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1. Report No
NASA TM-73724

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
RELIABILITY ANALYSIS OF FORTY-FIVE STRAIN-GAGE SYSTEMS MOUNTED ON THE FIRST FAN STAGE OF A YF-100 ENGINE

5. Report Date
September 1977

6. Performing Organization Code

7. Author(s)
Raymond Holanda and Lloyd N. Krause

8. Performing Organization Report No.
E-9274

10. Work Unit No.

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D. C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))
Strain gages
Instrumentation
Reliability analysis
Jet engine

18. Distribution Statement
Unclassified - unlimited
STAR Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Pr
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

A reliability analysis of 45 strain-gage systems mounted on the first fan rotor of a YF-100 engine was performed. Half of the systems were installed by the flame-spray process and half were epoxy cemented. A total of 56 percent of the system failed in 11 hours of engine operation. Flame-spray system failures were primarily due to high gage resistance, probably caused by high stress levels. Epoxy system failures were principally erosion failures, but only on the concave side of the blade. Lead-wire failures between the blade-to-disk jump and the control room could not be analyzed.

E-9274

INTRODUCTION

The most commonly used instrument for the measurement of stress levels and associated vibration or flutter frequencies of rotating compressor blades during engine test programs is the electric resistance strain gage. The strain gages are mounted directly on the blades at points chosen to give information on vibratory stress characteristics. Lead wires are attached to the strain gage and routed down the blade to the root. Then a jump is made from the blade to the disk in such a way as to allow for the relative motion between the blade and the disk. The lead wires then proceed from the disk, along the shaft to a slip-ring system, and to the recording and monitoring instrumentation in the control room.

This strain-gage system must survive in an environment consisting of rotating machinery generating high-g loads; a high-temperature, high-velocity gas stream with entrained erosive particles usually produced by corrosion in the ground test facilities; and a wide variety of stress levels caused by complex vibratory modes. NASA, the Air Force, and some aircraft engine companies have been involved in a continuing effort to improve strain-gage reliability under the severe environment of full-scale engine testing.

Failure rates of strain-gage systems have been high in some recent Air Force and NASA test programs under this severe environment. It has not always been possible to document and control each strain-gage installation, or to perform a systematic evaluation of the gage systems after testing to pinpoint the exact causes of failure.

This report describes an engine test that had a high level of documentation and control of strain-gage installation methods and procedures followed by an extensive post-mortem examination of the strain-gage systems. The goal was to determine the reliability of state-of-the-art, strain-gage systems in this complex and severe environment.

BACKGROUND

The fan blade flutter research program involving the strain-gage systems reported herein is a part of the Full-Scale Engine Research Program at the NASA Lewis Research Center. Ninety strain gages were mounted on the first three fan rotor stages of a YF-100 engine. Then the engine was operated at various points within its operating envelope, and the strain gages were used to determine the mode and magnitude of the fan flutter instabilities. The initial strain-gage installations experienced 40 hours of engine operations and had a total of 75-percent failure at the end of this period (referred to as build I). Flutter conditions were experienced for only about 10 minutes near the end of the 40-hour run. The engine was reinstrumented with 90 new strain-gage systems and run for 32 hours (build II), suffering 84-percent failure in that time and being in flutter conditions for about 1 hour. At this time an interruption in the running program allowed 45 new strain gages to be mounted on 12 first-stage fan rotor blades that were installed on site. This portion of the test program is referred to as build IIA. This report is primarily concerned with the performance of the 45 strain-gage systems associated with build IIA.

Six of the blades had gages installed by Pratt & Whitney Aircraft, East Hartford, Connecticut, and the other six were Pratt & Whitney Aircraft, West Palm Beach, Florida, installations. The gages were installed by two different methods, flame spray and epoxy. The installation procedures were carefully documented and controlled. Table I lists the materials used. Figure 1 is the location map for the strain gages, showing the location of each gage according to manufacturer, method of installation, blade number, slot number, and position of the gage on the blade.

