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# RESEARCH MEMORANDUM

## EFFECT OF FORGING TEMPERATURE AND HEAT TREATMENT ON THE PERFORMANCE OF INCONEL 700 BUCKETS AT 1625° F IN A J33-9 TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE
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# EFFECT OF FORGING TEMPERATURE AND HEAT TREATMENT ON THE PERFORMANCE OF INCONEL 700 BUCKETS AT 1625° F IN A J33-9 TURBOJET ENGINE

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## SUMMARY

An investigation was undertaken to determine the effects of forging temperatures and solution treatments on the engine performance of Inconel 700 buckets. The buckets were evaluated in a J33-9 turbojet engine operated at a bucket material temperature of 1625° F in 20-minute cycles, 15 minutes at rated speed (11,500 rpm) and approximately 5 minutes at idle (4000 rpm). The results of the investigation show that Inconel 700 buckets are capable of operating for more than 450 hours at rated speed. The best performance was obtained when a high forging temperature (2225° F) and a high solution-treating temperature (2275° F) were employed.

## INTRODUCTION

The high-performance turbojet engines required for future supersonic planes have stimulated the development of new high-strength materials that are capable of operating at increased temperatures. One of the more recently introduced materials that appears capable of operating at high temperatures is Inconel 700.

This material, which is an age-hardenable nickel-base alloy containing titanium and aluminum, was developed for turbine rotor blades ("buckets") in the 1600° to 1650° F temperature range. Manufacturer's data indicate that the stress-rupture life of Inconel 700 at 1600° F varies with the heat treatment and that the best life is obtained when the material is solution-treated at 2280° F or above, depending upon the aging temperature used (fig. 1). The data also show that a double aging treatment yields a better stress-rupture life than a single aging treatment when the alloy is solution-treated above 2200° F. However, solution-treating temperatures above 2100° F greatly increase the grain size (fig. 1), and such increase is considered undesirable by some manufacturers of gas turbines.

Since Inconel 700 is a new bucket alloy, a program was undertaken to determine the effects of the variables of forging temperatures and heat treatments on the life of the buckets in a full-scale engine at a bucket material temperature of 1625° F.

The Inconel 700 buckets were forged from a single heat of material and were fabricated by one manufacturer. The buckets were evaluated in a J33-9 engine operated in repetitive 20-minute cycles, 15 minutes at rated speed (11,500 rpm) and approximately 5 minutes at idle (4000 rpm). At rated speed, a temperature of 1625° F was maintained in the bucket airfoils at a point 2.3 inches above the base platform, the point where the combined effects of centrifugal stress and temperature were determined to be most critical. The stress-rupture life for the bucket material was determined with specimens machined from the airfoils. Metallographic studies were made of both new and operated buckets.

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## MATERIAL, APPARATUS, AND PROCEDURE

### Turbine Buckets

A single heat of Inconel 700 alloy with the following composition was forged into the buckets used in this investigation:

| Weight, percent | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ni | Co | Cr | Mo | Al | Ti | Fe | Si | C | Mn | Cu | S |
| 47.94 | 28.42 | 14.76 | 2.76 | 2.93 | 2.18 | 0.58 | 0.20 | 0.10 | 0.08 | 0.02 | 0.007 |

The forging temperatures and heat treatments are shown in table I.

After heat treatment by the manufacturer and before engine operation, the buckets were subjected to radiographic and fluorescent post-emulsion oil penetrant (PE zyglo) examinations for internal and external defects. All buckets passed both inspections. The buckets used in the performance test were examined periodically for surface defects and cracks with the PE zyglo. Buckets that exhibited excessive cracks or damage were removed from the engine.

*Stress and temperature distributions in buckets during engine operation.* - The centrifugal-stress distribution in the turbine buckets for rated-speed operation was determined by a graphical method that utilizes bucket geometry, density, radius of rotation, and angular velocity. The results of these calculations are shown in figure 2.

The temperature distribution along the span of the bucket airfoil at midchord was determined during the initial stages of operation using four thermocoupled S-816 turbine buckets placed 90° apart in the rotor disk. Once the temperature distribution was determined, the temperature at the midspan of the buckets was periodically verified with two thermocoupled buckets placed 180° apart. The midspan temperature was maintained by controlling the temperature of the exhaust gases. All temperatures were recorded on a fast-action electronic potentiometer. The average temperature distribution in the buckets during rated-speed operation is also shown in figure 2.

Predicted bucket life based on stress-rupture considerations. - By using the stress- and temperature-distribution data determined for the buckets (fig. 2) in conjunction with stress-rupture values for the material, it is possible to approximate the life expectancy of a bucket material in an engine if the sole cause of failure is assumed to be the combination of centrifugal stress and temperature. Predicted lives for two lots of Inconel 700 buckets (lots 2 and 6, table I) were determined and are presented in figure 3. Predicted-life curves were not determined for the remaining lots of material because of lack of reliable stress-rupture data for those specific conditions of heat treatment. The curves of figure 3 were obtained by interpolating between isothermals of the manufacturer's stress-rupture data for the stress and temperature conditions existing at incremental distances along the span of the buckets. The data show that the minimum expected life of a lot 2 bucket is 430 hours, and the minimum expected life of a lot 6 bucket is 960 hours. Since the minimum is at 2.3 inches above the base platform, it would be expected that failures should occur in a region near this point. This region is considered the critical zone. Experience has shown that factors other than stress-rupture, such as vibrational stress, thermal shock, and corrosion, decrease the life expectancy of the buckets and may cause failure outside the critical zone (ref. 1).

