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RESEARCH MEMORANDUM

CYCLIC ENGINE TEST OF CAST VITALLIUM TURBINE BUCKETS - II

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted to provide data that may be used to correlate the engine service performance of cast Vitallium turbine buckets with metallurgical properties. Data were obtained from four turbine wheels of Timken alloy with cast Vitallium buckets. In order to accelerate bucket deterioration beyond the rate encountered in service operation, the turbine wheels were subjected to 20-minute cycles consisting of 5 minutes at idle and 15 minutes at rated speed.

Examination of 12 broken buckets indicated that 8 of the failures were probably caused by fatigue and 4 by impact with pieces of other broken buckets. Examinations of broken and of unbroken buckets disclosed no significant differences between the two groups with respect to chemical composition, epsilon-phase distribution, or carbide-mesh distribution.

INTRODUCTION

As part of a general evaluation of various heat-resisting alloys for jet-engine and gas-turbine application, investigations were made of four Timken-alloy turbine wheels with cast Vitallium buckets in an effort to provide data to be used to correlate the performance of turbine buckets in actual engine operation with the results of metallurgical laboratory examinations of the bucket material.

Cast Vitallium buckets of the current production type were investigated in order to establish a criterion for evaluating materials that have not been previously used in this application.

Each of the turbine wheels was run through the same cyclic engine test. The cyclic type of test was chosen to subject the turbine buckets to a greater thermal shock than would be encountered in normal operation in order to reduce the time necessary to cause bucket failure.

Identification of the nature of the mechanism that caused the failures is important because such an identification would permit an appraisal of the relative importance of the physical properties. Chemical analyses and metallurgical examinations were therefore made of broken and of unbroken buckets.

APPARATUS AND PROCEDURE

The investigation of cast Vitallium turbine buckets was conducted on turbojet engines mounted on a pendulum-type sea-level test stand. The turbojet engines, incorporating a dual-entry centrifugal compressor, 14 combustion chambers, and a single-stage turbine, have a thrust rating of 4000 pounds. Wherever possible, standard metallurgical procedures were used for the examination of the buckets. In those cases where these procedures proved unsatisfactory, they were altered as required.

Engine Operation

The apparatus, fuel, and instrumentation used are described in reference 1. The engine was operated on a 20-minute cycle (5 min at idle and 15 min at rated speed). The operating conditions are shown in the following table:

Duration		Rotor speed (rpm)	Gas temperature at exhaust-cone outlet (°F)
(min)	(sec)		
5	0	3500 ± 50	1110 maximum
0	15	Acceleration to 11,500	1450 ± 50
15	0	11,500 ± 50	1240 ± 20
0	15	Deceleration to 3500	1240 maximum

In order to permit a thorough metallurgical examination to be made, the procedure described in reference 1 was altered as follows: After a failure had occurred, the initially broken bucket, the diametrically opposite bucket, and, in random cases, the adjacent bucket were removed from the wheel for metallurgical examination. In those cases in which more than one bucket failed, all damaged buckets were removed.

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Metallurgical Examination

The following metallurgical examination procedure was used:

Identification. - The buckets to be examined were identified by assigning to each the number of the wheel and a number indicating its circumferential position on the wheel relative to an arbitrarily selected point. For example, bucket 53 on wheel 1 is designated bucket 1-53.

Visual examination. - The broken buckets were visually examined without magnification and under a low-power microscope before they were sectioned for further analysis. Surface irregularities, surface and fracture-face texture, and coating color were particularly noted.

Radiographic examination. - All buckets were radiographed after removal from the test wheel.

Coating examination. - The coatings of randomly selected buckets were mechanically removed and examined by X-ray diffraction methods.

Macroexamination. - The buckets were electrolytically etched in 10-percent hydrochloric acid to reveal the macrostructure. Grain-size measurements were made at six representative positions (A, B, E, F, I, and J, fig. 1) on the blade surface. The standard A.S.T.M. grain-size procedure was followed except that a magnification of unity was used instead of the usual 100X. It was noted whether the fracture being examined was intercrystalline or transcrystalline.

Chemical analysis. - The dovetail section of each bucket examined was cut off with an abrasive wheel and chips were removed from each section. These chips were analyzed by a commercial laboratory. Random check analyses were also made by the National Bureau of Standards and by a commercial laboratory.

Microexamination. - The blade areas of both the broken and the unbroken buckets were sectioned as indicated in figure 1. Sections A and B were polished for metallographic examination in both the longitudinal and the transverse directions, together with the top transverse surfaces of sections E, F, I, and J. The samples were electrolytically etched in aqueous hydrochloric acid. The transverse samples were rated for carbide-mesh distribution by measuring the number of carbide-island intersections encountered on eight random lines, each 1 inch long at a magnification of 100X. The average of the eight values thus obtained was called the carbide-mesh number.

Hardness surveys. - Rockwell C hardness measurements were made every 1/4 inch along the longitudinal face of section K, along the bottom transverse faces of sections E, F, I, and J, and along the top transverse face of sections C and D.

X-ray examination. - Glancing X-ray diffraction photographs were taken with a 225-millimeter camera using a collimating slit, an iron tube, and a manganese filter from the following positions: (a) unbroken buckets - near the edges on the bottom of the transverse faces of sections A and B; (b) broken buckets - on the fractured surfaces of the buckets near the leading and trailing edges.

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RESULTS AND DISCUSSION

Cyclic engine tests were made on four turbine wheels with cast Vitallium buckets. Metallurgical examinations were made on 12 broken and 13 unbroken buckets.

Engine Operation

Wheel 1. - The first and second bucket failures, in cycle 22 at 7 hours and 20 minutes and in cycle 25 at 8 hours and 12 minutes, respectively, are described in reference 1. The third bucket, 1-53, broke in cycle 26 at a total running time of 8 hours and 34 minutes (fig. 2).

Wheel 2. - The first bucket failure (bucket 2-18) occurred in cycle 29 at 9 hours and 28 minutes (reference 1). The second bucket, 2-48, broke in cycle 106 at a total running time of 35 hours and 10 minutes (fig. 3).

Wheel 3. - Buckets 3-16 and 3-43 were removed for examination after cycle 229 at 76 hours and 20 minutes total running time. Two new buckets were installed, the wheel balanced and the running continued. Upon inspection after cycle 260 (86 hr, 40 min, total running time), bucket 3-34 was found to be cracked on the convex surface. This bucket was replaced, the wheel balanced, and the running continued. In cycle 268 (89 hr, 17 min), a failure occurred that broke eight buckets and so damaged the others that running could not be continued with this wheel (fig. 4). Four of the eight broken buckets (3-33, 3-36, 3-45, and 3-49) were removed for examination.