The running schedule of the engine for build IIA is shown in table II. Inlet air temperatures up to 340° F and rotor speeds up to 8500 rpm were experienced. At the conclusion of the testing, 23 strain gages were recorded as inoperative at the control room monitoring station. In addition, an inspection added two other gages to the failure list, one that had been intermittent and one with a section of lead wire hanging loose whose failure was imminent, bringing the total apparent failures to 25. The failed gages are shown by the shading on the gage location map (fig. 1), and the rate of gage failure is compared in figure 2 with the rates of failure for builds I and II. The time in flutter for build IIA was about 20 minutes.

GENERAL FAILURE ANALYSIS

The failure analysis of the strain gages was based on the following information:

(1) The reports from control room monitoring of strain gage dynamic output during operation and at its conclusion

(2) Periodic static resistance measurements at selected times between runs

(3) A post-test static resistance measurement and a resistance-to-ground measurement made at the point on the rotating connector where it plugs into the slip-ring

(4) Post-test static resistance measurements at the blade-to-disk jump and visual inspection of the blades

(5) Analysis of blades in the Lewis instrument shop, consisting of microscopic examination, resistance measurements at several points on each strain-gage circuit, and measurements of installation thickness on each strain-gage lead-wire path.

The gage resistance measurement was made within approximately 1 centimeter of the gage. The gage itself could not be exposed for detailed examination because it was too fragile to withstand the procedure used to expose it, which involves abrading the cover coating of flame-sprayed material.

(6) Vibration tests of selected gages in the Lewis vibration laboratory

(7) Written report by Pratt & Whitney Aircraft

Table III shows the 25 gage system failures tabulated according to the gage sensor location on the blade. No location was exempt from a high failure rate, and the rates are distributed with a small deviation about the mean. Table IV lists these gage failures according to installation method and installer. Flame-sprayed gage installations suffered significantly higher failure rates than did the epoxy installations. Table V shows the gage resistance measurements taken at various stages of the investigation. On the basis of these measurements and the visual inspection of the blades, the types of gage failure can be isolated and grouped as shown in table VI. The failures were analyzed according to these groups.

FAILURES ON BLADE

The category "failures on blade" refers to those failures that were verified by measurements or observations to occur in the blade portion of the strain-gage system installation. For the purposes of this report, the blade portion refers to the entire blade piece, including blade platform, root, and midspan dampers, and all lead wires attached to these surfaces, up to but not including the blade-to-disk jump. Thirteen gage failures occurred on the blade.

Table VII shows the same information as table III for the 13 failures, and no systematic failure pattern emerges based on gage location. Table VIII shows, even more strongly than table IV, that flame-sprayed gages failed significantly more often than epoxy-cemented gages on the blade. Among the flame-sprayed gages, those installed by Pratt & Whitney, Florida, had the highest failure rate.

In Pratt & Whitney Aircraft's failure analysis one of the failure modes referred to was high-resistance or supersensitive gages. As a result of their testing experience, they evaluated gages with elevated gage resistances of 10 percent or more as unreliable, unstable, or in a failure mode.

Fatigue failure analysis (refs. 1 and 2) and manufacturer's strain gage data (ref. 3) also refer to increasing gage resistance as a sign of progressive deterioration that can be correlated with the stress level and the number of cycles. The resistance elevation can be the result of elastic deformation due to stresses above the elastic limit; or fatigue microcracks, which can form from stresses above or below the elastic limit; or a combination of the two. Increases in resistance greater than 10 percent, as observed in these tests, are considered large. Of the 13 gage failures on the blade, elevated gage resistance is the largest category, affecting five gages. In addition, four other gages that had failed in some other mode also experienced elevated gage resistance. Resistance measurements made directly at the gage (table V, column 4) had ±1-percent accuracy. The average

Pratt & Whitney Aircraft, Florida, flame-sprayed strain gage had a resistance increase of 10 ohms; the average increase of Pratt & Whitney Aircraft, East Hartford, flame-sprayed gages was 3.5 ohms. A probable explanation for this difference in gage resistance is that Pratt & Whitney, Florida, used a hardening agent on their installations to improve erosion resistance. This addition stiffens the flame spray structure and may have been a significant contributor to the high failure rates as a result of increased gage resistance. Extrapolation of resistance curves would result in two more failures by this mode in a 50-hour test. The epoxy installations had negligible resistance increase.