## Engine Operation

The buckets selected for engine evaluation were operated in a J33-9 engine in cycles of 20-minute duration, 15 minutes at rated speed (11,500 rpm) and approximately 5 minutes at idle speed (4000 rpm). During rated-speed operation, the midspan bucket temperature was measured with two buckets having thermocouples mounted in the midchord section, 2 inches above the base. The electromotive force of the thermocouples was transmitted from the buckets through a system of slip rings attached to the drive shaft of the engine to a recording instrument as described in reference 2. The times of failure reported herein refer to the cumulative time at rated speed only.

Engine operation was interrupted to inspect buckets, to replace failed buckets, and to perform normal maintenance at the end of each work day. A J33-9 engine, modified to permit operation at a bucket temperature of 1625° F, was used for this test. Three percent of the compressor air was bled off to minimize the possibility of encountering compressor stall at rated speed while operating at the elevated temperature. (Normal bucket operating temperature is 1500° F.) The test was terminated after 447.5 hours of rated-speed operation because of lack of bucket replacements capable of operating at 1625° F.

## Bucket-Elongation Measurements

Half-inch gage lengths for elongation measurements, as shown in figure 4, were scribed on the suction (convex) side of 12 buckets. Elongation readings were taken at frequent intervals during necessary engine shutdowns. The elongation of each scribed segment was measured with an optical extensometer having a sensitivity of 0.0001 inch. However, accuracy of the elongation measurements was influenced by the degree of bucket oxidation, distortion, and warpage. The maximum error in an elongation reading was of the order of 0.001 inch, which is equivalent to ±0.2-percent elongation.



## Macro- and Micro-Examination of Buckets

Macro-examination of buckets. - Two new buckets of each of the six lots listed in table I were macroetched to reveal grain structure and flow lines. All buckets that were operated were macro-examined after removal from the engine to determine their failure mechanisms.

A bucket was considered failed when actual fracture occurred or when the bucket was cracked or damaged so severely that fracture was imminent. Fractured buckets were classified according to the mechanism that caused failure as follows:

(1) Stress-rupture: Bucket failure occurred by cracking within the airfoil or by fracturing in an irregular, jagged, intercrystalline path. Other similar cracks sometimes occurred near the origin of the main fracture.

(2) Stress-rupture followed by fatigue: Bucket failures appeared to be caused by a combination of two mechanisms, stress-rupture and fatigue. The fracture surface consisted of a small area having characteristics of stress-rupture and a larger area with fatigue characteristics. A further criterion was the appearance of secondary stress-rupture cracks near the nucleation site of the main crack.

(3) Damage: Buckets showing nicks or dents in the airfoil that might possibly initiate fracture were not considered in the analysis of the data, since they do not yield a true indication of material properties.

A basic difficulty in defining the failure mechanism from the appearance of the fracture surface alone is that the effect of superimposed fatigue damage is not always evident. In many cases, the fracture surface of the specimens showed no evidence of fatigue damage, although reduction in life was caused by the superimposed vibratory loads (ref. 1).

Micro-examination of buckets. - Metallographic specimens of airfoil chord sections were taken from the new buckets as shown in figure 5. Two buckets of each lot were examined. In addition, metallographic studies were made of the first and last bucket failures of each lot. Two specimens were taken from each of these buckets, the first containing the fracture region and the second the chord section of the region immediately below the fracture.

The specimens were electrolytically etched in a solution containing 40 percent hydrochloric acid, 10 percent nitric acid, and 50 percent water. Grain size was determined by using ASTM grids with photomicrographs taken at 100 times magnification.

Hardness measurements. - Hardness measurements were made on the metallographic specimens (the chordwise cross sections of buckets shown in fig. 5). The hardness readings for the different lots of buckets were compared.

Stress-rupture tests. - Four stress-rupture specimens, machined from the airfoils of two buckets, were tested for each lot of material. Figure 5 shows the location in the airfoils from which specimens were cut. The stress-rupture tests were conducted at 1600° F under constant-load conditions that produced nominal initial stresses of 30,000, 25,000, and 20,000 psi.

## RESULTS

### Performance of Buckets

The results of the engine evaluation show that heat-treated Inconel 700 buckets can operate several hundred hours at a bucket temperature of 1625° F (in the critical zone). A comparison of engine performance of the six lots of Inconel 700 is presented in figure 6 and in table II.

Best performance was obtained from the lot 6 buckets. Eighty-nine percent (8 out of 9) of these buckets were still usable when the test was discontinued after 447.5 hours of rated-speed operation. The only failure in this lot occurred after 105 hours and probably was not representative of the lot.