Wheel 4. - The first bucket, 4-28, failed in cycle 156 at a total running time of 51 hours and 57 minutes (fig. 5). The broken bucket and two unbroken ones, 4-1 and 4-29, were removed from the wheel for examination. Three new buckets were installed, the wheel balanced, and the running continued. In cycle 188 (62 hr, 37 min, total

running time), bucket 4-1A broke. This bucket (fig. 6) was one installed after the first failure and had been operated for 32 cycles (10 hr, 40 min). The bucket was replaced, the wheel balanced, and the running continued. The third bucket, 4-39, broke during cycle 190
822 at a total running time of 63 hours and 16 minutes (fig. 7).

Summary of bucket failures. - The results of the engine investigations are summarized in the following table:

Wheel	Bucket	Total running time		Cycles
		(hr)	(min)	
		First bucket failure		
1	13	7	20	22
2	18	9	28	29
3	34	86	40	260
4	28	51	57	156
		Second bucket failure		
1	2	8	12	25
2	48	35	10	106
3	All	89	17	268
4	1A	10	40	32
		Third bucket failure		
1	53	8	34	26
2	------	----	-----	------
3	------	----	-----	------
4	39	63	16	190

Metallurgical Examination

Results of the metallurgical examination of the buckets showed that:

1. All buckets were radiographically sound.

2. The chemical analyses of the buckets presented in table I indicated that no significant differences in composition existed between broken and unbroken buckets.

3. Appearance of the fracture faces of broken buckets permitted classification of the failures into primary and secondary failures, examples of which are shown in figures 8(a) and 8(b), respectively.

4. The fracture faces of the eight primary-failure buckets exhibited three distinct zones that are quite different in appearance (fig. 8(a)). One zone has a smooth appearance and is coated with a tight oxide film ranging in color from light straw to dark gray. Contrary to data presented in reference 1, this zone occurred randomly at either edge and in one case at the center of the bucket. This apparent discrepancy in the results was probably caused by the increased number of buckets examined in this investigation. The second zone had the fibrous appearance that is characteristic of fractured ductile material and was coated with a loose porous oxide film ranging in color from a deep blue to dull gray or black. The third zone was a transitional one between the other two zones both in location and in characteristics. Fractures of the primary class were transcrystalline across the entire bucket and occurred in the center third of the blade length (fig. 9(a)). These observations lead to the conclusion that the primary type of failure is caused by fatigue, which originates in the smooth zone and progresses until the centrifugal stress on the remaining portion of the blade exceeds the ultimate strength of the material and the blade fails in tension. The location of the origin of fatigue within the smooth zone was extremely difficult to determine, particularly because the fractured surface was always coated with a thick oxide layer, which was difficult to remove by methods that did not damage the fracture face.

5. The fractured faces of four buckets representative of the secondary type of failure (fig. 8(b)) exhibited an appearance, uniform across the entire bucket, that was similar both in color and in texture to the fibrous zone previously described. This type of failure was also transcrystalline and had a random distribution along the blade length (fig. 9(b)). These failures probably occurred upon impact with segments of other broken buckets.

6. The grain size, as determined by macroexamination, varied considerably from bucket to bucket and in most cases within the bucket itself. Slight differences, however, did exist between broken and unbroken buckets and between failures due to fatigue and those probably due to impact. The grain size of all buckets examined may be summarized as follows:

(a) Grain size over entire bucket, average of all buckets examined

Broken buckets	27 grains per square inch
Unbroken buckets	36 grains per square inch

(b) Grain size over entire bucket, average of all broken buckets

Fatigue failures	19 grains per square inch
Impact failures	37 grains per square inch

(c) Grain size at zone of failure, average of all broken buckets

Fatigue failures	27 grains per square inch
Impact failures	54 grains per square inch

From the above summary it may be seen that:

(a) Buckets that broke had a somewhat coarser grain than unbroken buckets. Within certain limits (reference 2), the high-temperature rupture strength of cast alloys of this type increases with increasing grain size. It therefore seems unlikely that the failures observed in this investigation were caused by low rupture strength.

(b) Buckets that failed from fatigue had somewhat coarser grains than buckets that failed by impact.

(c) In the immediate zone of failure, buckets that failed by fatigue had much coarser grains than buckets that failed by impact.

(d) Of the buckets that failed by fatigue, the grain size at the failure zone was finer than over the bucket in general.

7. As can be seen in table II, a very wide scatter of Rockwell C hardness values was observed from bucket to bucket as well as in the various sections of a single bucket. This scatter of values is the expected condition in very coarse-grained cast materials. The buckets, however, tended to harden with increasing running time and most of the buckets were harder at the center than at either the tip or the base. No significant differences were observed between the broken and unbroken buckets.

8. The microstructure appeared the same for broken and unbroken buckets. The concentration of eutectic material noted in the nucleus area in reference 1 was not apparent in this investigation.

9. After engine operation, a nonuniform distribution of the epsilon phase existed in the broken and unbroken buckets with some buckets of each type being completely devoid of the phase. No significant differences in quantity or in distribution of the epsilon phase could be detected by visual examination of the diffraction patterns between the two types of bucket.

10. No significant differences could be detected in carbide-mesh distribution between broken and unbroken buckets.

SUMMARY OF RESULTS

The results of the investigation of four Timken-alloy turbine wheels with cast Vitallium buckets may be summarized as follows:

1. The results of failures during the cyclic engine tests were:

Wheel	First bucket failure			Second bucket failure		
	Cycle	Total running time		Cycle	Total running time	
		(hr)	(min)		(hr)	(min)
1[a]	22	7	20	25	8	12
2	29	9	28	106	35	10
3[b]	260	86	40	268	89	17
4	156	51	57	188[c]	10	40

[a]Third bucket failure, cycle 26 (8 hr, 34 min).
[b]All buckets badly damaged (four buckets – 3-33, 3-36, 3-45, and 3-49 – removed for examination).
[c]This bucket, a replacement of a previous failure, operated only 32 cycles.

2. This investigation covered the metallurgical examinations of 12 broken and 13 examined but unbroken cast Vitallium turbojet buckets. Of the failures, eight were caused by fatigue and four were probably caused by impact. The two types of failures were both transcrystalline but were easily differentiated by the appearance of the fractured surfaces.

3. All buckets examined showed the wide scatter of metallurgical properties that is associated with coarse-grained cast materials. This scatter may have obscured small but important differences that might have existed between broken and unbroken buckets.