One positive aspect in the grouping of failure modes is the absence of jump failures and delaminations of flame-sprayed installations. These had been the predominant failure modes of previous builds. It is evident that with state-of-the-art techniques, these failures can be virtually eliminated. Also, no low-resistance-to-ground failures were found.

The erosion problem was evaluated by thickness measurements made at various points on the blade (fig. 3) and by visual inspection. The convex side of the blade showed negligible erosion for both flame-sprayed and epoxy materials; the concave side showed high erosion rates.

Assuming zero erosion for the convex side, and assuming that the initial thicknesses of concave and convex installations were the same for a particular blade, the erosion rates for the concave side were determined from the thickness measurements. The results showed a 35-percent erosion rate for epoxy on the concave side between the root and the shroud during the 11 hours of testing. An extrapolation would lead to 100-percent gage failure in a 50-hour test, assuming a linear erosion rate. The flame-sprayed installations eroded about 10 percent, but a greater variation from gage to gage makes this value less certain. Indications are that few failures would be attributed to this mode in a 50-hour test.

Lead-wire failures have occurred along the top of the platform and at the root. Epoxy was used to secure lead wires in place in these areas, both on the epoxy-cemented and flame-sprayed gage blades. This is a region where the lead wires are bunched together and it is very difficult to ensure that the epoxy material adheres to each lead securely. Also, the full effect of centrifugal loading occurs along the top of the blade platform, a splice occurs here, and there is an erosion effect observed at the edge of the platform. The net result was two gages lost because wires pulled out of the epoxy and two other gage open circuits in regions where the wires were still secured in place.

A strain-gage failure curve of the type shown in figure 2 appears in figure 4. The failures include only those occurring on the blade, and they are grouped according to the installation method and the side of blade on which the gages were installed. The curves have been extrapolated to 50 hours of engine running time. The extrapolations are based on post-test examination of the blades and take into account such things as erosion rates and rates of increase of gage resistance. The curves dramatically depict the superiority of epoxy-cemented gages on the convex side of the blade both in the actual and in the estimated portions of the curve.

The primary cause of failure in flame-sprayed gages is high gage resistance, probably from high stress levels imposed by the severe running conditions of the flutter program. Temperatures encountered in these tests are considered low for flame-sprayed installations. During portions of the program, some strain gages were subjected to strain levels up to about ±600 microstrain. This value of strain is near the upper endurance limit for conventional flame-sprayed installations, assuming a typical vibration frequency of 1000 hertz and 20 minutes of flutter time for build IIA. It is possible that gage location on the blade could be changed to deal with this problem.

Because of their superior fatigue strength, the epoxy-installed strain gages were not adversely affected by these strain levels. The primary cause of gage failure in epoxy-cemented strain gages was erosion, but only on the concave side. Wherever possible, a high-endurance foil gage cemented with epoxy on the convex side of the blade should be used. Epoxy-cemented gages maintain a fatigue strength advantage over flame-sprayed installations up to a temperature of about 500° F.

DISK LEAD-WIRE AND ROTATING CONNECTOR FAILURES

The resistance measurements at the jump were compared with the resistance measurements at the rotating connection. Both were static resistance measurements. This comparison showed that five strain-gage circuits were open between the connector and the jump. It was not possible to inspect the connector, which would have verified any failures at that point. The failures could also be in the disk lead-wire work or in the splice made when installing the blades for build IIA, although the external appearance of this area showed no observable deterioration. Failures in this portion of the circuit could also have occurred during build II, since this portion of the circuit was not changed from build II to build IIA. From the first set of measurements in the build IIA running program, it was found that two of these five gages were among initial failures. Therefore, it is assumed that these two failures probably occurred in this portion of the circuit during the 40-hour run of build II. The other three failures occurred during the running program of build IIA.

