operations.

6.4 Taxying Loads

Up to this point, no reference has been made to loads experienced during taxying.

In Reference 12, Benoy concludes from theoretical analyses supported by experimental data that the Cessna 180 service

failures at the rear spar of the wing root were primarily due to appreciable tensile stresses developed during taxiing on rough surfaces.

Figure 12 shows the mean stress and stress amplitude frequency distributions for a taxiing speed of 20 knots. Reference 12 states that the effect of taxiing at various speeds may be represented by the application of these distributions for a total time of 30 seconds per ground-air-ground cycle.

Calculations show that the damage resulting from imposition of these taxiing loads for a single period of 30 seconds is approximately 40 times greater than that resulting from the loads experienced during one hour's flight at the same mean stress level.

Figure 13 shows the ratio of taxiing damage for three flight-per-hour frequencies to flight-hour damage plotted against mean level flight stress, on the assumption that the stress amplitude - frequency distribution during taxiing remains invariant.

Figure 14 shows the estimated fatigue life with and without taxiing loads plotted against mean level flight stress. The estimated life of approximately 2000 hours at stress levels below 4 ksi is in close agreement with the minimum service life of 1610 hours reported in Reference 12.

If the taxiing damage based on the Cessna 180 data were to be included in a general assessment of the total fatigue damage, it would be necessary to increase the total damage calculated from equation (6) by an amount equal to $N_1 \cdot N_4 (2.42 \times 10^{-5})$, where N_1 is the number of flight hours and N_4 is the total number of ground-air-ground cycles per flight hour.

7.0 CONCLUSIONS

The formula developed in equation (6) of this note may be used to estimate the cumulative damage resulting from flight and ground loads, excluding taxiing loads, for an aircraft employed on agricultural operations, provided that the stresses in critical areas are known or can be estimated.

It is shown that at low stress levels, the damage resulting from the loads imposed during taxiing on rough surfaces may be, on the average, two orders of magnitude greater than that resulting from the flight loads. However, it must be emphasized that the taxiing load estimates are based on a small amount of data from one aircraft type only, and it would be grossly incorrect to arrive at any general conclusions. Aircraft types other than the Cessna 180 would undoubtedly exhibit entirely different stress distributions and failure modes.

Nevertheless, it is considered that sufficient evidence has been presented concerning the possible serious effects of taxiing loads to warrant thorough investigation of these effects for other aircraft types.

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APPENDIX A

TYPICAL CROP-DUSTING FLIGHT PROFILE BASED ON
AUSTRALIAN EXPERIENCE WITH BEAVER AIRCRAFT

Average flight duration (including ground time)	5.5 minutes.
Ground time (touchdown to lift-off)	1.0 minutes.
Fuel load at start of flight	1400 lb.
Mean take-off weight	5900 lb.
Payload	2240 lb.
Mean flying weight	4730 lb.
Number of runs per flight	3
Number of turns per flight	3
Average flight speeds:	
Lift-off to start of run 1	75 knots (86 mph)
Start of run 1 to end of run 3	100 knots (115 mph)
End of run 3 to start of approach	115 knots (132 mph)
Approach	75 knots (86 mph)
Speed on entering turns:	
Flap-aileron turns	90 knots (104 mph)
Aileron only turns	115 knots (132 mph)
Average amount of flap used in flap-aileron turns	15-20 degrees
Positive acceleration with flap selected	1.5g to 2.5g
Maximum acceleration recorded (aileron only turn)	3.5g

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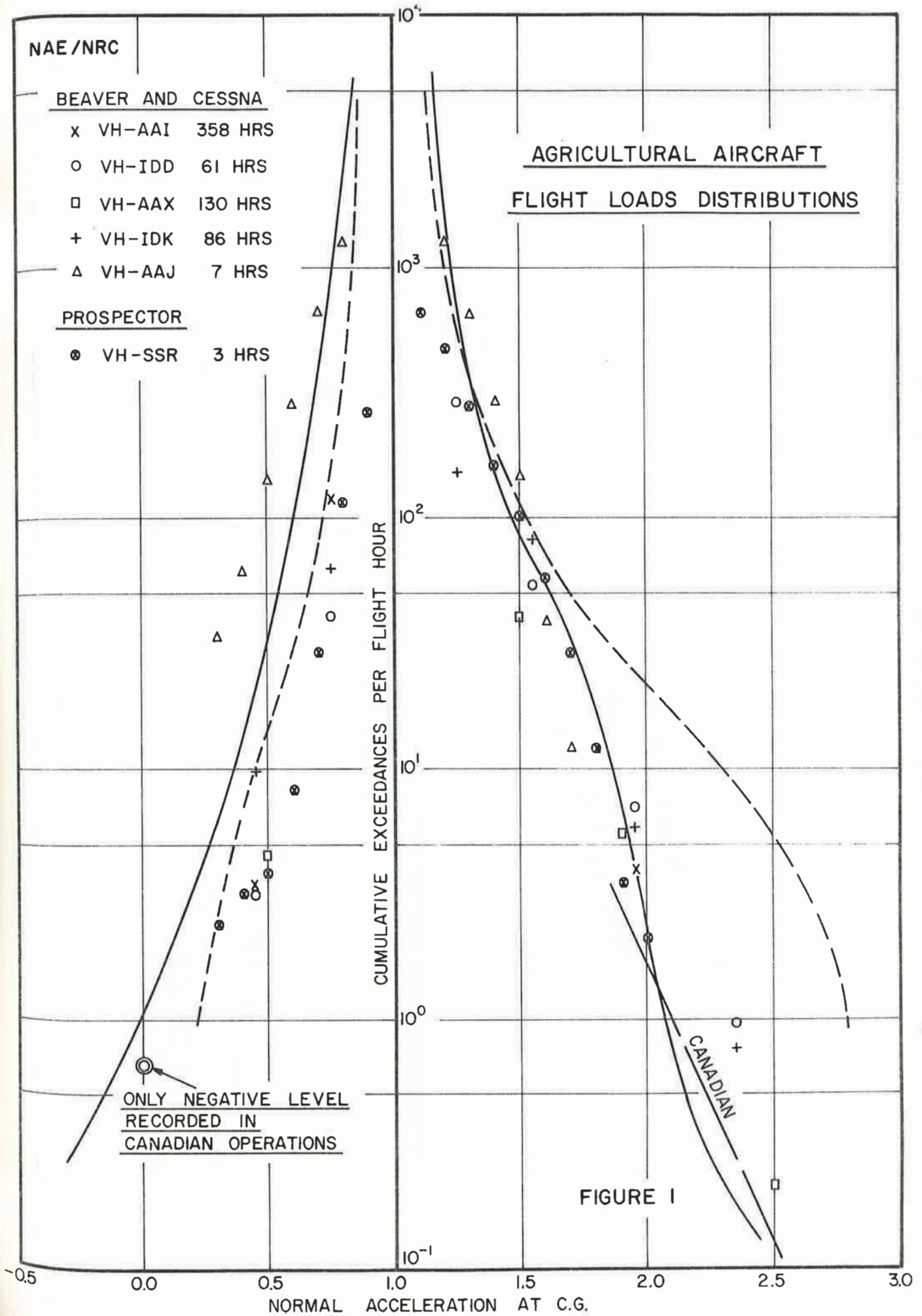
BEAVER AND CESSNA

