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RESEARCH MEMORANDUM

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NATIONAL ADVISORY COMMITTEE
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PERFORMANCE OF INCONEL 739 BUCKETS IN J33-9 TURBOJET ENGINE

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SUMMARY

An investigation was made to determine the performance of Inconel 739 (a nickel-base alloy of low critical-element content) buckets in a J33-9 engine operating under cyclic conditions and to determine the stress-rupture life of the alloy at 1500° F. The results of this investigation show that the engine life of Inconel 739 alloy buckets, ranged from 244 to 304 hours compared with engine life of S-816 buckets which ranged from 50 to 357 hours. This indicated that the engine life of Inconel 739 buckets was at least equivalent if not superior to the engine life of S-816 buckets. The scatter band of failures of Inconel 739 buckets was considerably narrower than that of S-816 buckets (60 hr against 307 hr). Bucket life (244 to 304 hr) was less than the 1300-hour life predicted from stress-rupture considerations alone. The failure mechanism was probably influenced by fatigue. The stress to cause rupture in 100 hours at 1500° F for Inconel 739 was approximately 30,000 psi as compared with 22,500 psi for S-816. Elongation during both engine operation and stress-rupture testing was considerably less in the Inconel 739 alloy than in S-816 (0.3 and 3.0 percent against 8.0 and 50 percent, respectively.)

INTRODUCTION

Inconel 739 is a new forgeable low-strategic-alloy-content bucket material designed to operate in jet engines at 1500° F. The material is a nickel-base alloy with 15 percent chromium. It contains no columbium, tantalum, cobalt, or tungsten but depends upon aluminum, titanium, and molybdenum additions for its high-temperature strength.

The stress-rupture life of Inconel 739 at 1500° F is better than the stress-rupture life of the currently used S-816 (refs. 1 to 3). In addition, its resistance to creep is greater. For example, Inconel 739 creeps 1 percent in 100 hours at 1500° F at a stress of 30,000 psi (ref. 1), while S-816 creeps 6 percent or more in 100 hours at 1500° F at the lower stress of 21,500 psi (NACA unpublished data). For certain engines, bucket creep during high-stress operation may be a limiting factor in the choice of the bucket alloy. Thus, the low creep rate of Inconel 739 could be an asset in bucket applications, because the alloy would not be expected to elongate excessively during service operation.

This investigation was made at the NACA Lewis laboratory to determine the performance of Inconel 739 buckets in a J33-9 turbojet engine. These buckets were run in an engine along with buckets of Inconel 550 and S-816. The data on Inconel 550 are reported in reference 4. The S-816 buckets were used as a standard of comparison.

Bucket performance was determined under cyclic operating conditions. Stress-rupture life of Inconel 739 specimens cut from bucket airfoils was determined at 1500° F under stresses of 20,000, 25,000, and 30,000 psi.

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MATERIALS, APPARATUS, AND PROCEDURE

Turbine Buckets

The chemical composition of Inconel 739 was

Ni	Cr	Mo	Al	Ti	C	Fe	Mn	S	Si	Cu
77.71	15.51	1.03	2.67	1.66	0.07	1.14	0.01	0.006	0.15	0.02

The buckets were precision forged at a temperature of 2150° F and heat treated prior to finishing. Heat treatment was completed by the following steps:

(1) Solution treatment at 2050° F for 1 hour followed by air cooling to room temperature

(2) Preliminary aging at 1800° F for 1 hour followed by air cooling to room temperature

(3) Aging at 1350° F for 1 hour followed by air cooling to room temperature

The seven Inconel 739 buckets to be evaluated in this engine were chosen randomly from a lot of 17 buckets. The test buckets were inspected by radiographic and zyglo methods and were found to be sound. The 17 S-816 buckets used in the test as a standard for comparison were picked randomly from a lot of 70 buckets of standard Air Force stock, but were not subjected to additional inspection at this laboratory.

Engine Operation

The buckets selected for engine evaluation were operated in a J33-9 engine under cyclic conditions. Cycles were of 20-minute duration and consisted of 15 minutes at the rated speed of 11,500 rpm and approximately 5 minutes at the idle speed of 4000 rpm.

Engine operation was interrupted to obtain data on bucket elongation, to check buckets for cracks, to replace failed buckets, to overhaul the engine when necessary, and to shut down at the end of each work day.

Stress and Temperature Distribution in Turbine Buckets During Engine Operation

The centrifugal stress and temperature distributions in a bucket during operating are shown in figure 1(a). The centrifugal stresses were calculated from the known rotor and material constants of radius, rotational speed, bucket geometry, and density. (See ref. 5 for details on centrifugal-stress computation.)

At the beginning of the test the temperature profile along the span of the bucket was determined from four thermocoupled S-816 buckets. Midspan bucket temperatures measured intermittently during operation with two thermocoupled S-816 buckets were recorded by an electronic potentiometer.

Using the stress and temperature distributions of figure 1(a), and knowing the stress-rupture properties of the airfoil material at a given temperature, it is possible to determine the expected life of the buckets, assuming that the buckets fail by stress-rupture alone. This life should represent the best life that could be obtained in an engine. Figure 1(b) shows a curve of stress-rupture life at various locations along the bucket length computed for the stress and temperature conditions in the airfoil. The stress-rupture properties at 1500° F were obtained from Inconel 739 airfoils, and the stress-rupture properties at other temperatures were calculated by the use of accepted parameters. Figure 2 shows the 1500° F stress-rupture data compared with published values for S-816. Stress-rupture tests are described in more detail later. The stress-rupture-life curve (fig. 1(b)) has a minimum value, which may be termed a "critical point," where the combination of centrifugal stress and temperature conditions is most severe. A region, in which stress-rupture failures usually occur, centers about the critical point and is considered the critical zone as shown in figure 1(b). The minimum value of 1300 hours is the expected life of Inconel 739 in the engine. It must be remembered that this assumes the failure mechanism to be one of pure stress rupture not complicated by fatigue, thermal shock, and oxidation effects.