UNVERIFIABLE FAILURES

Seven of the gages that were reported as inoperative in the control room at the end of the build IIA running program checked out as good in all the tests performed in this failure analysis. These failures must therefore be in one of the following categories:

(1) A failure in the circuit from the slip-ring end of the rotating connector to the control room (includes the slip-ring)

(2) An intermittent failure anywhere in the rotating portion of the strain-gage circuit, which shows up as a failed gage during run conditions but which checks out as a working gage in static measurements

Category 1 cannot be evaluated, but the blades were subjected to vibration testing while monitoring the gage's dynamic signal to determine if intermittent failures occur under these conditions. This signal was analyzed by the same criteria used in the control room to classify operative and inoperative gages. The test conditions consisted of approximately 10^6 cycles at frequencies from 0 to 650 hertz, including three bending modes and one torsion mode, with gage outputs from about ±50 to ±500 microstrain, with most gages in the lower portion of this range. No intermittent failures occurred during these tests, and no deterioration was observed in any of these gages. Therefore, it is likely that these seven gages are still intact at the blade. This means the failures are attributable to other parts of the circuit and remain unverifiable.

CONCLUSIONS AND RECOMMENDATIONS

A reliability analysis of 45 strain-gage systems mounted on the first fan rotor of a YF-100 engine has been described. Half of the systems were installed by the flame-spray process and half were epoxy cemented. The engine test program was terminated after a running time of 11 hours with 20 strain-gage systems still operating satisfactorily. The findings of the analysis include the following:

1. The primary cause of blade-mounted failures of the epoxy-installed gages was erosion, but only on the concave side (pressure side) of the blade. Erosion rates on the convex side were mild enough for such an installation to withstand a 50-hour test. It is recommended that epoxy-cemented gages mounted on the convex side be used whenever testing programs operate within the temperature

limits of epoxy-installed gages (less than 500° F). The survival rate for epoxy gages on the convex side of a blade was about 90 percent for 11 hours of testing, counting only failures on the blade.

2. The primary cause of blade-mounted failures of the flame-sprayed gages was high gage resistance, probably due to high stress levels imposed by the severe engine test conditions. During portions of the program, strain levels imposed on the gages were near the safe limits for conventional flame-sprayed installations. It is possible that gage location on the blade could be changed to deal with this problem. However, erosion of flame-sprayed installations was mild enough to indicate that few failures would be attributed to erosion in a 50-hour test. The survival rate for flame-sprayed gages on the blade was about 60 percent for 11 hours of testing.

3. Almost half of the strain-gage system failures occurred off the blade, but their exact failure mode was not determined because portions of the systems were unavailable for analysis.

4. One positive aspect was the absence of jump failures and delaminations of flame-sprayed installations. These had been dominant failure modes of previous engine tests. Thus, with state-of-the-art techniques, these failures can be virtually eliminated.

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2. Harting, Darrell R.: The - S/N - Fatigue-Life Gage: A Direct Means of Measuring Cumulative Fatigue Damage. Exp. Mech., vol. 6, no. 2, Feb. 1966, pp. 19A-24A.
3. Fatigue of Strain Gages. TN-130-2, Micro-Measurements Div., 1972.