- x VH-AAI 358 HRS
- o VH-IDD 61 HRS
- VH-AAX 130 HRS
- + VH-IDK 86 HRS
- △ VH-AAJ 7 HRS

PROSPECTOR

- ⊗ VH-SSR 3 HRS

AGRICULTURAL AIRCRAFT
FLIGHT LOADS DISTRIBUTIONS



COMPARISON OF AGRICULTURAL
AND PIPELINE PATROL FLIGHT LOADS

AVERAGE SPEED 100 KNOTS

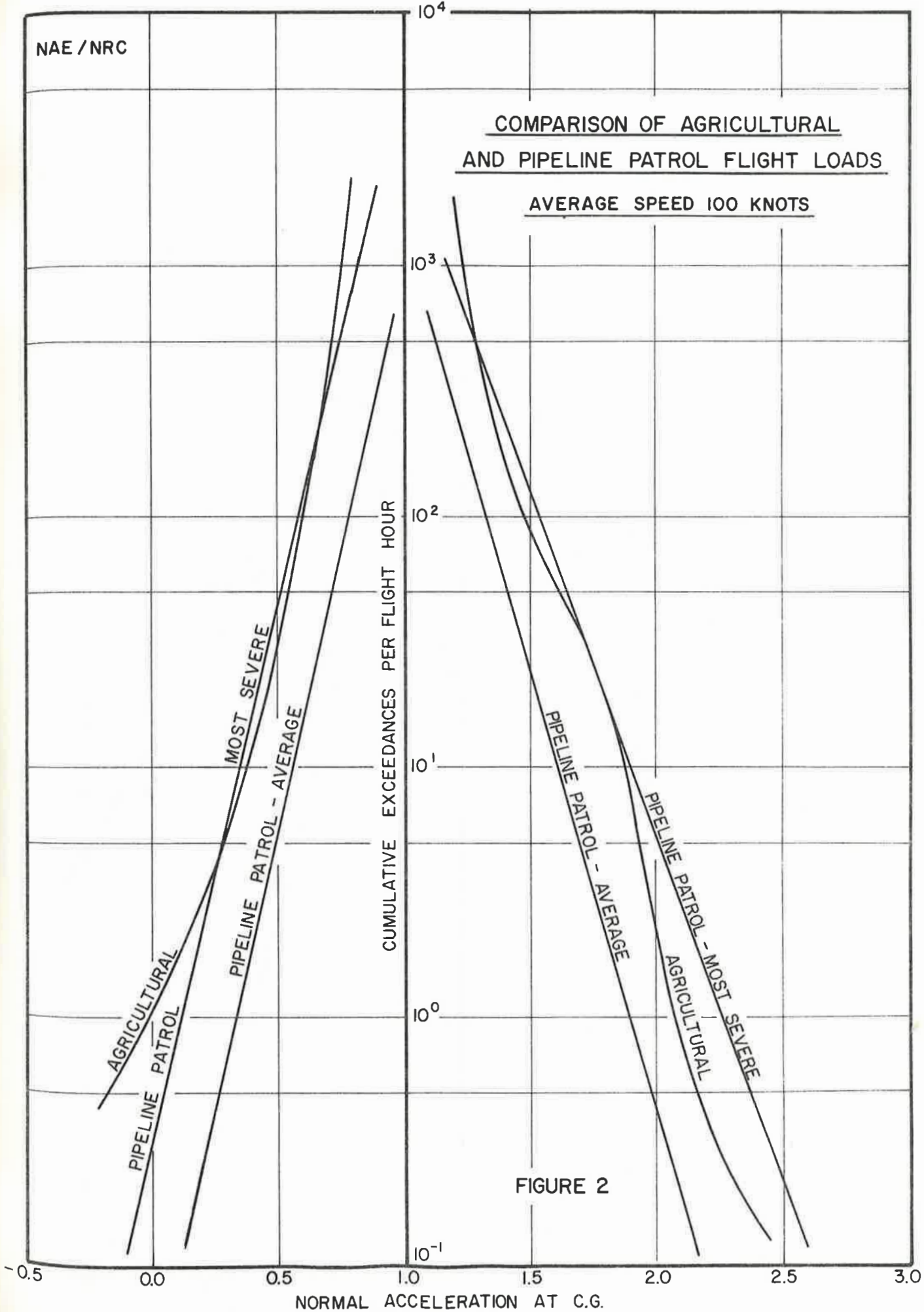
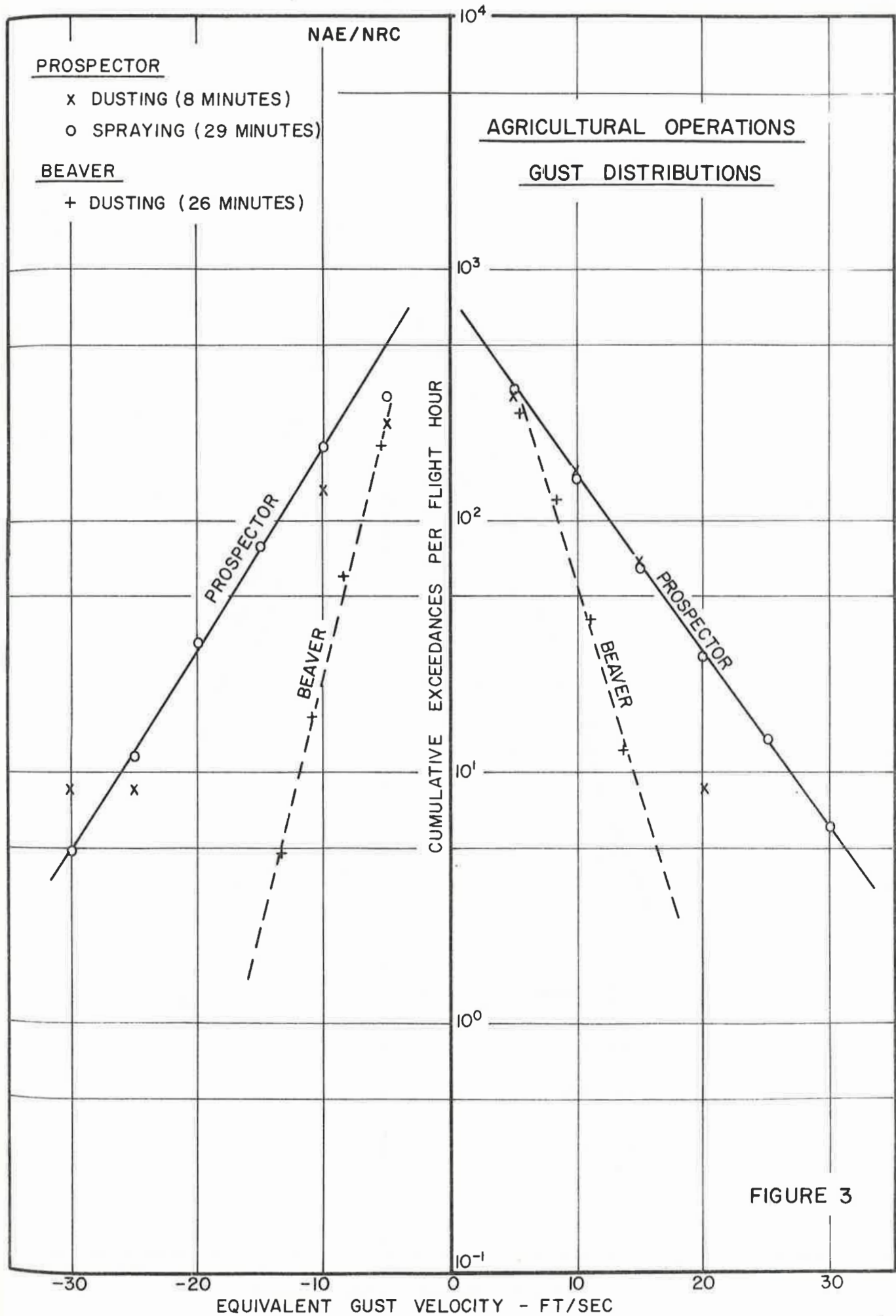
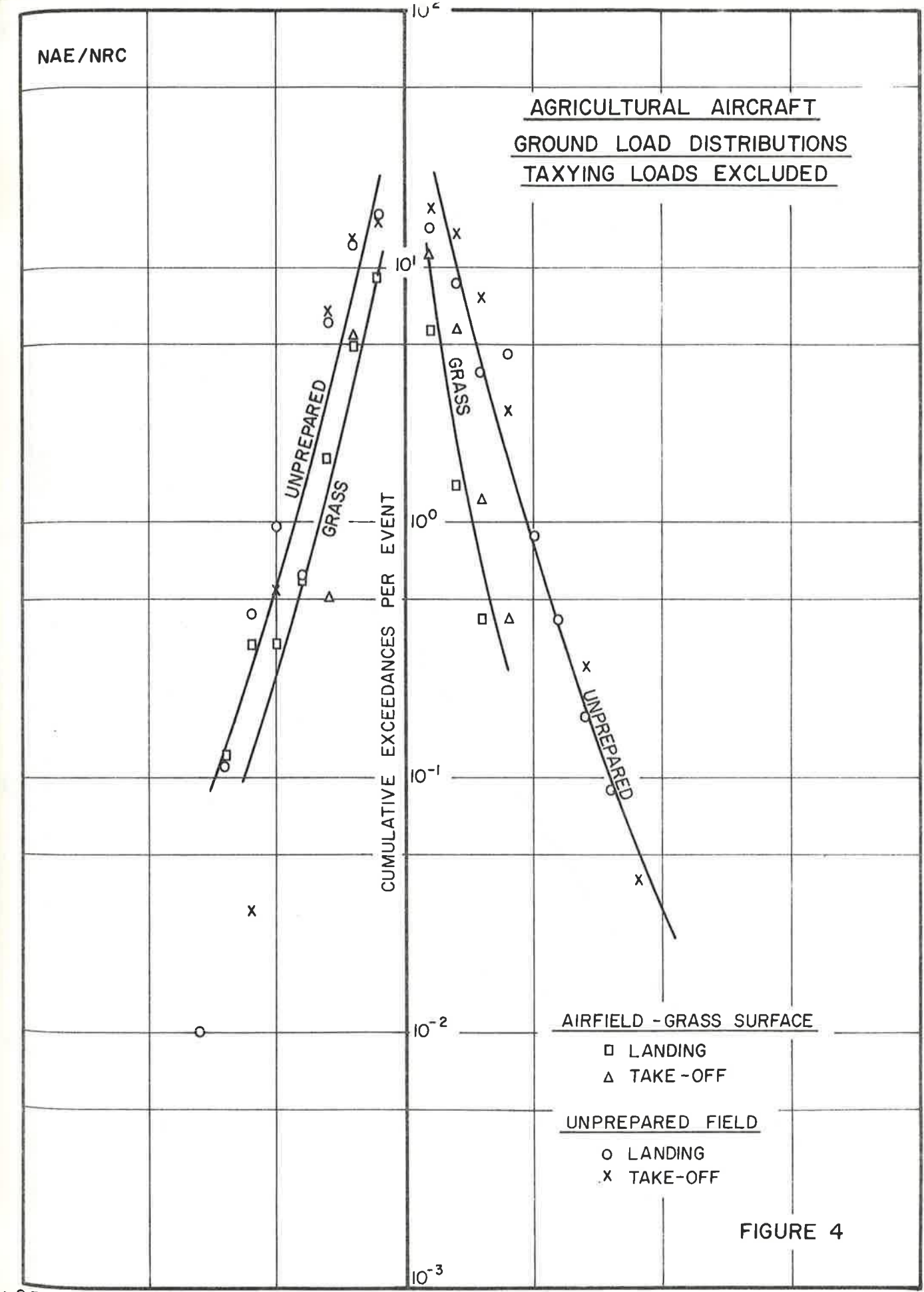