4. No significant differences were detected between broken and unbroken buckets in chemical composition, hardness, epsilon-phase quantity or distribution, or carbide-mesh distribution. It was noted, however, that the buckets were somewhat harder in the center than at either the tip or the base.

5. After operation, it was noted that a nonuniform distribution of the epsilon phase existed in both broken and unbroken buckets, with several of each having no epsilon phase.

6. Although a very wide scatter of data was observed, the buckets that failed by fatigue were somewhat coarser in grain size than the unbroken buckets.

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REFERENCES

1. Farmer, J. Elmo, Darmara, F. N., and Poulson, Francis D.: Cyclic Engine Test of Cast Vitallium Turbine Buckets - I. NACA RM No. E7J23, 1948

2. Grant, Nicholas J.: Structural Variation in Gas Turbine Alloy Revealed by the Stress-Rupture Tests. Trans. A.S.M., vol. XXXIX, 1947, pp. 335-359; discussion, pp. 359-367.

Table I. - Chemical analyses of turbine buckets

Wheel	Bucket	Condition	Element, percent														
			Cr	Ni	Co	Mo	Ti	Cu	Cb	W	Si	C	N_2	Mn	S	P	Fe
1	2	Broken	27.96	3.04	63.92	5.80	0.01	--	0.16	0.08	0.53	0.33	--	0.25	0.05	0.026	0.49
	13	Broken	27.78	2.66	63.90	5.85	.01	--	.19	.08	.57	.29	--	.33	.05	.029	.75
	53	Broken	27.81	2.38	61.49	5.68	.00	.00	.00	.00	.66	.240	0.14	.56	.008	.024	--
	12	Unbroken	28.40	2.31	62.69	5.80	.00	.00	.00	.00	.52	.250	.09	.61	.029	.014	--
	26	Unbroken	27.71	2.97	61.31	5.55	.00	.00	.00	.00	.58	.202	.15	.51	.012	.036	--
2	18	Broken	27.95	2.81	63.37	5.60	0.01	--	0.19	0.16	0.53	0.32	--	0.31	0.05	0.031	1.06
	48	Broken	27.90	2.45	62.51	5.37	.00	0.00	.00	.00	.54	.264	.06	.68	.037	.036	--
	21	Unbroken	27.51	2.70	62.00	5.85	.00	.00	.00	.00	.49	.244	.13	.54	.025	.034	--
	49	Unbroken	28.20	2.53	61.31	5.73	.00	.00	.00	.00	.58	.261	.15	.77	.020	.038	--
3	33	Broken	27.90	2.44	61.86	5.67	0.00	0.00	0.00	0.00	0.60	0.193	0.11	0.49	0.008	0.012	--
	34	Broken	27.68	2.25	62.22	5.63	.00	.00	.00	.00	.57	.202	.13	.58	.007	.024	--
	36	Broken	27.65	2.24	61.49	5.65	.00	.00	.00	.00	.55	.193	.15	.48	.011	.024	--
	45	Broken	27.44	2.29	62.52	5.47	.00	.00	.00	.00	.68	.207	.11	.51	.007	.018	--
	49	Broken	27.84	2.26	62.13	5.39	.00	.00	.00	.00	.75	.175	.13	.47	.009	.018	--
	6	Unbroken	27.84	2.26	62.13	5.37	.00	.00	.00	.00	.65	.226	.17	.61	.007	.024	--
	9	Unbroken	27.68	2.19	62.19	5.65	.00	.00	.00	.00	.61	.221	.11	.53	.009	.024	--
	16	Unbroken	28.16	2.27	62.73	5.60	.00	.00	.00	.00	.41	.231	.13	.49	.024	.020	--
	18	Unbroken	27.71	2.45	61.45	5.57	.00	.00	.00	.00	.69	.211	.15	.64	.010	.020	--
	22	Unbroken	27.87	2.42	61.71	5.83	.00	.00	.00	.00	.55	.216	.12	.46	.008	.026	--
	43	Unbroken	28.34	2.15	62.85	5.21	.00	.00	.00	.00	.49	.235	.12	.31	.024	.020	--
4	1A	Broken	27.50	2.74	61.35	5.48	0.00	0.00	0.00	0.00	0.52	0.306	0.17	0.65	0.012	0.016	--
	28	Broken	27.20	2.66	62.34	5.59	.00	.00	.00	.00	.55	.322	.15	.63	.031	.038	--
	1	Unbroken	28.28	2.60	61.40	5.70	.00	.00	.00	.00	.63	.247	.12	.63	.038	.030	--
	28A	Unbroken	27.97	2.29	61.73	5.62	.00	.00	.00	.00	.52	.32	.23	.51	.011	.009	--
	29	Unbroken	27.59	2.76	61.71	5.70	.00	.00	.00	.00	.65	.291	.14	.68	.038	.036	--

Table II. - Rockwell C hardness survey of turbine buckets

Values represent average values for each position

Wheel	Bucket	Total running time (hr)	Total running time (min)	Condition	Rockwell C: Tip, Leading edge	Tip, Trailing edge	Center, Leading edge	Center, Trailing edge	Base, Leading edge	Base, Trailing edge
1	53	8	34	Broken	--	--	39	41	37	38
	12	8	12	Unbroken	31	32	35	31	30	26
	26	8	34	Unbroken	35	32	32	34	34	37
2	18	9	28	Broken	--	--	37	36	28	25
	48	35	10	Broken	--	--	37	37	36	35
	21	35	10	Unbroken	24	24	31	37	41	40
	49	35	10	Unbroken	--	--	39	38	36	37
3	33	89	17	Broken	--	--	43	39	34	35
	34	86	40	Broken	--	--	42	37	44	45
	36	89	17	Broken	--	--	44	34	41	45
	45	89	17	Broken	--	--	42	39	35	38
	49	89	17	Broken	--	--	43	41	34	32
	6	89	17	Unbroken	--	--	45	42	34	37
	9	89	17	Unbroken	43	41	43	42	38	35
	16	76	20	Unbroken	--	--	41	37	--	--
	18	89	17	Unbroken	38	39	39	41	36	35
	22	89	17	Unbroken	--	--	42	45	43	44
	43	76	20	Unbroken	42	39	42	39	30	29
4	1A	10	40	Broken	--	--	--	--	38	39
	28	51	57	Broken	--	--	42	42	--	--
	1	51	57	Unbroken	32	32	42	33	40	35
	28A	10	40	Unbroken	--	--	33	36	38	37
	29	51	57	Unbroken	39	32	44	45	33	33