TABLE I. - MATERIALS USED FOR STRAIN-GAGE INSTALLATION - BUILD IIA

Blade	Instrumented by -	Component or procedure	Material or process
1, 2, 38	P&WA, E. Hartford	Gages	Micro-Measurements WK-06-125BS-120
		Lead wires	0.0127-cm (0.005-in.) diameter copper with polyimide enamel insulation
		Jump wires	32 AWG, stranded, nickel-clad copper with Kapton insulation
		Surface preparation	Grit blasting with number-120-grit aluminum oxide
		Gage adhesive	Micro-Measurements M-Bond 610
		Epoxy	Micro-Measurements M-Bond GA-60
		Overcoat	0.00762-cm (0.003-in.) fiber-glass cloth impregnated with GA-60
6, 16, 30	P&WA, E. Hartford	Gages	BLH HT-1212-2A (120-ohm platinum tungsten) P&WA PR112 (0.8255 cm by 0.147 cm; 0.325 in. by 0.058 in.); 120-ohm platinum tungsten
		Lead wires	0.0127-cm (0.005-in.) diameter Chromel
		Jump wires	32 AWG, stranded, nickel-clad copper with Kapton insulation
		Surface preparation	Grit blasting with number-60-grit aluminum oxide
		Precoat	Metco 443
		Base coat	Rokide H
		Cover coat	Rokide H
		Upper platform	0.00762-cm (0.003-in.) fiber-glass cloth impregnated with GA-60
11, 20, 21	P&WA, Florida	Gages	Micro-Measurements WK-06-125BS-120
		Lead wires	0.016-cm (0.0063-in.) diameter copper with polyurethane enamel insulation
		Jump wires	28 AWG stranded nickel-clad copper with Kapton inner and Teflon outer insulation (blades 20 and 21) 32 AWG, stranded, silver-plated copper with Teflon insulation (blade 11)
		Surface preparation	Grit blasting with number-120-grit aluminum oxide
		Gage adhesive	Micromeasurements M-Bond 610
		Epoxy	Micromeasurements M-Bond GA-60
		Overcoat	0.00762-cm (0.003-in.) fiber-glass cloth impregnated with GA-60
19, 25, 35	P&WA, Florida	Gages	BLH HT-1212-2A (120-ohm platinum tungsten) PWA PR112 (0.8255 cm by 0.147 cm; 0.325 in. by 0.058 in.); 120-ohm platinum tungsten
		Lead wires	0.0127-cm (0.005-in.) diameter Chromel
		Jump wires	32 AWG, stranded, silver-plated copper with Teflon insulation
		Surface preparation	Grit blasting with number-30-grit aluminum oxide
		Precoat	Metco 443
		Base coat	Rokide H
		Cover coat	Rokide H with SP-1 binder
		Upper platform	0.00762-cm (0.003-in.) fiber-glass cloth impregnated with GA-60

TABLE II. - ENGINE RUNNING SCHEDULE

FOR BUILD IIA

Date	Time, hr	Nature of run	Total time
7/20/76	0.5	Balance	-------------
7/21/76	1		-------------
7/22/76	.75		-------------
8/18/76	.75		-------------
8/26/76	1		4 hr, 2 min
9/2/76	.75	Shakedown	4 hr, 45 min
9/9/76	3.5	Data run	8 hr, 15 min
9/14/76	2.5	Data run	10 hr, 58 min

TABLE III. - STRAIN-GAGE SYSTEM FAILURES ACCORDING TO LOCATION OF SENSORS[a] - BUILD IIA

Sensor location	Side of blade	Number of gages	Number of failures	Failure rate, percent
Tip	Convex	11	6	55
Above shroud, maximum thickness	Convex	10	4	40
Above shroud, trailing edge	Concave	11	7	64
Shroud	Convex and concave	10	6	60
Root fillet	----------	3	2	67
Total		45	25	55

[a] Failures did not necessarily occur at sensor location.

TABLE IV. - TOTAL STRAIN-GAGE SYSTEM FAILURES ACCORDING TO INSTALLATION METHOD AND INSTALLER - BUILD IIA

Installation method	Installer	Total number of gages	Total number of failures	Failure rate, percent
Epoxy	P&WA, Florida	11	4	36
Flame spray	P&WA, Florida	12	7	58
Epoxy	P&WA, E. Hartford	11	5	45
Flame spray	P&WA, E. Hartford	11	9	82