FIGURE 2



AGRICULTURAL AIRCRAFT
GROUND LOAD DISTRIBUTIONS
TAXIING LOADS EXCLUDED

CUMULATIVE EXCEEDANCES PER EVENT



AIRFIELD - GRASS SURFACE

- LANDING
- △ TAKE-OFF

UNPREPARED FIELD

- LANDING
- x TAKE-OFF

FIGURE 4

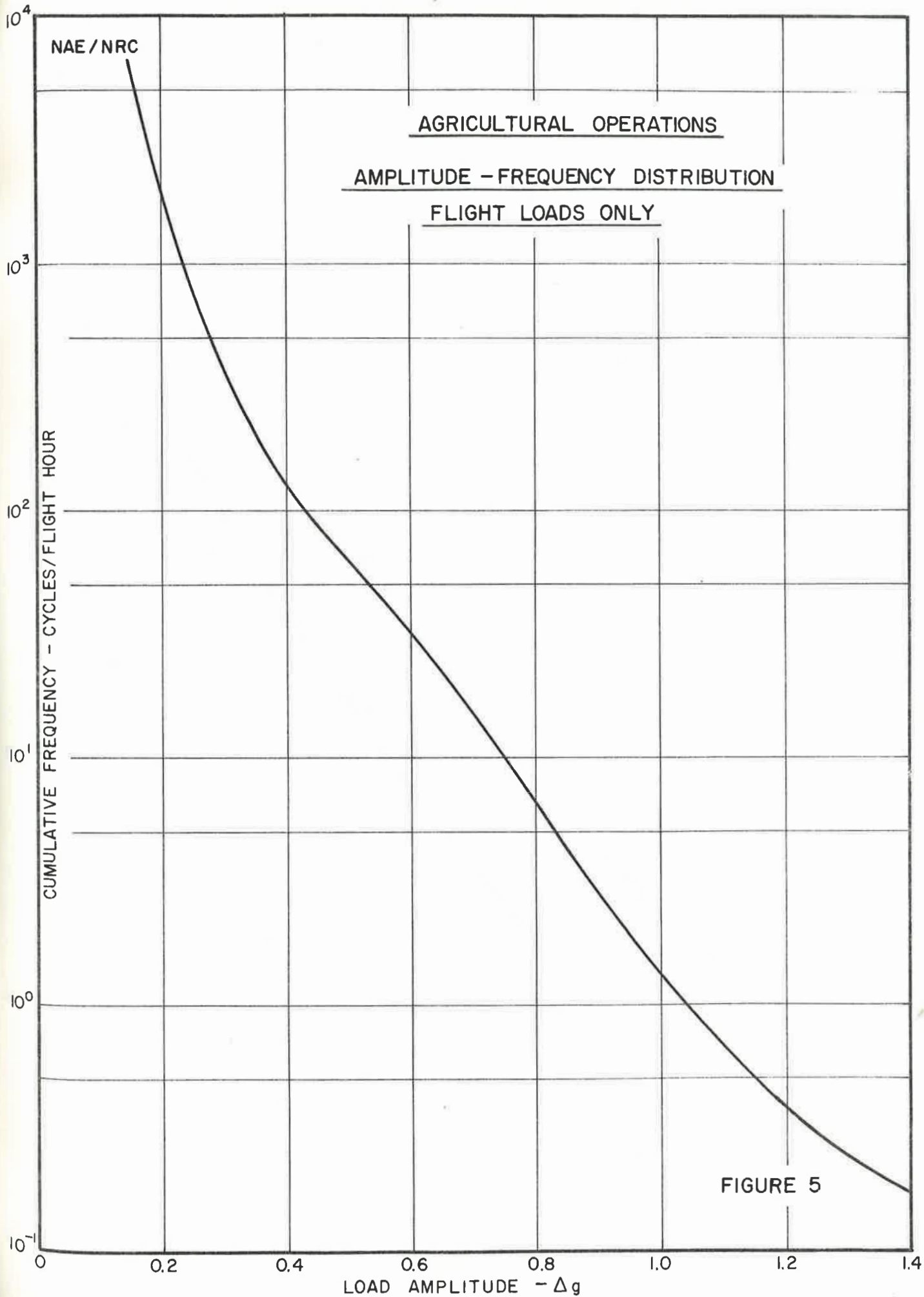


FIGURE 5

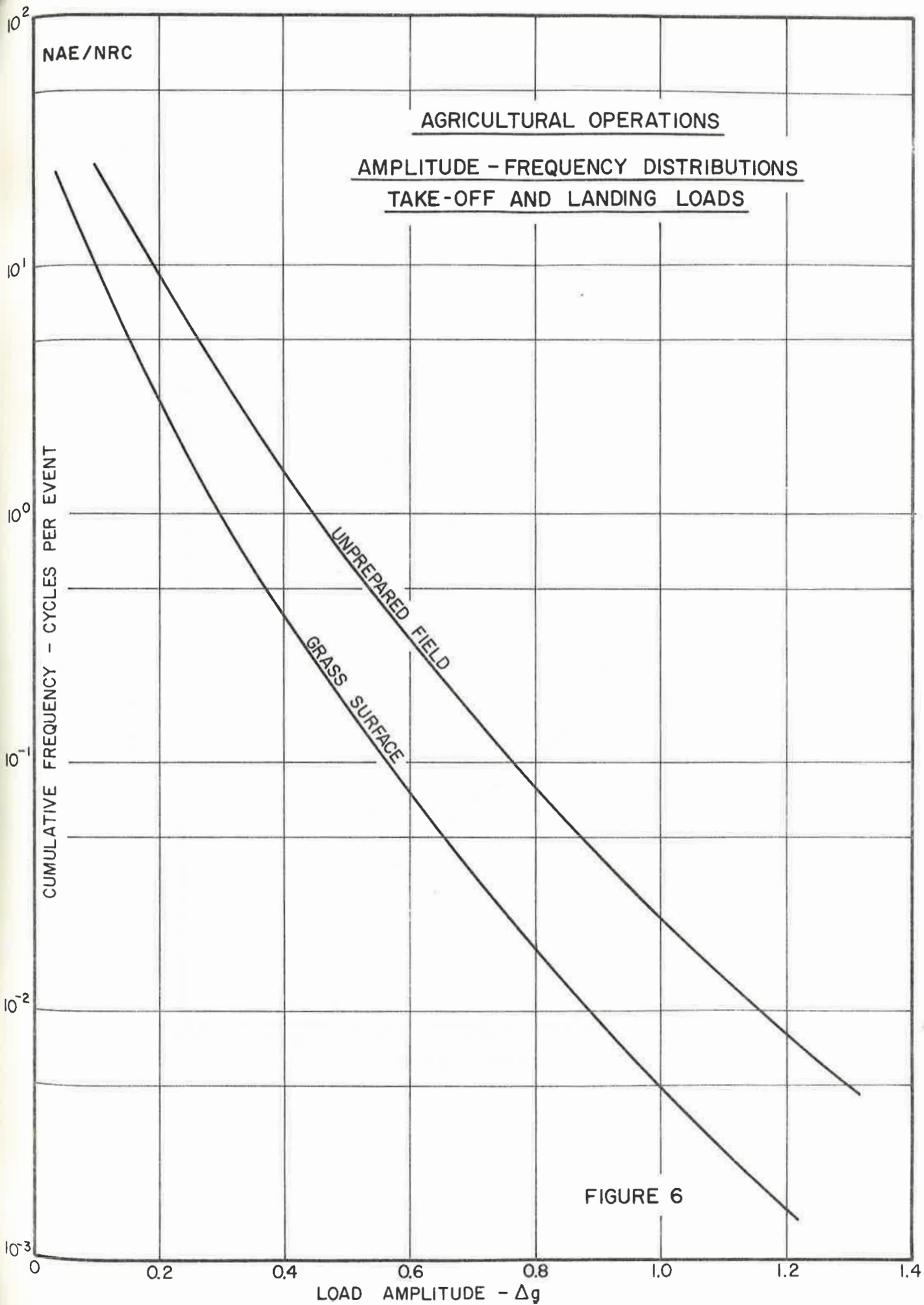


FIGURE 6

FLIGHT LOADS DISTRIBUTION