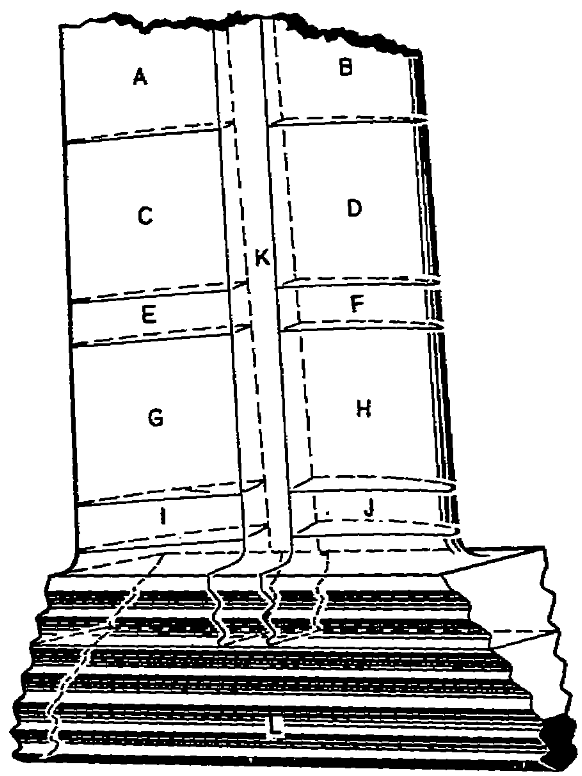

Figure 1. - Diagram showing manner in which buckets were sectioned to permit metallurgical examination.

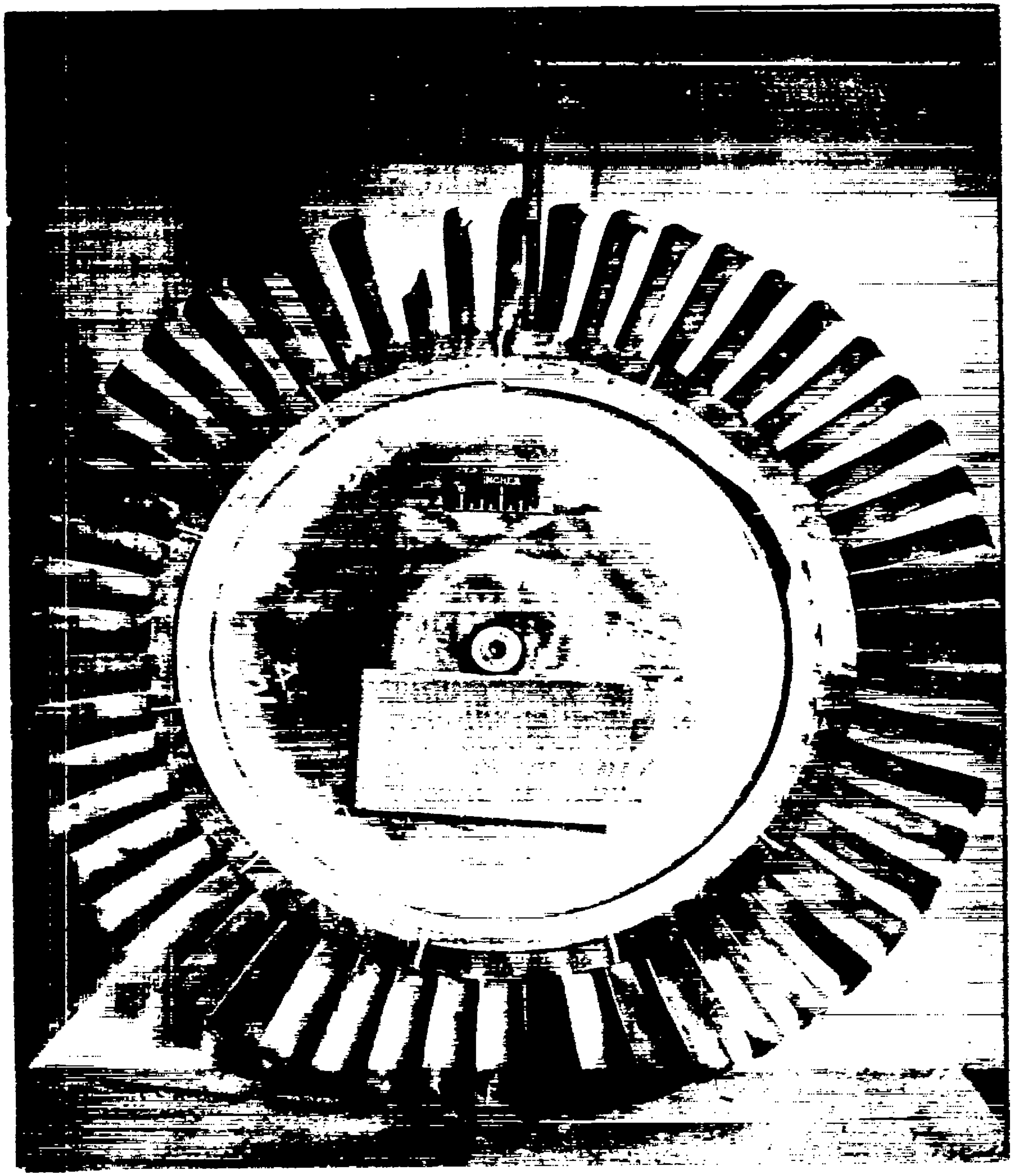

Figure 2. - Wheel I after third bucket failure (bucket I-53) during cycle 26 at total running time of 8 hours and 34 minutes.