TABLE V. - STRAIN-GAGE STATIC RESISTANCE MEASUREMENTS - BUILD IIA

Strain gage	Strain-gage static resistance, ohms			Strain gage	Strain-gage static resistance, ohms		
	At connector	At jump	At gage		At connector	At jump	At gage
1	125	121	121	25	(a)	176	134
3	162	159	123	26	124	121	121
4	124	121	121	27	150	(a)	122
5	(a)	(a)	(a)	28	166	(a)	133
6	(a)	(a)	140	30	125	(a)	121
7	(a)	(a)	(a)	31	192	152	122
8	125	121	121	32	155	151	123
9	158	153	121	33	(a)	170	140
10	(a)	154	120	34	125	121	121
11	161	157	124	35	192	121	121
12	125	121	121	36	124	121	121
13	125	121	121	37	125	121	121
14	125	121	121	38	151	147	120
15	124	121	121	39	(a)	121	121
16	(a)	(a)	(a)	40	128	121	121
17	161	155	125	41	(a)	(a)	(a)
18	129	121	121	42	158	(a)	121
19	125	121	121	43	(a)	(a)	(a)
20	150	146	122	44	161	157	124
21	151	146	120	46	186	176	137
22	125	121	121	47	(a)	(a)	152
23	(a)	121	121	48	131	127	125
24	175	121	121				

[a] Open.

TABLE VI. - TYPE OF GAGE FAILURE

Type of failure	Number of failures
Measurable failures on blade:	
Epoxy delamination	1
Erosion of epoxy on concave side	2
Broken lead wires at blade root (also one high gage resistance)	2
Strain-gage wire failure	1
Blade platform lead-wire failures (also both high gage resistances)	2
High gage resistance	5
Total	13
Failures in disk-lead-wire-to-rotating-connector portion of circuit	5
Unverifiable failures	7

TABLE VII. - STRAIN-GAGE SYSTEMS FAILURES ACCORDING TO LOCATION OF GAGE - BUILD IIA

Gage location	Side of blade	Number of gages	Number of failures	Failure rate, percent
Tip	Convex	11	3	27
Above shroud, maximum thickness	Convex	10	2	20
Above shroud, trailing edge	Concave	11	3	27
Shroud	Convex and concave	10	3	30
Root fillet	----------	3	2	67
Total		45	13	29

TABLE VIII. - STRAIN-GAGE SYSTEM FAILURES ON BLADE ACCORDING TO INSTALLATION METHOD AND INSTALLER - BUILD IIA

Installation method	Installer	Total number of gages	Total number of failures	Failure rate, percent
Epoxy	P&WA, Florida	11	2	18
Flame spray	P&WA, Florida	12	6	50
Epoxy	P&WA, E. Hartford	11	1	9
Flame spray	P&WA, E. Hartford	11	4	36

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Gage location	Side of blade	Blade												Number of gages
		1	2	6	11	16	19	20	21	25	30	35	38	
		Strain-gage installer[a]												
		EH	EH	EH	FLA	EH	FLA	FLA	FLA	FLA	EH	FLA	EH	
		Installation type[b]												
		EP	EP	FS	EP	FS	FS	EP	EP	FS	FS	FS	EP	
		Strain gage[c]												
Tip	Convex	1		3	4	5	6	7	8	9	10	11	12	11
Above shroud, maximum thickness	Convex	13	14		15	16	17	18	19	20	21		22	10
Above shroud, trailing edge	Concave	23	24	25	26	27	28		30	31	32	33	34	11
Shroud	Convex		35		36				37		38		39	5
Shroud	Concave	40		41		42		43				44		5
Root fillet	--------						46			47		48		3

[a] EH denotes Pratt & Whitney Aircraft, East Hartford, Connecticut; FLA denotes Pratt & Whitney Aircraft, Florida.

[b] EP denotes epoxy; FS denotes flame spray.

[c] Shading indicates locations of failed gages.

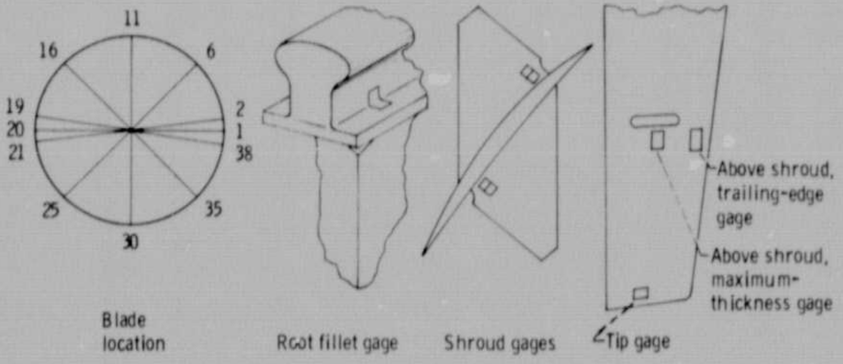


Figure 1. - Strain-gage location map.