VARIATION OF MEAN LOAD
WITH AMPLITUDE

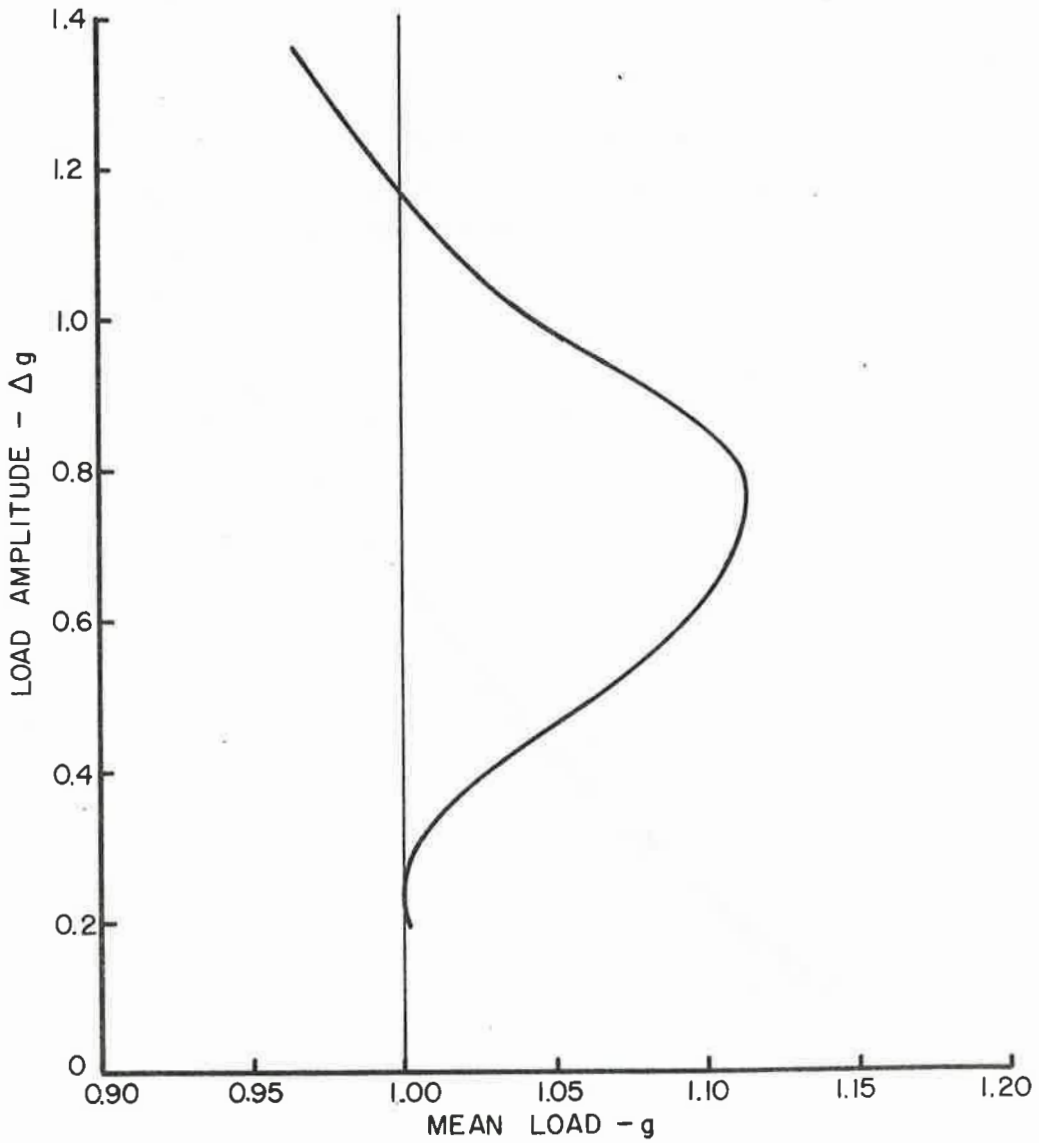


FIGURE 7

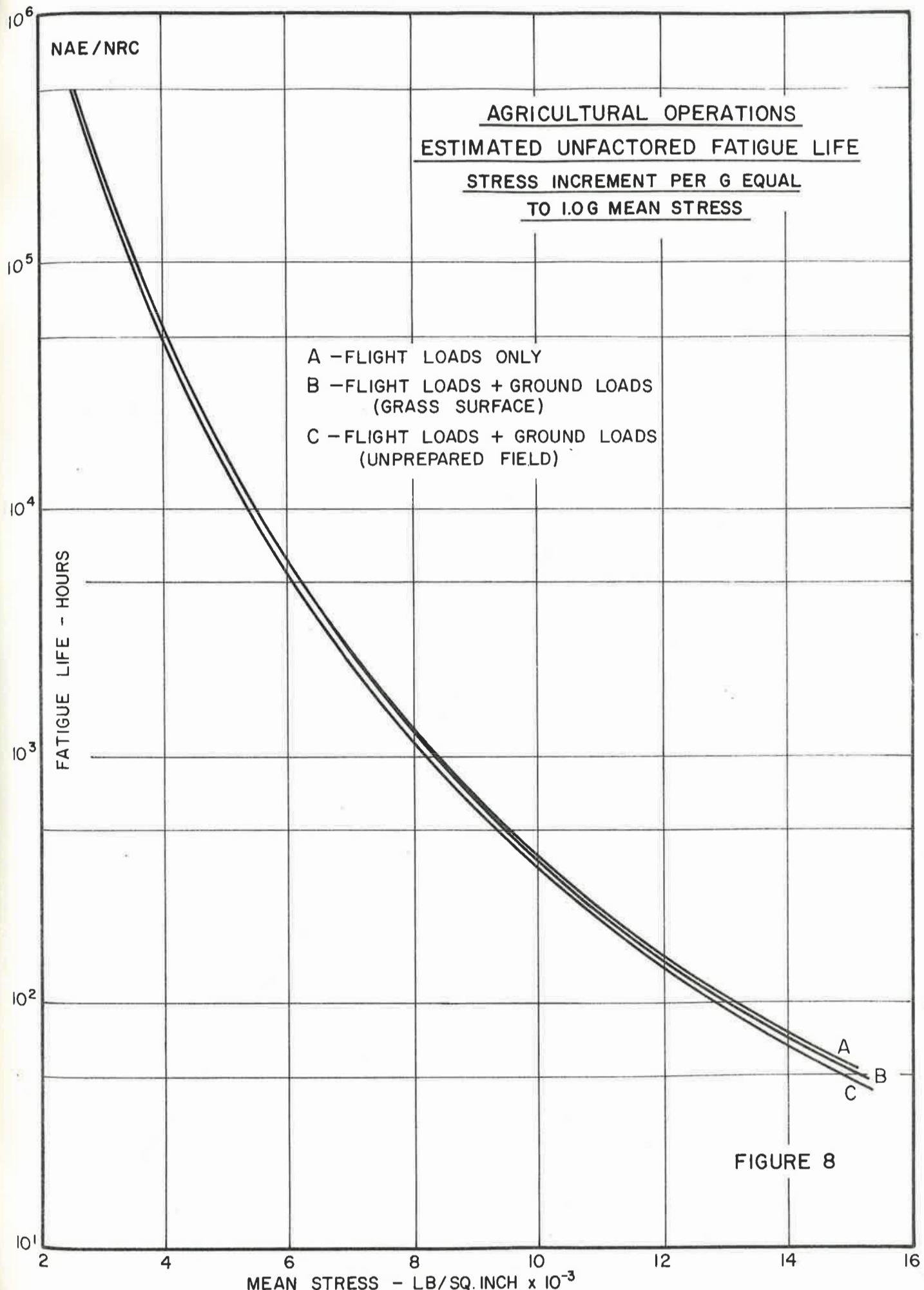


FIGURE 8

NAE /NRC

AGRICULTURAL OPERATIONS