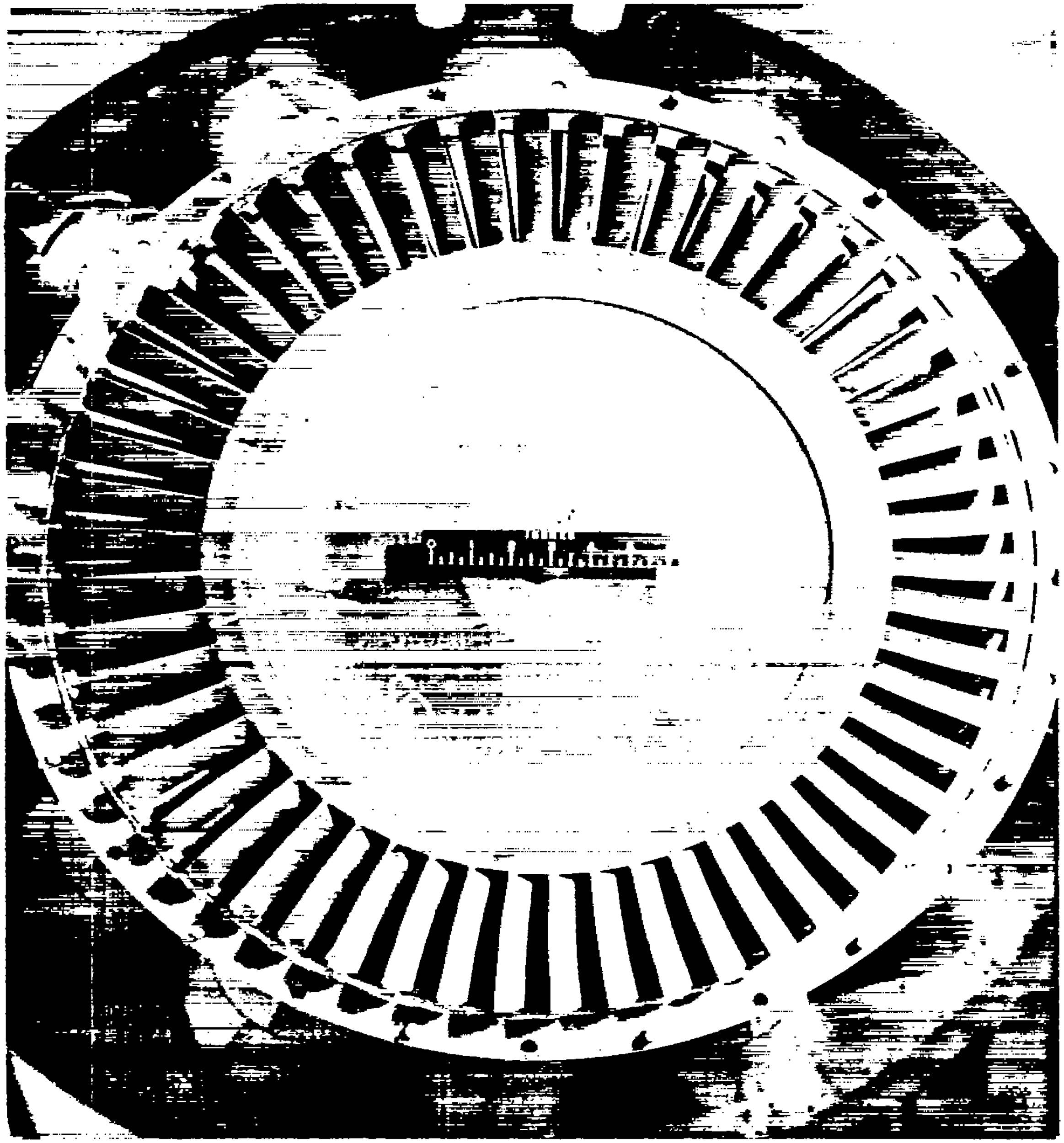

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Figure 3. - Wheel 2 after second bucket failure (bucket 2-48) during cycle 106 at total running time of 35 hours and 10 minutes.

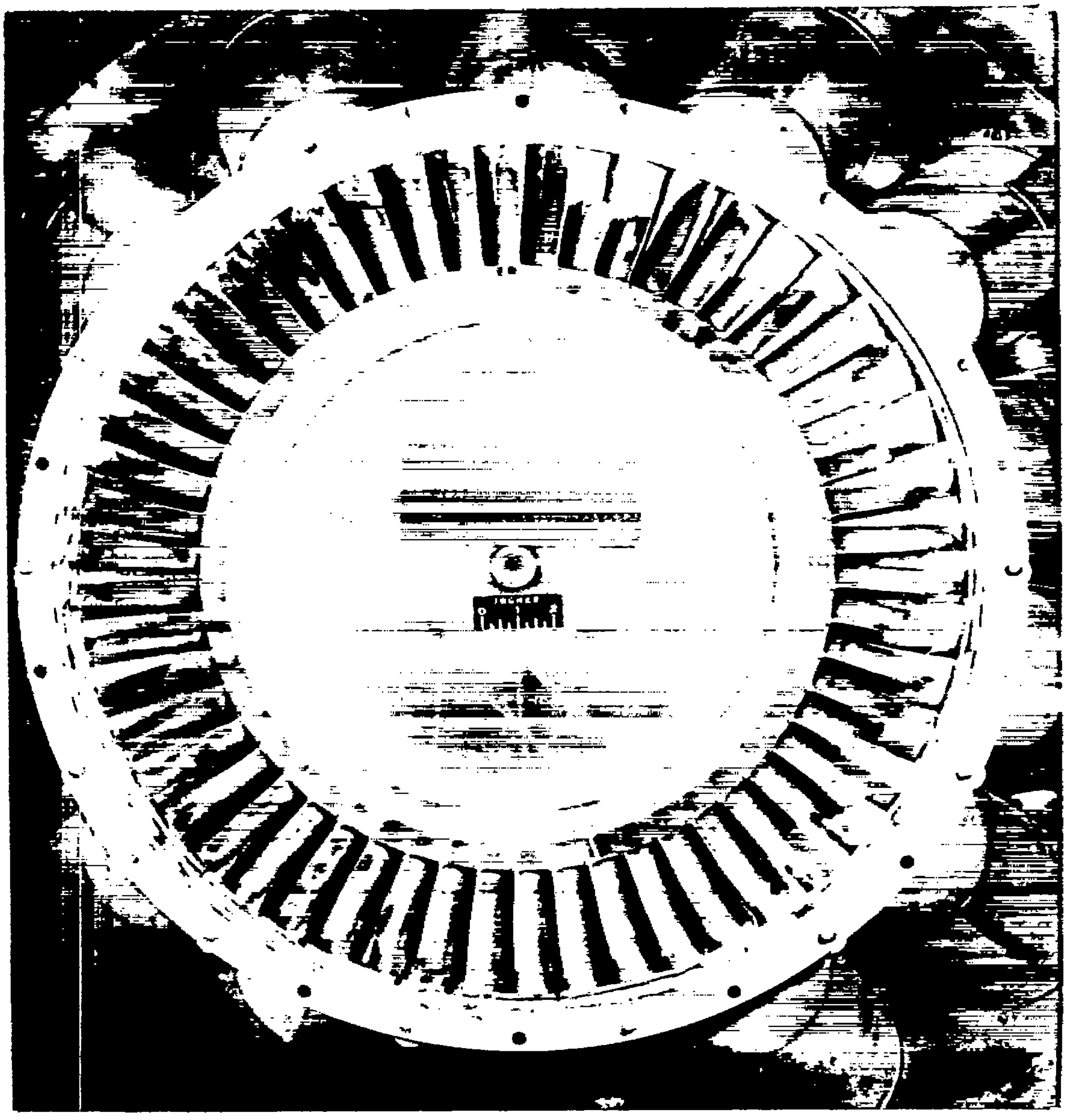

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Figure 4. - Wheel 3 after second bucket failure occurred during cycle 268 at total running time of 89 hours and 17 minutes damaging eight buckets.