Bucket Elongation Measurements

Two buckets of Inconel 739 were scribed at 1/2-inch intervals along the span as shown in figure 3. Elongation measurements were made at approximately 8-hour intervals for the first 25 hours of operation and at approximately 20-hour intervals for the remainder of the test. The elongation of each scribed segment was measured with an optical extensometer having a sensitivity of 0.0001 inch. Accuracy of the elongation measurements is, however, influenced by the degree of bucket distortion and warpage. The maximum error in an elongation reading is 0.001 inch, which is equivalent to an error of 0.2 percent in the 1/2-inch gage length used.

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Macro- and Microexamination of Buckets

Six new Inconel 739 buckets were macroetched in an 80 percent hydrochloric acid and 20 percent hydrogen peroxide solution to reveal grain size and flow lines. These buckets were used for macro- and microstudies and stress-rupture tests.

The engine test buckets were inspected for cracks at intervals throughout the engine-operating phase of the investigation. A bucket was considered failed either when actual fracture occurred or when cracks in the airfoil made it apparent that failure was imminent. Failed buckets were examined at low magnification to determine as closely as possible the manner by which the failure originated. The failures were classified as stress rupture, fatigue, stress rupture followed by fatigue, or damage. A complete description of each failure type can be obtained in reference 5.

Stress-Rupture Tests

Stress-rupture tests were conducted to determine the stress-rupture life at 1500° F of specimens machined from the airfoils (fig. 4). Five specimens were tested under constant load, one at 30,000 psi, one at 25,000 psi, and three at 20,000 psi (fig. 2).

RESULTS AND DISCUSSION

Bucket Performance During Engine Operation

Life of the Inconel 739 and S-816 buckets is listed in table I and shown in figure 5. The average life of S-816 was 188 hours, with the first failure occurring at 50 hours and the final failure at 357 hours. The average life of Inconel 739 was 280 hours, the first failure occurring at 244 hours and the final failure at 304 hours. This high average life and narrow scatter band indicate that Inconel 739 is suitable as a turbine bucket material.

Stress-Rupture Life

The stress-rupture life at 1500° F of Inconel 739 specimens taken from bucket airfoils is compared with stress-rupture life of S-816 bar stock (ref. 2) in figure 2. Inconel 739 has a better stress-rupture life at 1500° F than S-816. Stress to cause rupture in 100 hours at 1500° F for Inconel 739 is approximately 30,000 psi, as compared with 22,500 psi for S-816. The stress to cause rupture in 1000 hours at 1500° F for Inconel 739 is approximately 19,000 psi as compared with 16,000 psi for the S-816.

Bucket Elongation

The Inconel 739 buckets exhibited very low elongation during engine operation. The maximum elongation determined was of the order of 0.3 percent. Elongation of S-816 buckets in the same engine showed a maximum elongation of the order of 8.0 percent.

Elongation of Inconel 739 (specimens cut from bucket airfoils) during stress-rupture testing (20,000 psi at 1500° F) ranged between 0 and 6.2 percent (table II) with an average elongation of 3 percent. Elongation of S-816 in stress rupture at a stress of 21,500 psi and at a temperature of 1500° F was over 50 percent in a 1-inch gage length (NACA unpublished data).

Macro- and Microexaminations

Typical macrostructure of the Inconel 739 buckets can be noted in figure 6. The grain size is relatively uniform over the entire bucket. Some large grains were noted in localized areas, however, no excessive grain growth (presence of "elephant" grains) was detected in the macroetched buckets.

Typical microstructures of Inconel 739 buckets are shown in figure 7. Figure 7(a) shows the microstructure of the as-heat-treated bucket and figure 7(b) shows the microstructure of a bucket operated for 300 hours at rated speed. The differences in microstructure noted in these figures are attributable to the increase in precipitation which occurred in the bucket during 300 hours of operation.

Bucket-Failure Mechanisms

During operation, turbine buckets are subjected to vibration, thermal shock, and an oxidizing atmosphere in addition to the centrifugal stresses and temperatures. These phenomena tend to decrease the engine life below the stress-rupture life of an alloy. Generally, fatigue has been shown to be a major contributing factor in blade failures in the J33-9 engine (refs. 6, 7, and 8). It can be noted in table I that, excepting damage failures, evidence of fatigue was observed at the fracture edges of all but one of the S-816 buckets.

Figure 8(a) shows a typical fractured Inconel 739 bucket, and figure 8(b) shows the fracture surface. Even though the jagged characteristics of the fracture edges are typical of stress-rupture failures, they are not necessarily the result of stress rupture alone. Research has shown that such fractures may occur in specimens having fatigue stresses superimposed on a mean tensile load (ref. 9). Because of the fatigue characteristics in the S-816 buckets, it may be logically assumed that all buckets run in this investigation were subjected to some fatiguing influence during operation. The fact that the life of the Inconel 739 buckets (244 to 304 hr) was much less than the life predicted (1300 hr) from stress-rupture conditions suggests that the failure mechanism was drastically influenced by something other than stress rupture.

SUMMARY OF RESULTS

The results of this investigation, which was conducted to determine the performance of Inconel 739 (an alloy of low critical-element content) buckets operating in a J33-9 turbojet engine at a bucket temperature of 1500° F may be summarized as follows:

1. Inconel 739 buckets had engine lives ranging from 244 to 304 hours, whereas the S-816 buckets had engine lives ranging from 50 to 357 hours. Thus the engine life of Inconel 739 buckets can be considered equivalent to if not superior to the engine life of S-816 buckets tested at the same time.

2. All seven Inconel 739 buckets failed in a narrow scatter band of 60 hours as compared to a scatter bnad of 307 hours for failure of 17 S-816 buckets.

3. Bucket life (244 to 304 hr) was less than the 1300-hour life predicted from stress-rupture considerations alone. The failure mechanism was probably influenced by fatigue.

4. Stress to cause rupture at 1500° F in 100 hours was approximately 30,000 psi for Inconel 739 as compared with 22,500 psi for S-816.