CUMULATIVE DAMAGE vs MEAN STRESS

FLIGHT LOADS

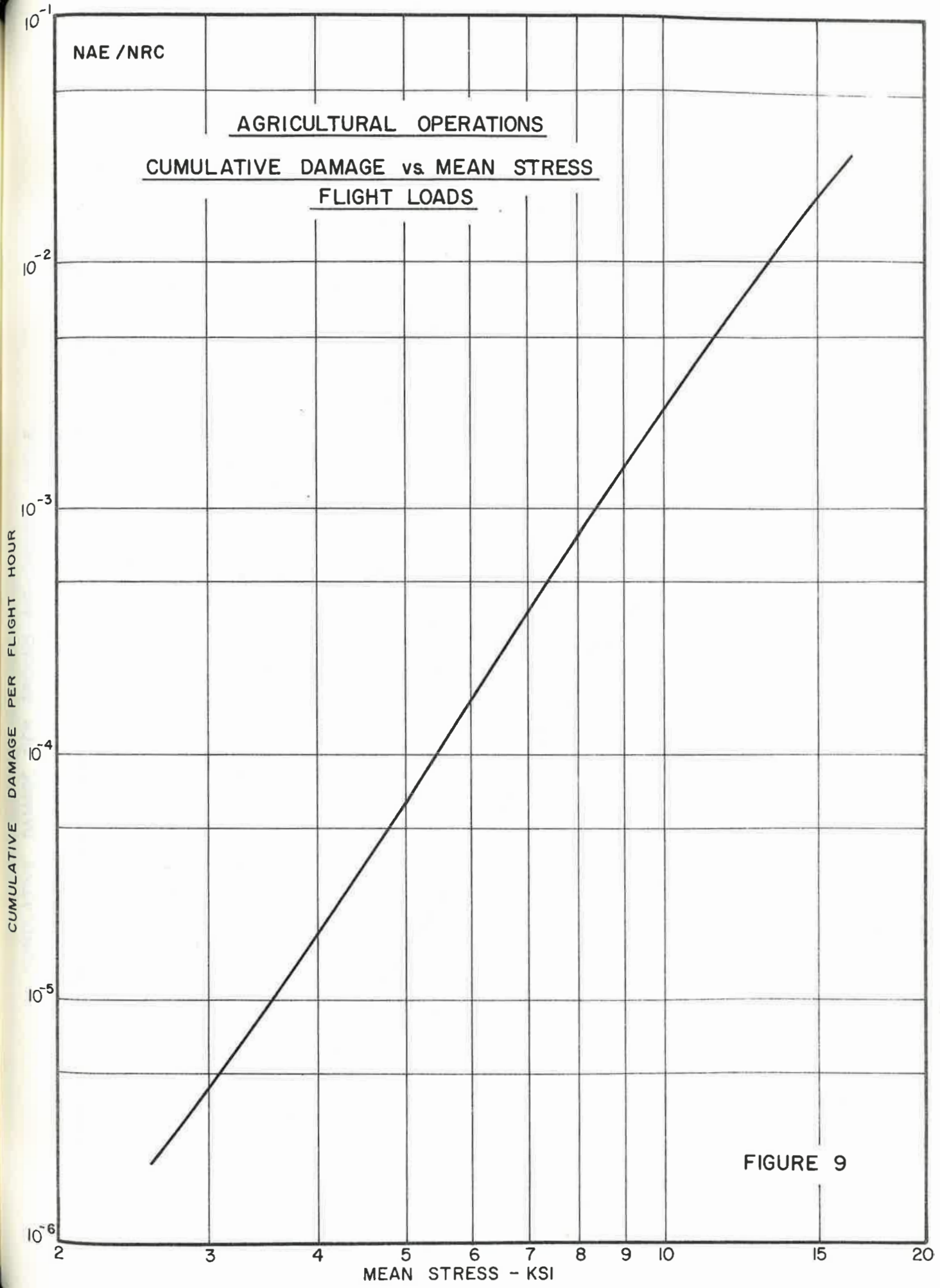


FIGURE 9

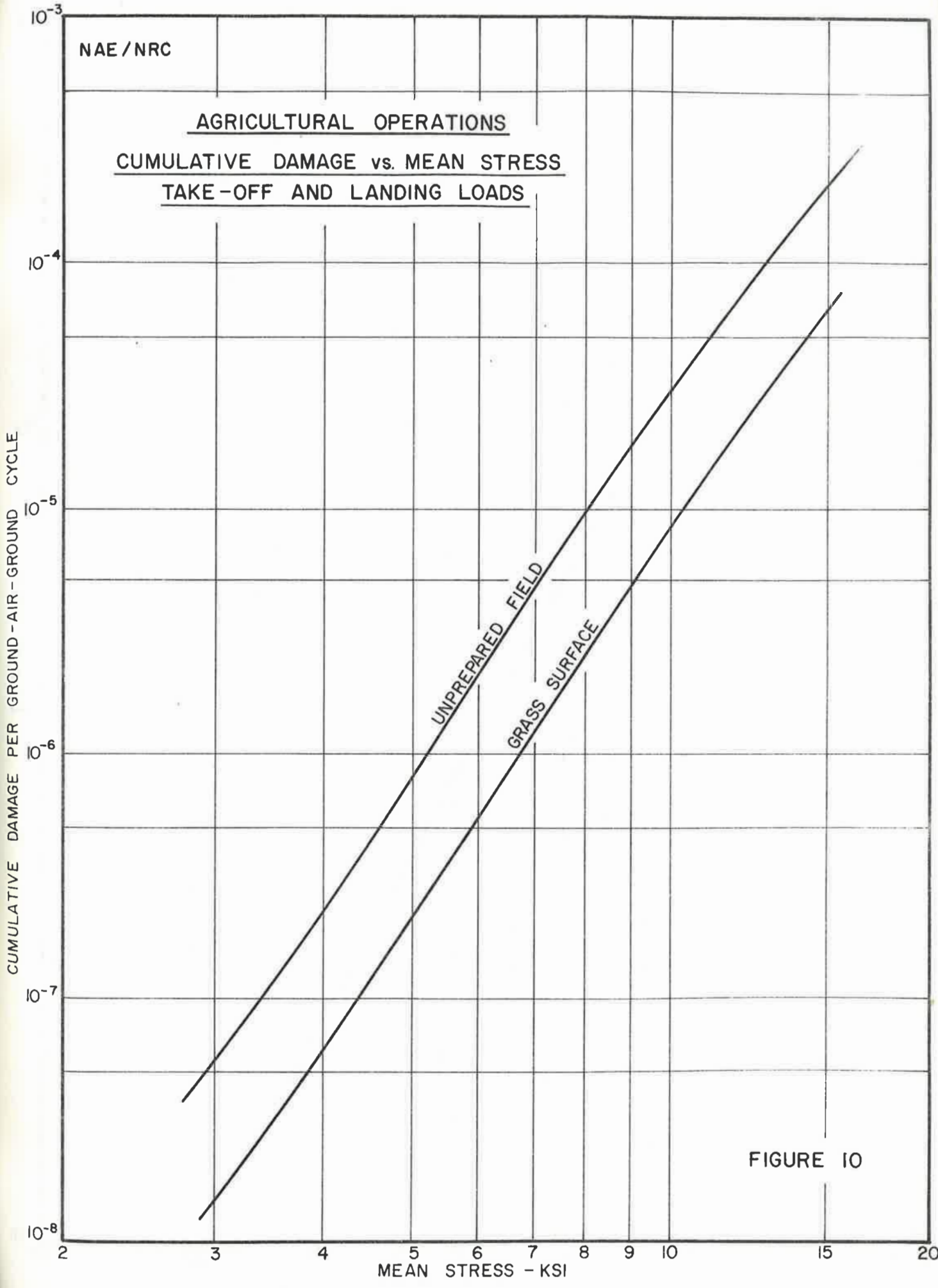


FIGURE 10

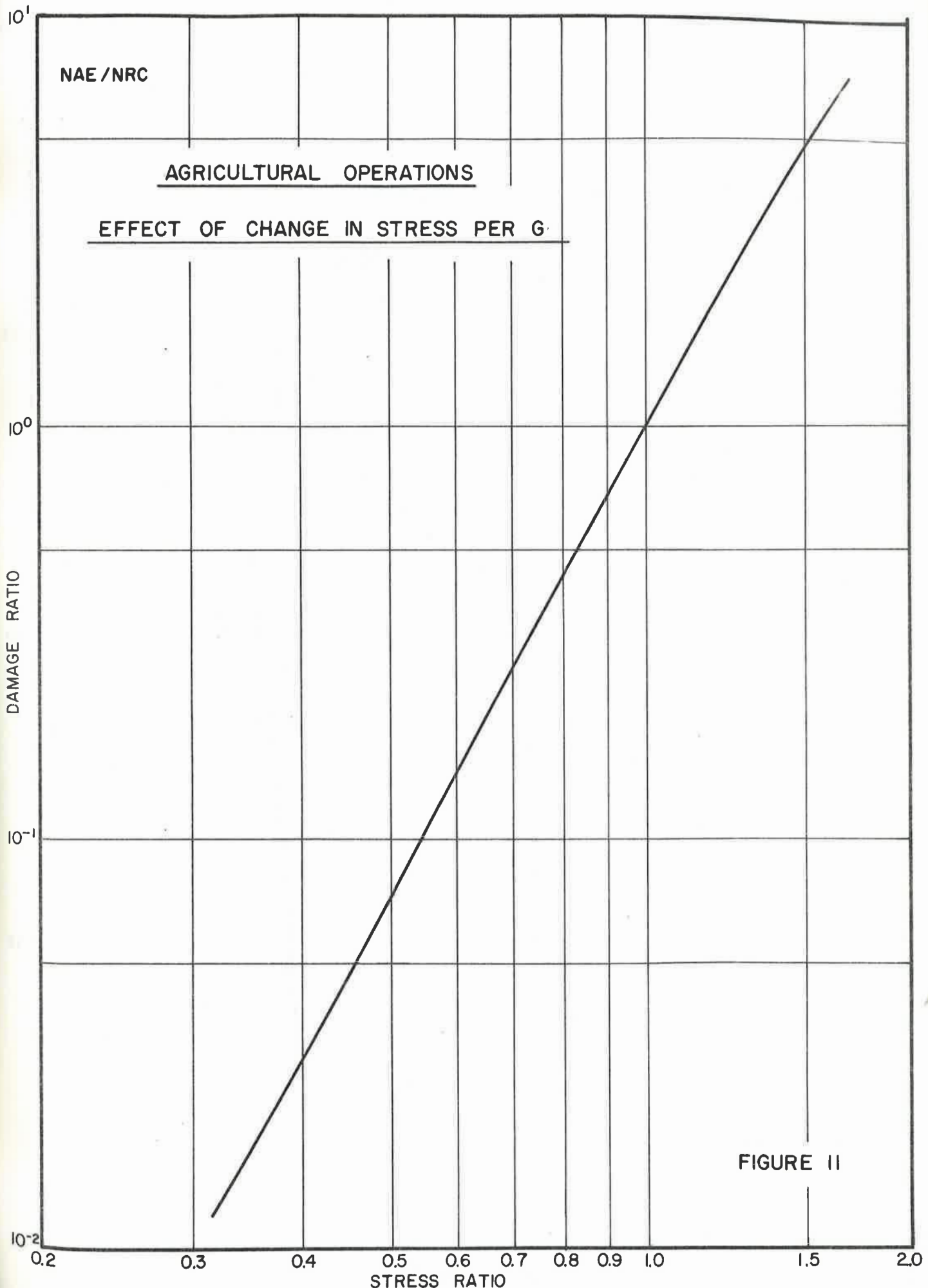