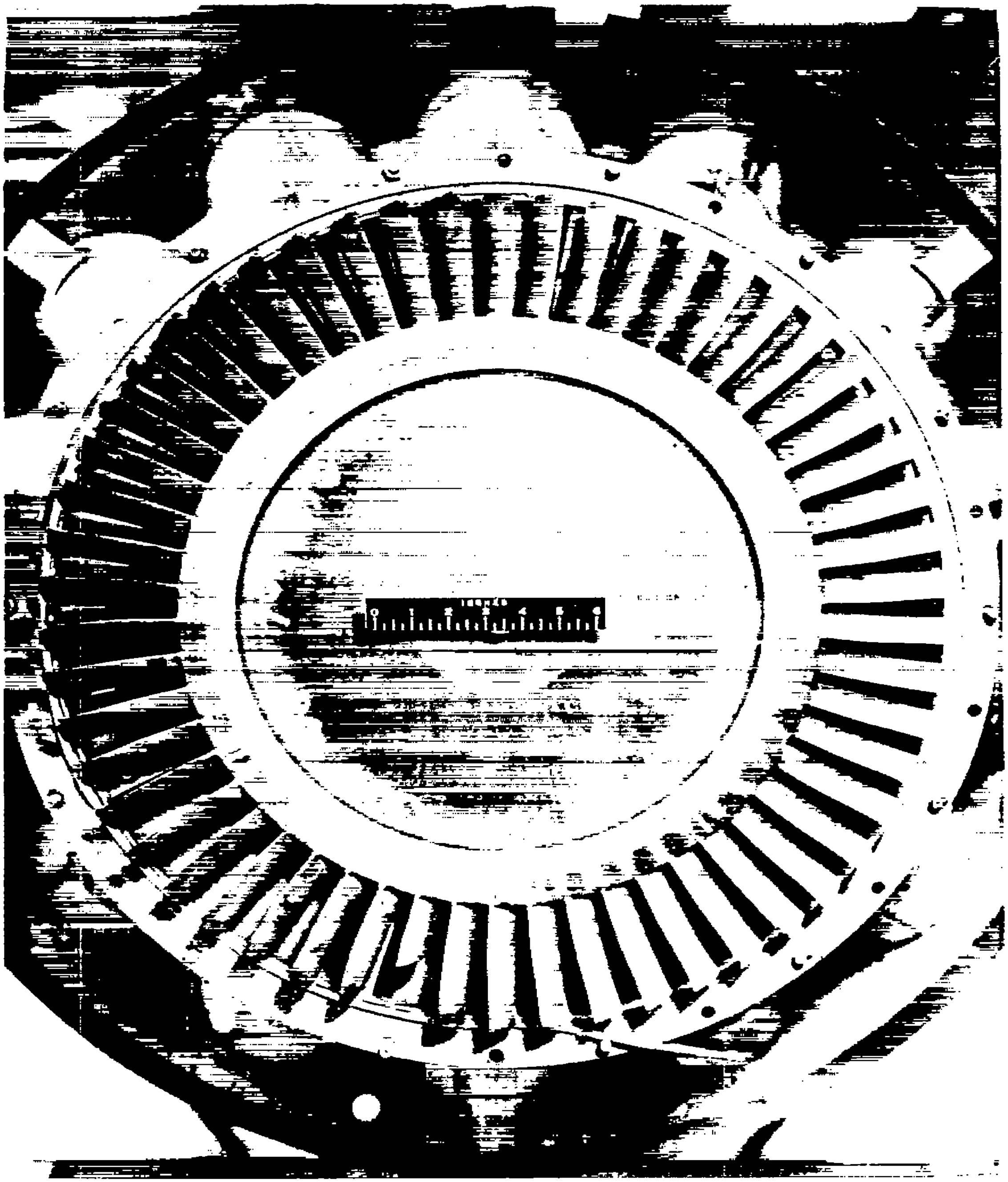

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Figure 5. - Wheel 4 after first bucket failure (bucket 4-28) during cycle 156 at total running time of 51 hours and 57 minutes.