5. During engine operation, maximum elongation of Inconel 739 buckets was 0.3 percent and of S-816 buckets was 8.0 percent. During stress-rupture tests at 1500° F maximum elongation of Inconel 739 buckets was 6.2 percent and of S-816 buckets was over 50 percent.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 5, 1956

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2. Anon.: Stress-Rupture Properties of S-816, S-590, and A-286 Alloys. Res. Labs., Allegheny Ludlum Steel Corp., Watervliet (N.Y.), June 1, 1955.

3. Anon.: Super Alloys - Physical Properties and Processing Data. Universal-Cyclops Steel Corp.

4. Gyorgak, C. A., Johnston, J. R., and Weeton, J. W.: Effects of a Straightening Operation on Performance of Inconel 550 Buckets. NACA RM E55L06, 1956.

5. Kemp, Richard H., and Morgan, William C.: Analytical Investigation of Distribution of Centrifugal Stresses and Their Relation to Limiting Operating Temperature in Gas-Turbine Blades. NACA RM E7L05, 1948.

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8. Signorelli, R. A., Garrett, F. B., and Weeton, J. W.: Engine Performance of Overtemperature Heat-Treated S-816 Buckets. NACA RM E55L06a, 1956.

9. Ferguson, Robert R.: Effect of Magnitude of Vibratory Load Superimposed on Mean Tensile Load on Mechanism of and Time to Fracture of Specimens and Correlation to Engine Blade. NACA RM E52I17, 1952.

TABLE I. - BUCKET FAILURE MECHANISMS AND LOCATION OF FAILURE ORIGINS

Alloy	Rated speed time to failure, hr	Type of failure (a)	Location of failure origin	
			Spanwise, in. above base	Chordwise (b)
Inconel 739	244.0	SR	$2\frac{3}{4}$	LE
	268.7	SR	$3\frac{1}{8}$	LE
	276.3	SR	$3\frac{1}{8}$	LE
	278.7	SR	$2\frac{1}{2}$	MC
	291.3	SR	$2\frac{5}{8}$	MC
	299.8	SR	3	LE
	304.1	SR	3	LE
S-816	49.8	SR	$2\frac{1}{2}$	TE
	52.7	F	$3\frac{3}{16}$	TE
	75.1	F	$1\frac{7}{8}$	TE
	84.5	F	$3\frac{3}{16}$	LE
	85.3	F	$1\frac{3}{4}$	TE
	132.8	SR→F	$2\frac{7}{16}$	LE
	151.3	SR→F	3	LE
	162.2	SR→F	$3\frac{1}{8}$	LE
	190.8	SR→F	3	LE
	208.8	SR→F	$2\frac{3}{4}$	LE
	221.8	Damage		
	253.0	Damage		
	258.6	F	$2\frac{3}{16}$	TE
	264.5	SR→F	$2\frac{1}{2}$	LE
	298.6	Damage		
	340.5	SR→F	$2\frac{15}{16}$	LE
	356.8	Damage		

[a]Determination of failure mechanism based on appearance of fracture surface only. Mechanisms abbreviated as follows:

- SR Stress rupture
- F Fatigue
- SR→F Stress rupture followed by fatigue

[b]Locations abbreviated as follows:

- LE Leading edge
- MC Midchord
- TE Trailing edge

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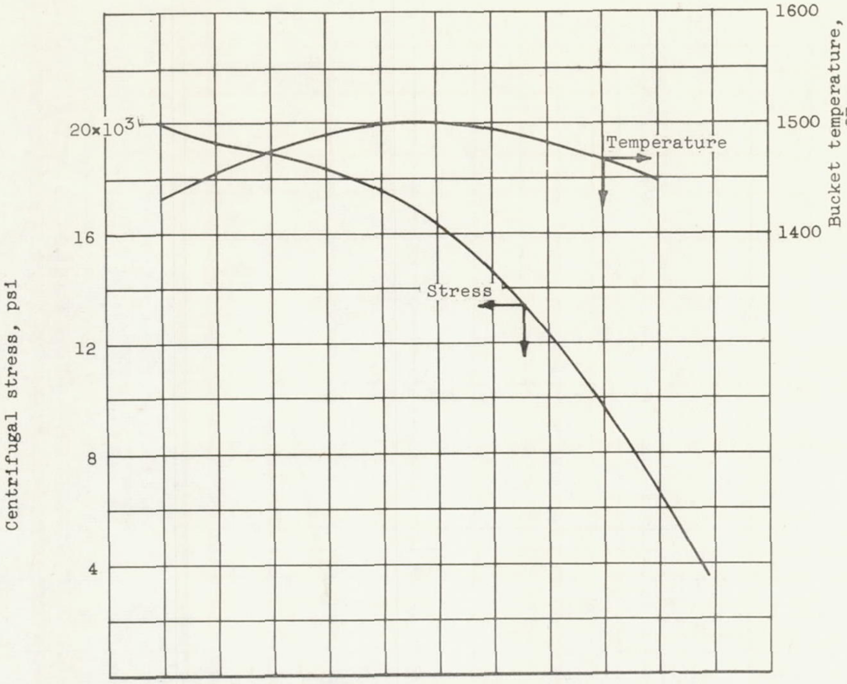
TABLE II. - STRESS-RUPTURE LIFE AT 1500° F OF INCONEL 739