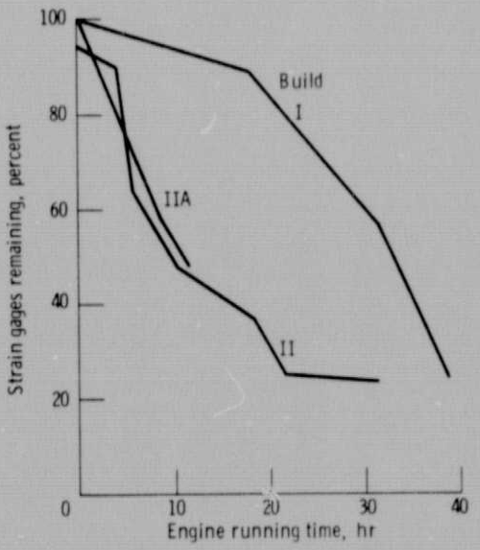
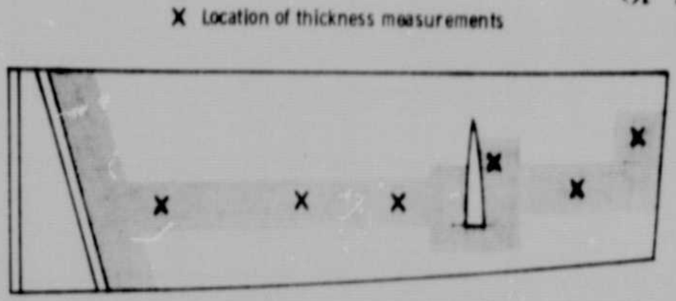
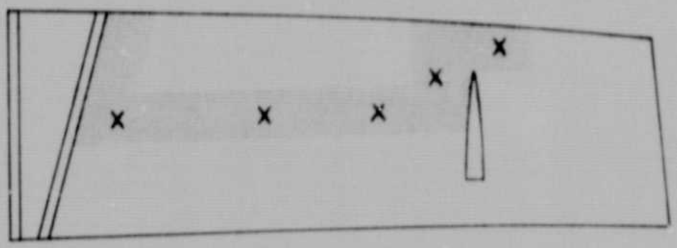


Figure 2. - Strain-gage failure rates for various builds.



(a) Convex side.



(b) Concave side.

Figure 3. - Strain-gage installation patterns (shaded areas), indicating locations of thickness measurements.

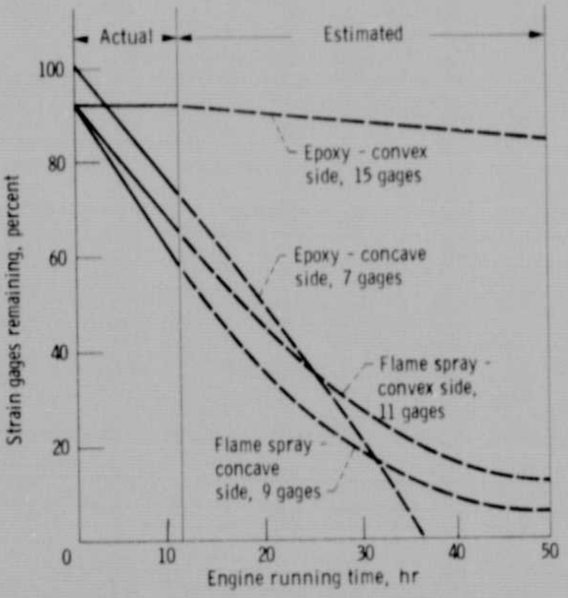


Figure 4. - Strain-gage failure rates for build IIA, failures on the blade. (Figure does not include three root gages.)