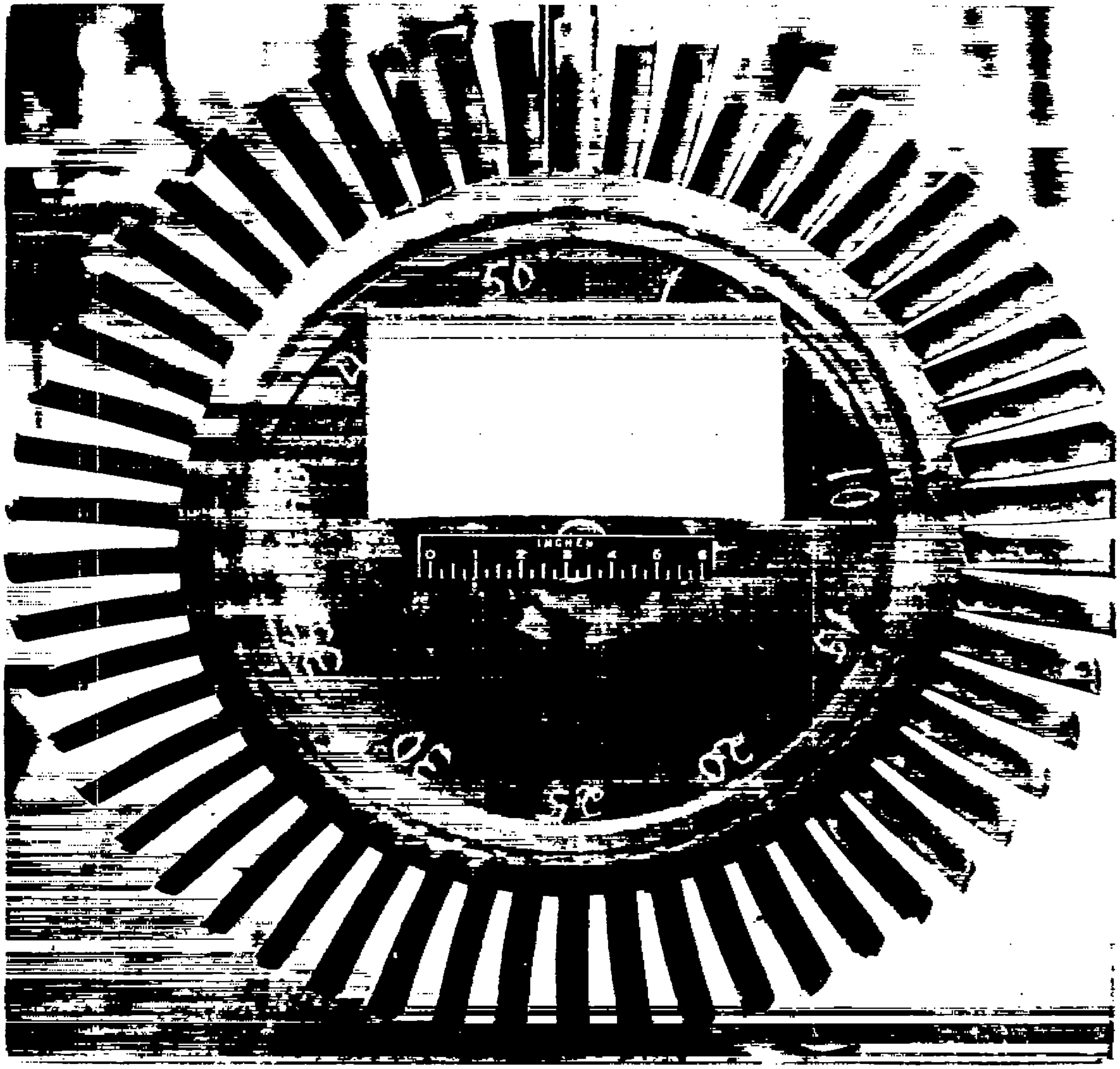

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Figure 6. - Wheel 4 after second bucket failure (bucket 4-1A) during cycle 188 at total running time of 62 hours and 37 minutes. This bucket was installed after first bucket failure and was run 32 cycles (10 hr, 40 min).

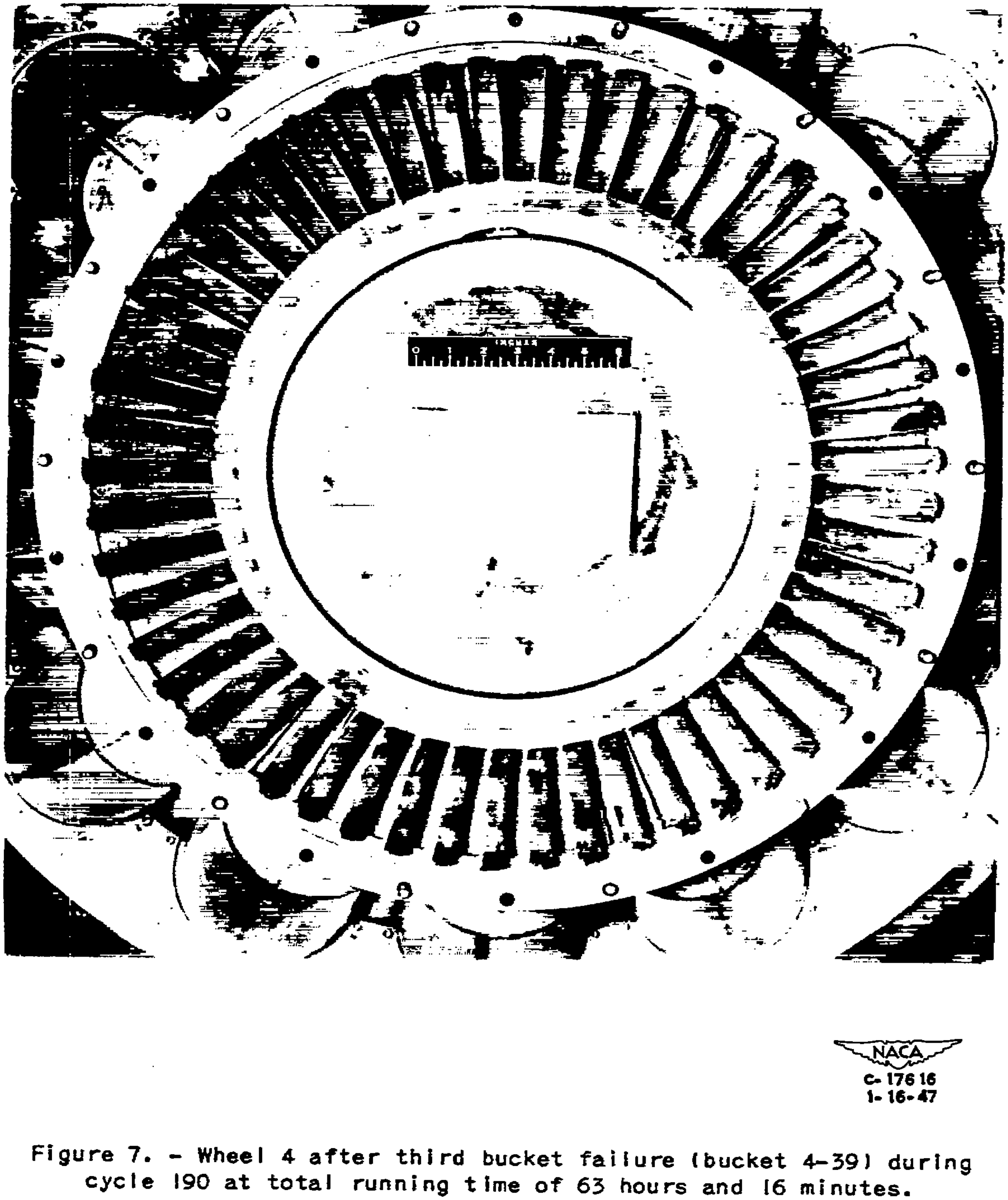
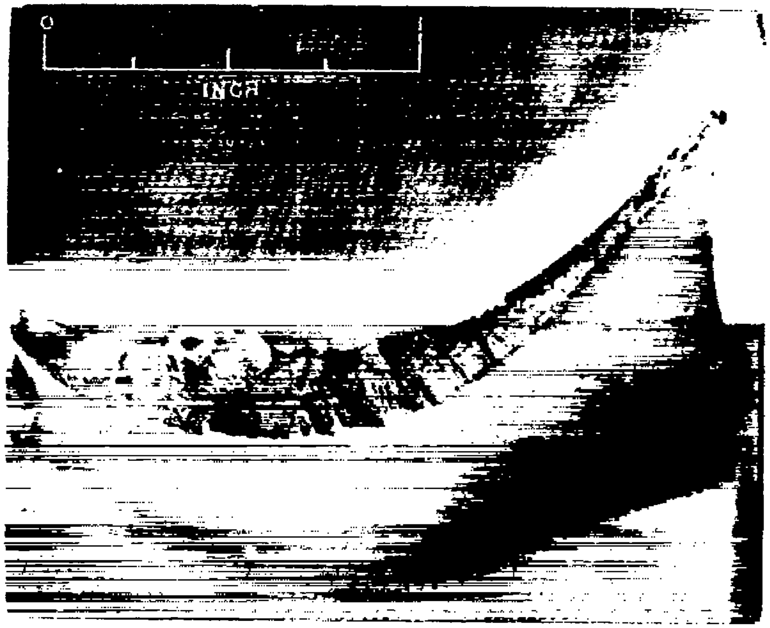