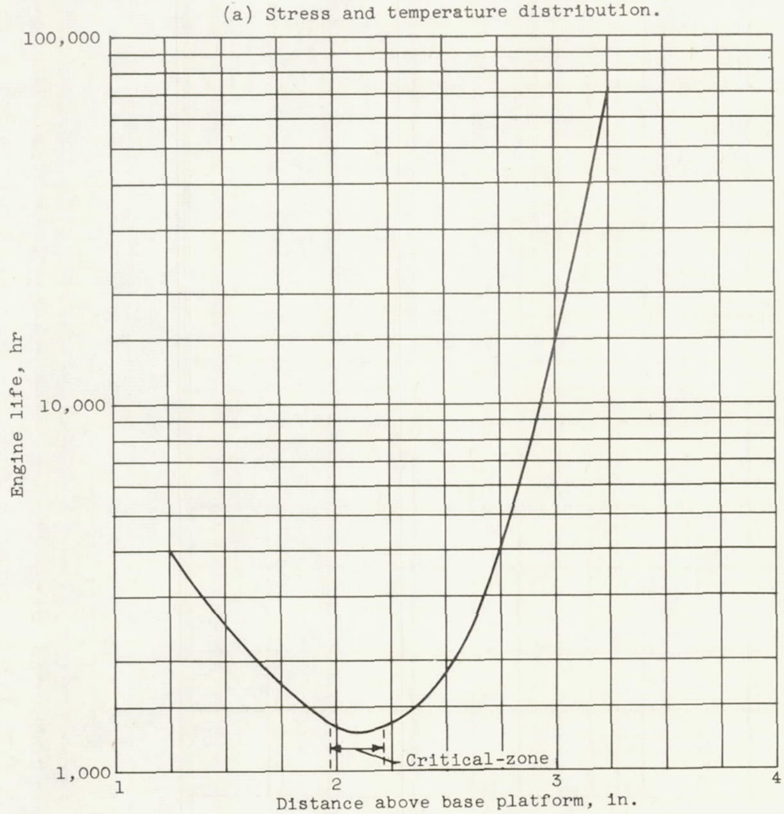
SPECIMENS CUT FROM BUCKET AIRFOILS

Stress, psi					
30×10^3		25×10^3		20×10^3	
Life, hr	Elongation in 1-inch gage length, percent	Life, hr	Elongation in 1-inch gage length, percent	Life, hr	Elongation in 1-inch gage length, percent
84.0	3.1	369.0	4.7	487.0	0
				716.6	6.2
				[a]831.0	3.1

[a]Total time on specimen, 859.0 hours; 28 hours at 1050° F at stress.



(a) Stress and temperature distribution.



(b) Stress-rupture life.

Figure 1. - Stress and temperature distribution in Inconel 739 buckets at rated speed (11,500 rpm in J33-9 engine) and corresponding theoretical engine life based on stress-rupture life of specimens cut from airfoils of Inconel 739 buckets.

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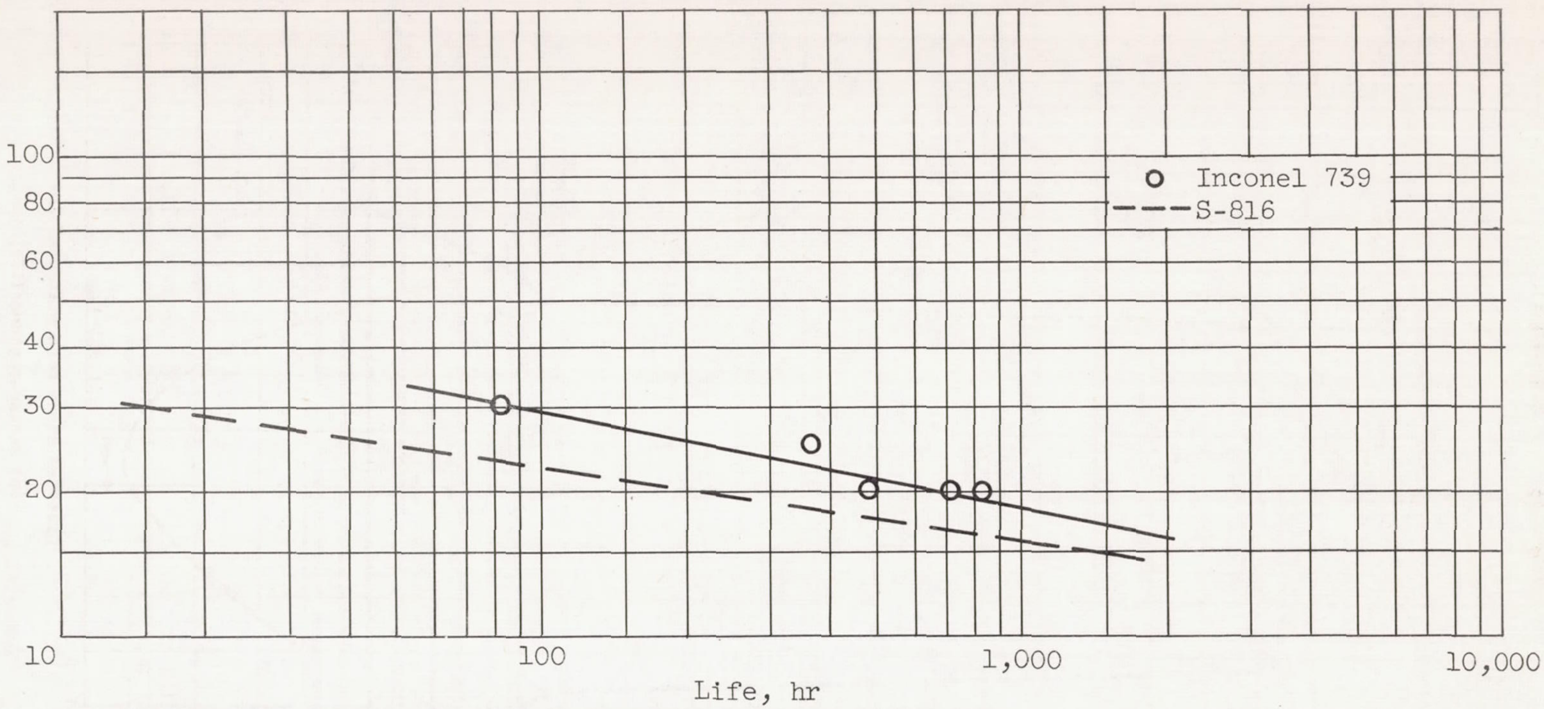

Figure 2. - 1500° F stress-rupture life of Inconel 739 specimens cut from bucket airfoils compared with stress-rupture life of S-816 bar stock (S-816 solution treated at 2150° F for 1 hr; water quenched; and aged at 1400° F for 16 hr; air cooled (ref. 2)).