FIGURE 11

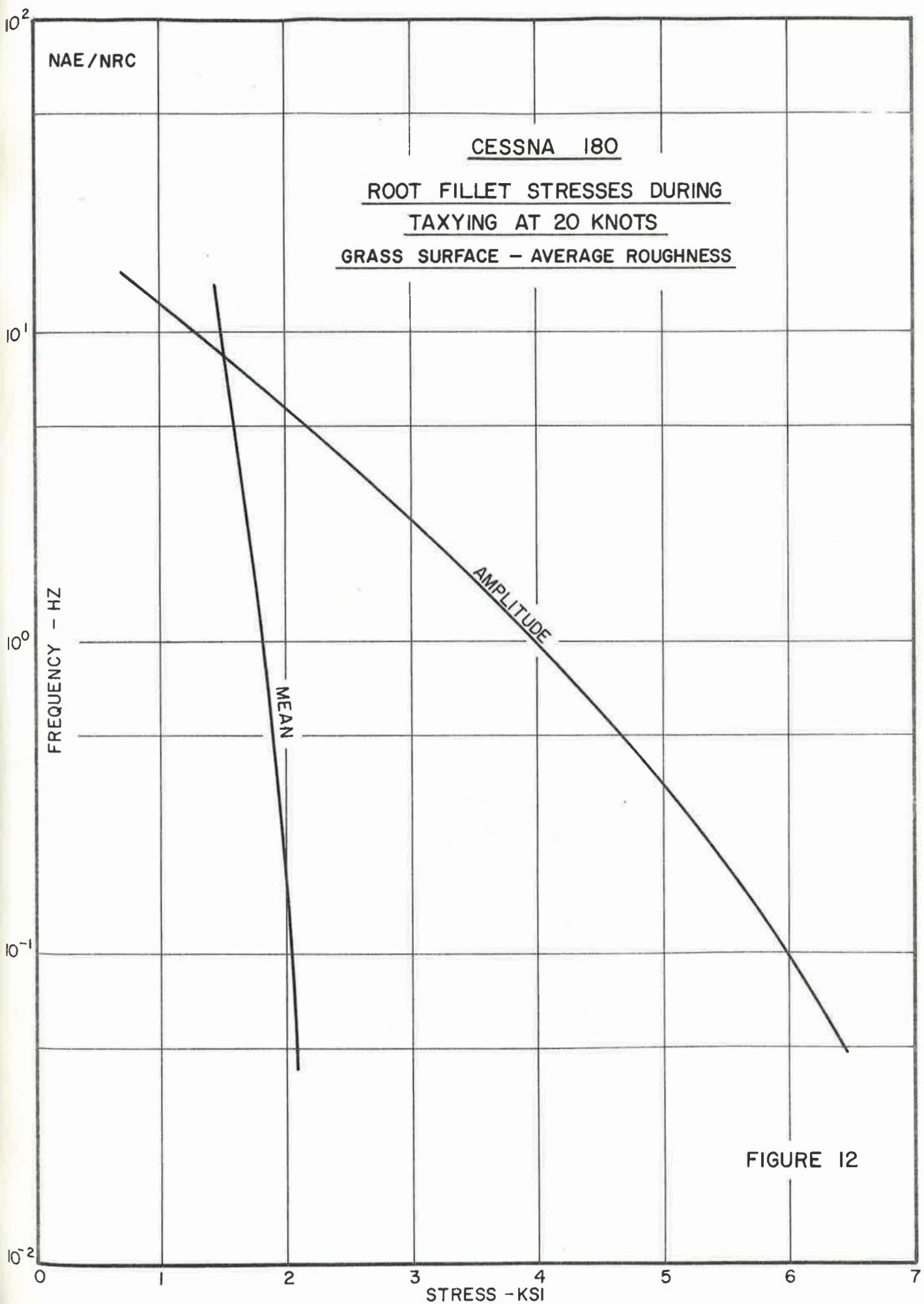


FIGURE 12

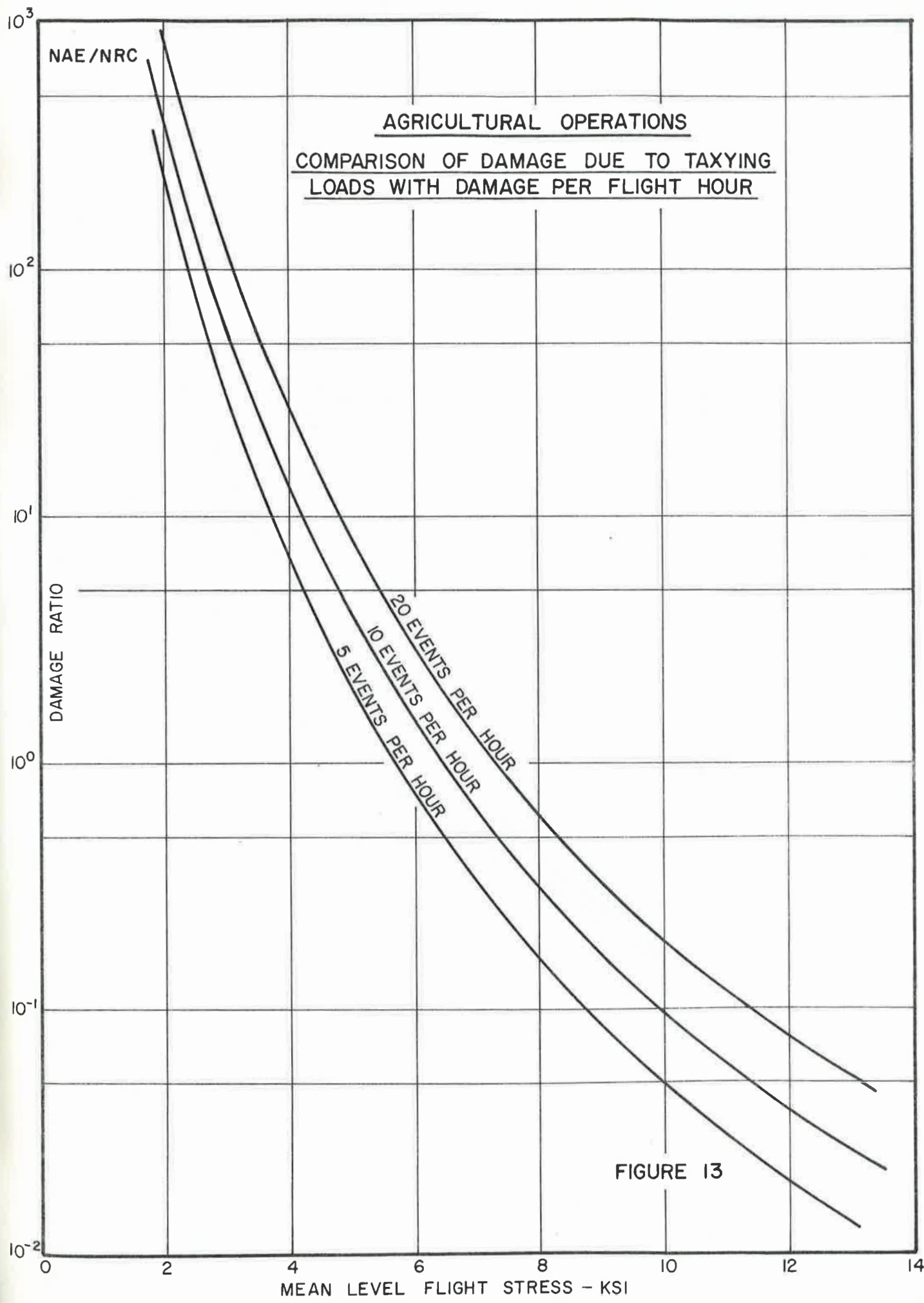


FIGURE 13

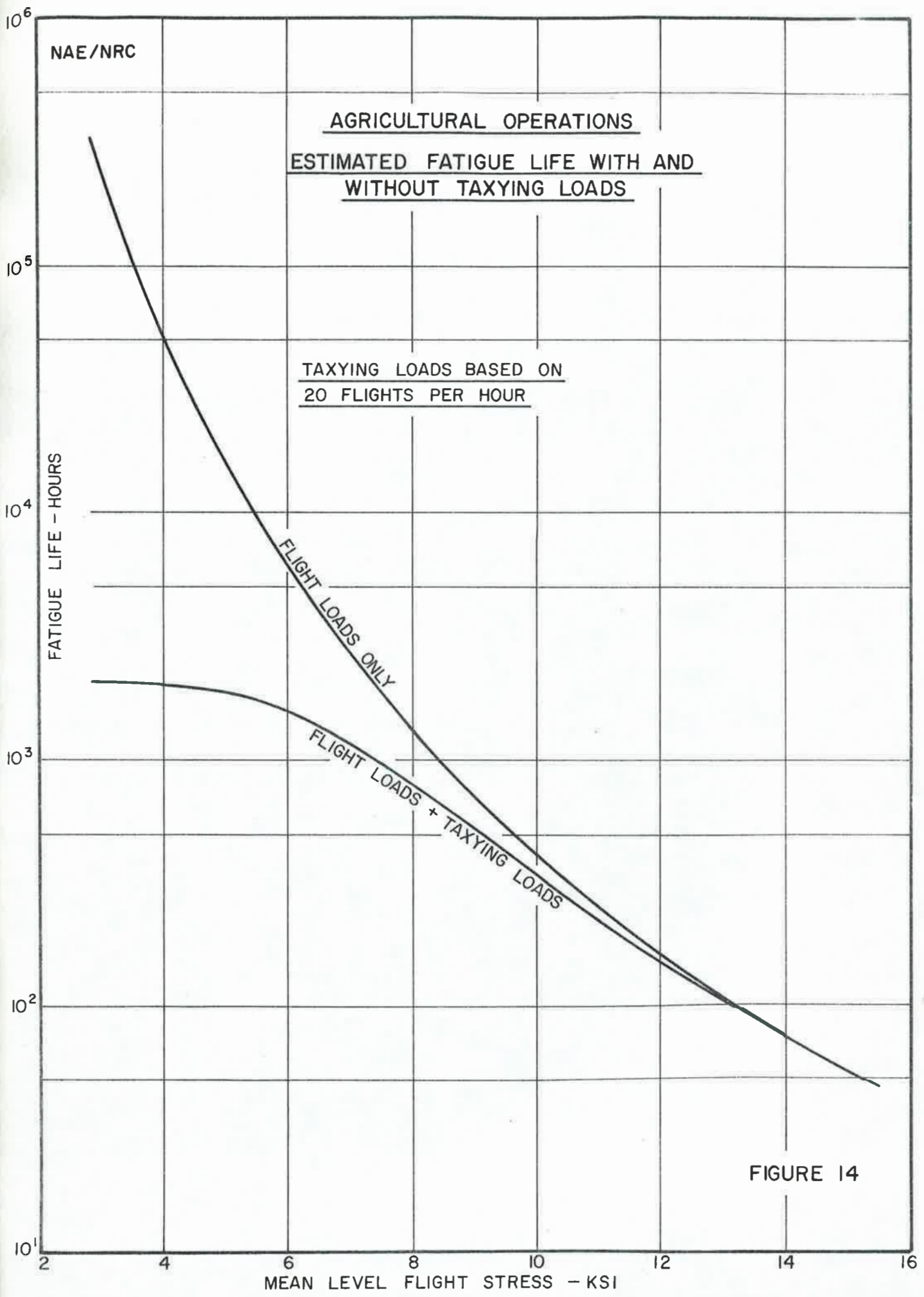


FIGURE 14