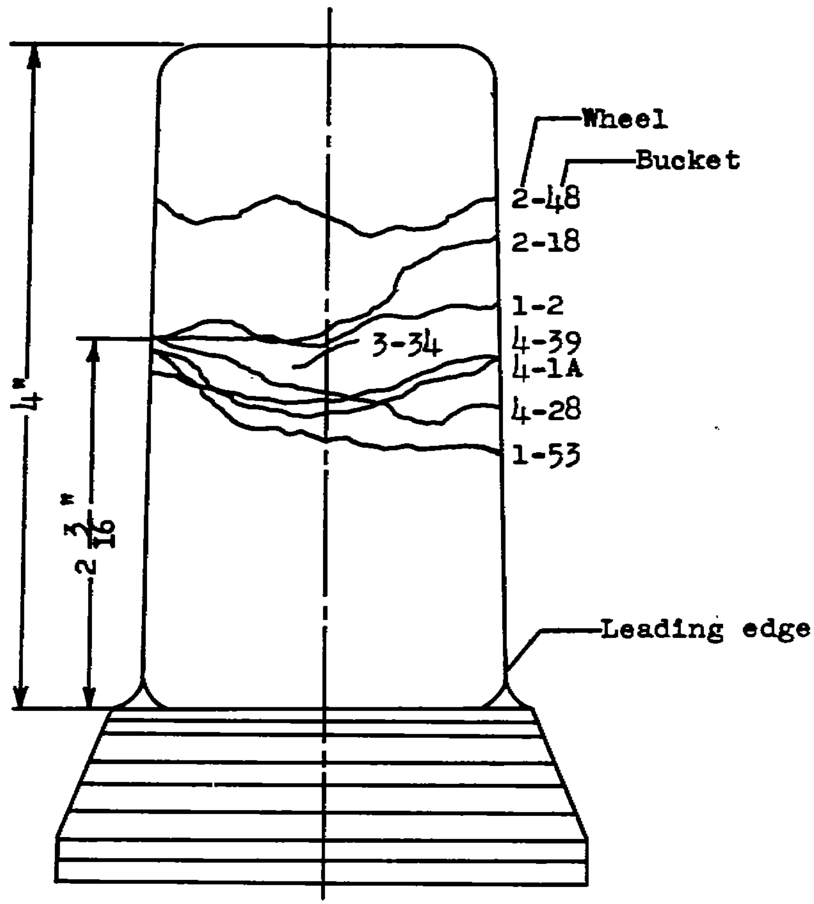
Figure 7. - Wheel 4 after third bucket failure (bucket 4-39) during cycle 190 at total running time of 63 hours and 16 minutes.



(a) Primary failure,
caused by fatigue.

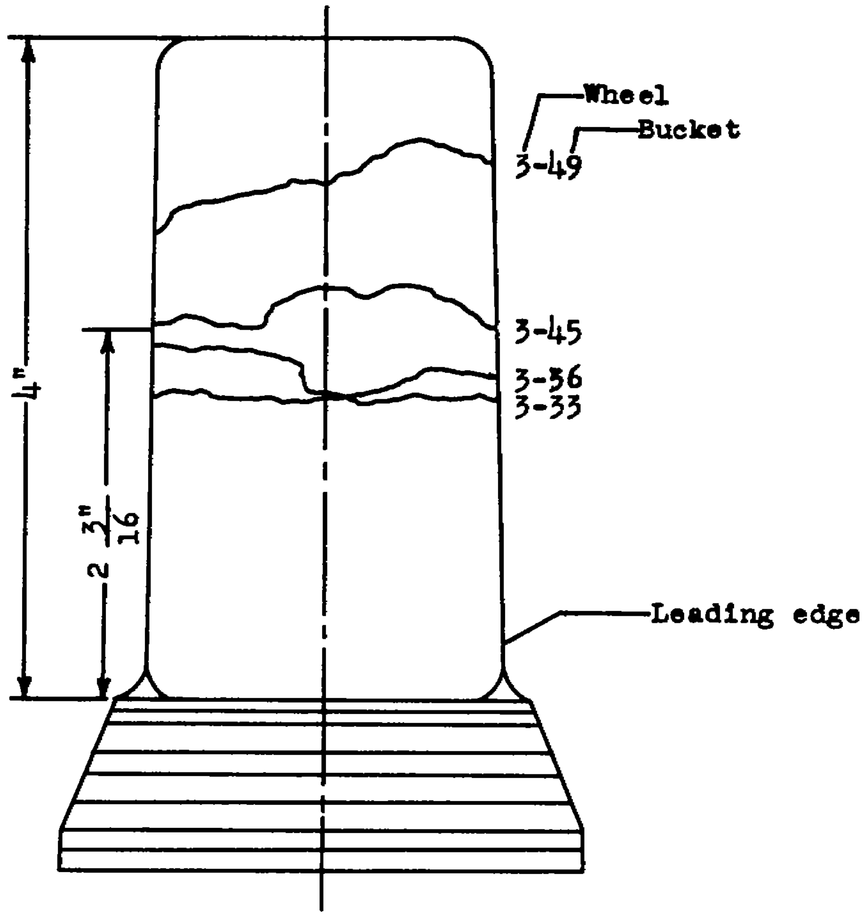
(b) Secondary failure, probably
caused by impact.

Figure 8. - Fractured faces of primary and secondary types of turbine-bucket failure.



(a) Failures caused by fatigue.

Figure 9. – Composite profile of failures of cast Vitallium turbine buckets.



(b) Failures probably caused by impact.

Figure 9. - Concluded. Composite profile of failures of cast Vitallium turbine buckets.