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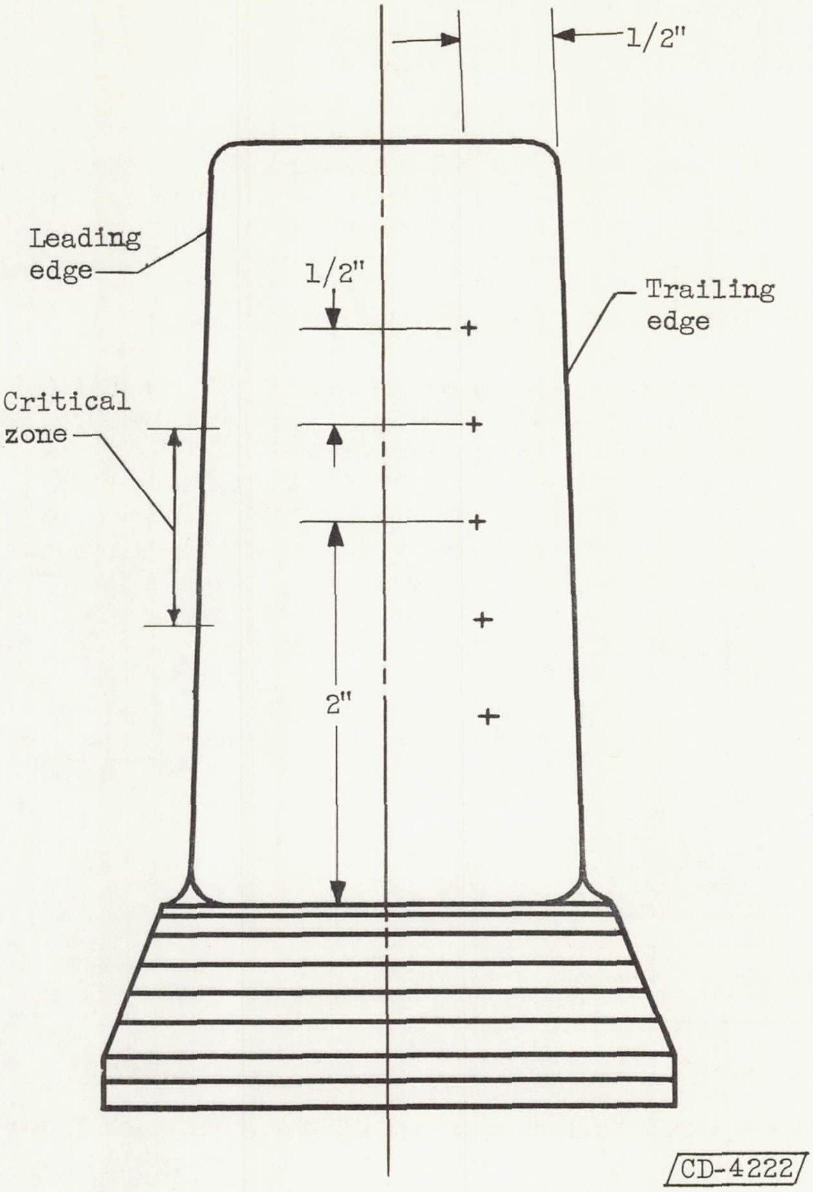

Figure 3. - Location of scribe marks on convex side of bucket for use in measuring elongation.

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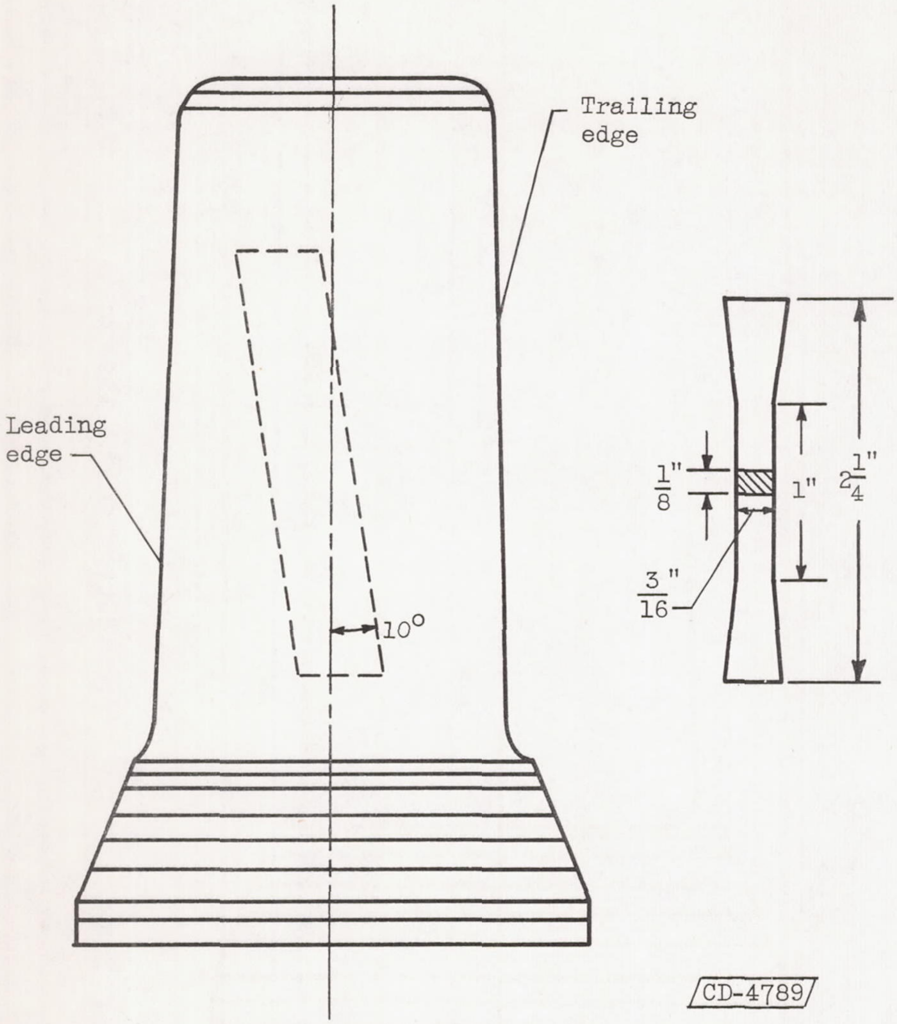

Figure 4. - Bucket stress-rupture specimen and zone from which it was machined.

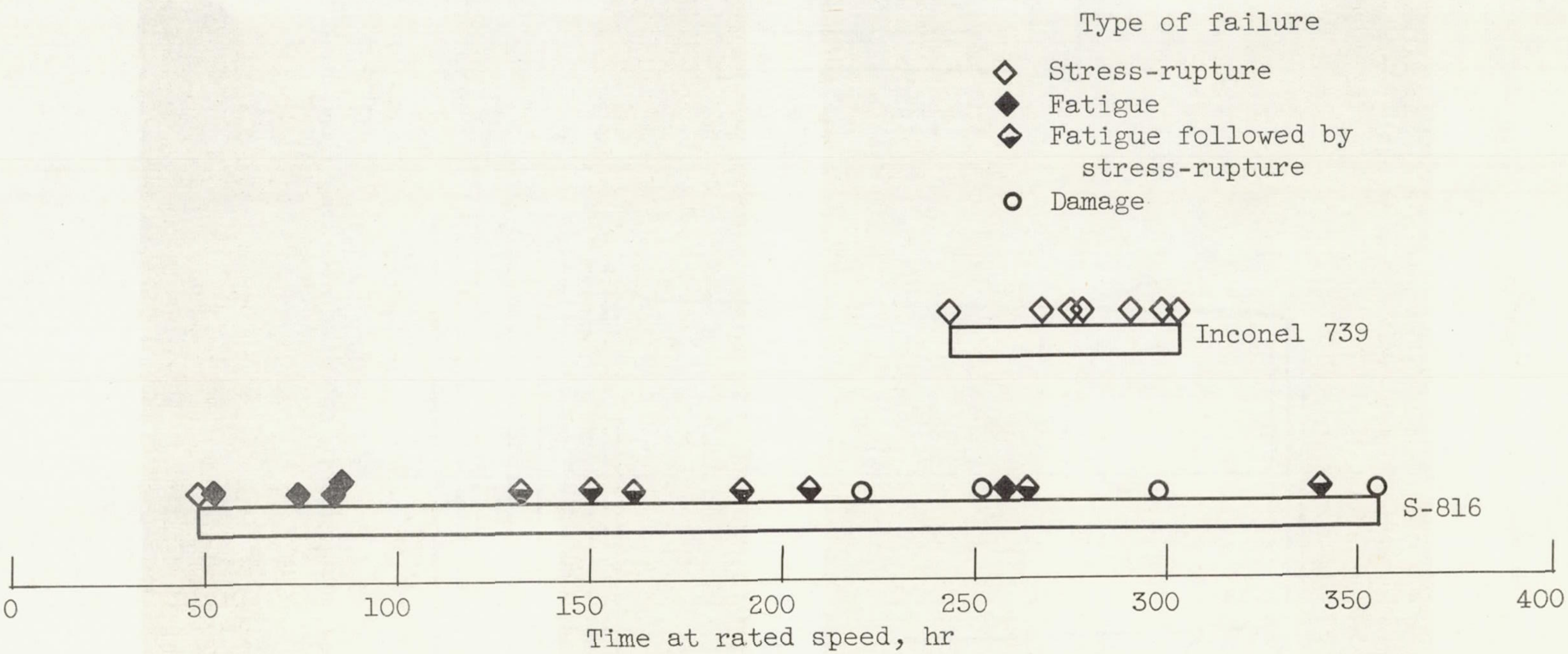

Figure 5. - Engine life of Inconel 739 compared with engine life of S-816 run simultaneously in J33-9 engine.

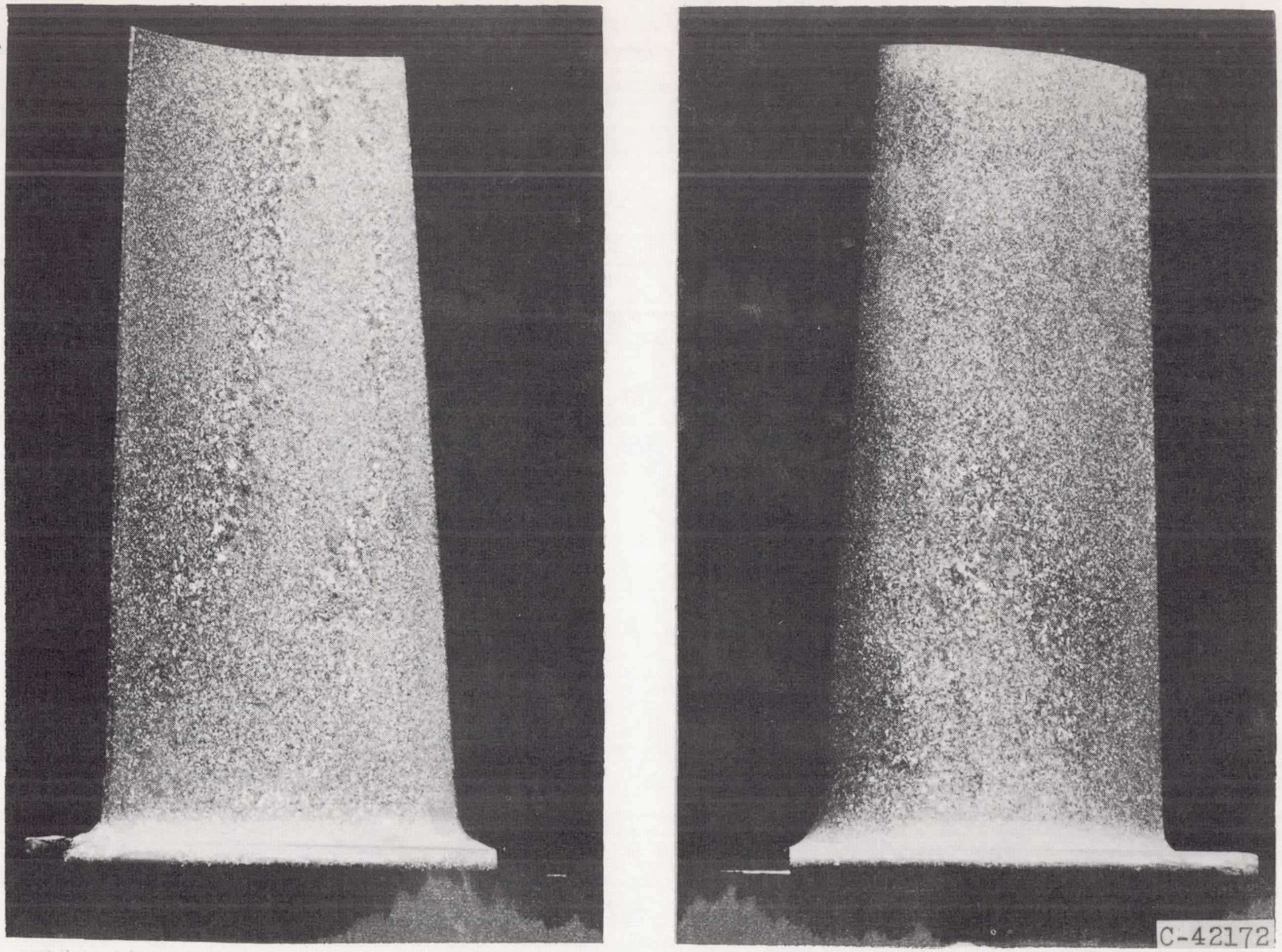

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Figure 6. - Typical grain size of Inconel 739 buckets.

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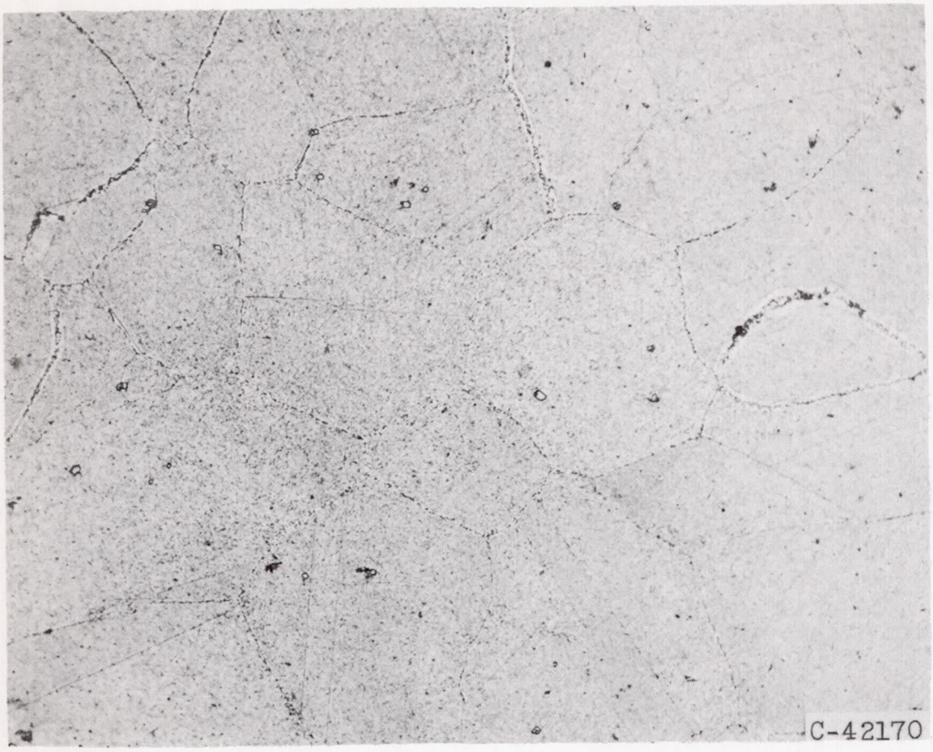
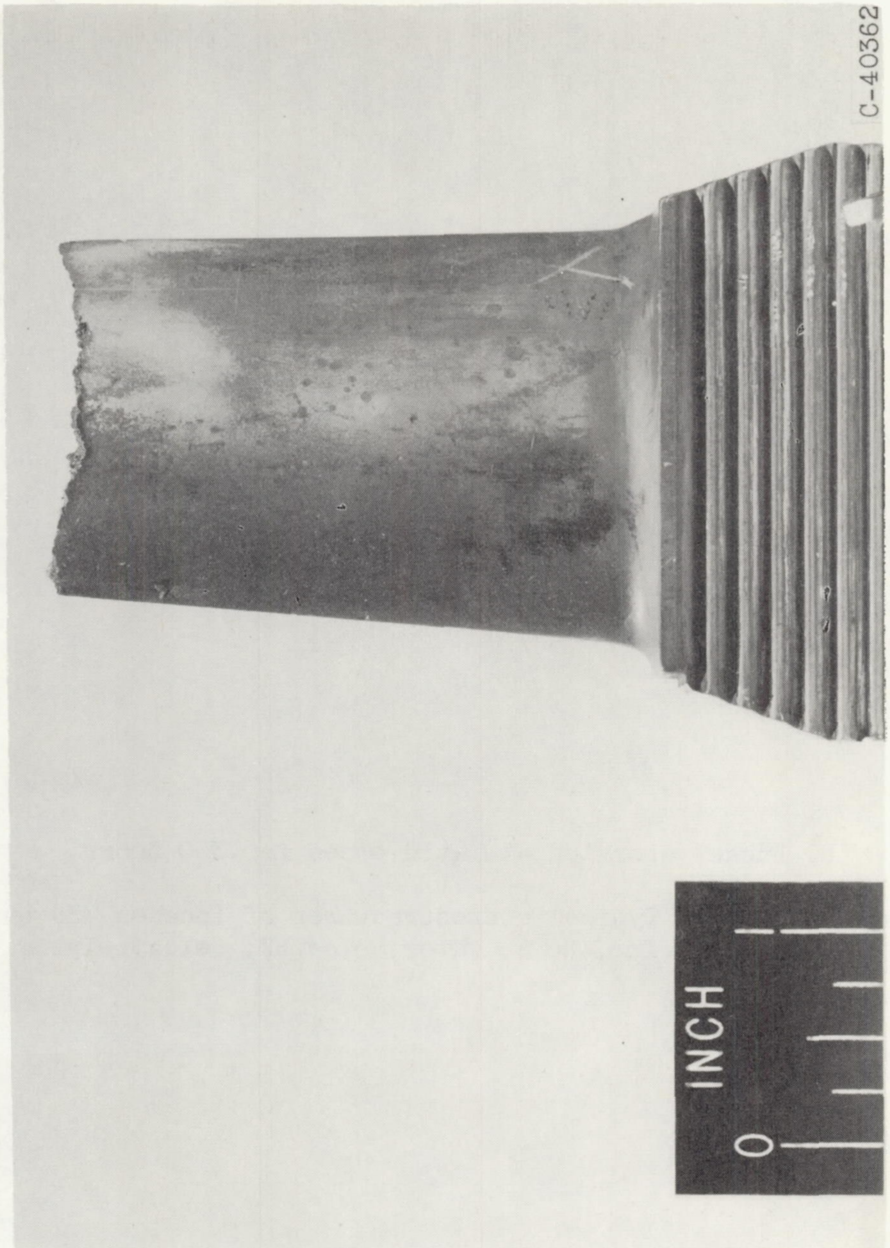
(a) As-heat-treated bucket.

Figure 7. - Typical microstructures of Inconel 739 bucket. Etchant: 20 cc glycerine, 20 cc water, 5 cc HF; electrolytic. X250.



(b) Bucket operated at rated speed for 300 hours.

Figure 7. - Concluded. Typical microstructures of Inconel 739 buckets. Etchant: 20 cc glycerine, 20 cc water, 5 cc HF; electrolytic. X250.



(a) Fracture edge.

Figure 8. - Inconel 739 bucket failure.

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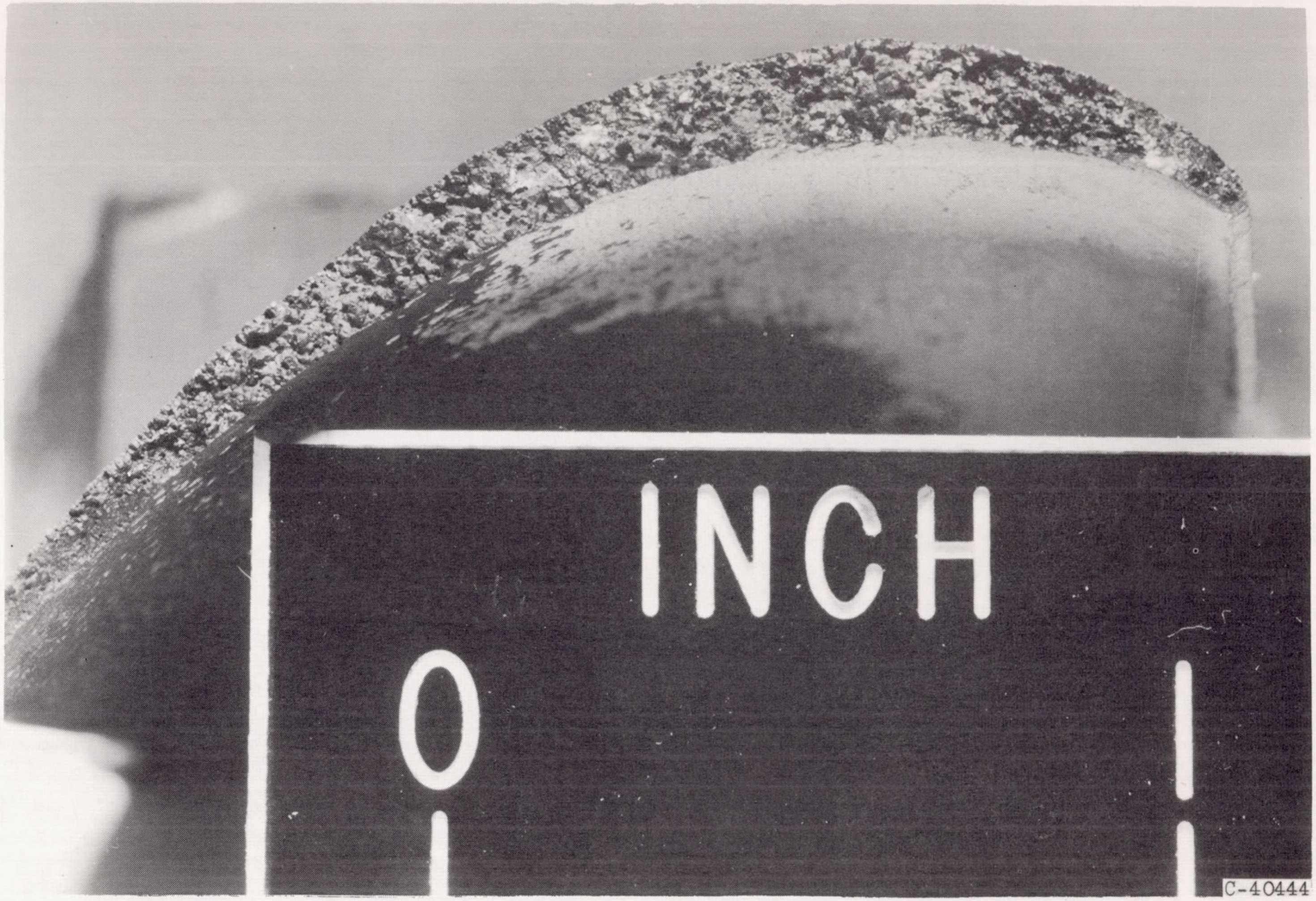

(b) Fracture surface. Intercrystalline fracture.

Figure 8. - Concluded. Inconel 739 bucket failure.