Good performance also was obtained from the lot 4 buckets. When the test was terminated, 42 percent (5 out of 12) of these buckets were still good. The first of the seven failures of this lot was a damage-induced failure and could not be considered normal. The first normal failure occurred at 245 hours.

The buckets of lot 5 had operated a fair length of time before the first failure, which occurred at 195 hours. During the next 85 hours of operation the remaining buckets of this lot failed.

Most of the bucket failures of lots 2 and 3 occurred at around 100 hours. One bucket of lot 3 and two buckets of lot 2 operated for several hundred additional hours, one bucket of lot 2 still remaining at the termination of the test. All the buckets of lot 1 either failed or were in danger of imminent failure by 70 hours of operation. 4217

<u>Bucket elongation during operation</u>. - Elongation of the buckets of each lot of Inconel 700 was negligible, as can be seen in table III. For all groups except 1 and 5, measured elongations for almost all of the buckets were smaller than the maximum allowable error of the method used ($\pm$0.2 percent). The as-forged and aged groups 1 and 5 had elongations of about 1 percent and 0.6 percent, respectively.

<u>Stress-rupture tests</u>. - The results of the stress-rupture tests at 1600° F on specimens taken from bucket airfoils are presented in table IV. During seven of the tests, excessive grip deformation was encountered; this was troublesome in that it superimposed a bending moment on the tensile load. The deformation caused either premature failure or slippage of the specimens from the grips. Duplicate tests could not be run because of a lack of material.

Although some of the stress-rupture data obtained from airfoil specimens were questionable, the remaining data compare favorably with the manufacturer's data, as shown in figure 7. It is interesting to note that one specimen from the lot 6 buckets had a stress-rupture life of nearly 1400 hours when stressed at 20,000 psi at 1600° F. This stress is comparable to that encountered in the critical zone of the buckets during rated-speed operation, and the temperature is within 25° F of the temperature in the critical zone of the bucket.

## Hardness

The results of the Rockwell A hardness measurement on airfoil sections of six lots of Inconel 700 alloy are presented in table V along with equivalent Rockwell C hardness readings. The hardness values for the as-forged and aged buckets (lots 1 and 5) are greater than those of the solution-treated and aged buckets (lots 2, 3, 4, and 6). This relation of hardness values is approximately maintained during engine operation.

## Macro- and Micro-Examination of New Buckets

The macrograin sizes of the various lots of buckets are shown in figure 8. The macrograin sizes were relatively uniform within each bucket. The grain sizes of lots of the solution-treated and aged buckets were slightly larger than those in the buckets that were not solution-
4217 treated. The grain measurements taken on microsections showed that the ASTM grain sizes ranged from 5 to 6 for the as-forged and aged (non-solution-treated) lot 1 buckets to -2 to 1 for the solution-treated lot 6 buckets, as shown in table VI and figure 9. Elongated grains, indicating the presence of cold-working, were detected in the two lots of buckets (1 and 5) that were not solution-treated.

The typical microstructures of the six lots of buckets are shown in figure 10. The photomicrographs do not show the matrix precipitates that are often visible in an age-hardenable alloy. In all probability the precipitates are too fine (or coherent) to be resolved optically. (Long-time aging in a furnace or operating the buckets in an engine will cause the precipitates to grow and become readily visible, as will be shown later.) The larger minor-phase particles present in these microstructures have been identified as titanium carbonitride Ti(C,N) (ref. 3).

While the structures shown in figure 10 are typical, there were isolated regions within buckets that differed. Examples of these microstructures are presented in figure 11. Figures 11(a) and (b) show slipline precipitates present in the leading and trailing edges of buckets that were forged and aged only (not solution-treated). Various degrees of grain-boundary precipitation in the buckets of all lots are presented in figure 11(c). Precipitation of the magnitude shown in the lower part of figure 11(c) was very rare. The development of void formation at the interface between titanium carbonitride and the matrix in the buckets that were solution-treated at 2275° F can be seen in figure 11(d). Figure 11(e) shows a region with sawtooth grain boundaries.

## Macro- and Micro-Examination of Failed Buckets

Macro-examination of failed buckets revealed that failures occurred by several different mechanisms - stress-rupture, stress-rupture followed by fatigue, and damage. The classification of failure mechanisms as determined visually is reported in table II and figure 6.

Most of the failures in lots 1, 2, 3, and 4 were stress-rupture failures. Practically all of the lot 1 buckets were removed from the engine after 69 hours because intergranular (stress-rupture) cracks were present that probably would have caused failure. The stress-rupture-followed-by-fatigue fractures were detected only in lot 5. Excluding damage failures, 36 bucket failures occurred during the investigation. Thirty of these buckets had failure origins outside the region considered the critical zone.

The micro-examination of the failed buckets revealed that appreciable precipitation occurred in the alloy during engine operation. An example of the typical precipitation is presented in figure 12. Occasionally, agglomeration of precipitates occurred in localized sections of buckets. An example of the precipitate agglomeration is shown in figure 13.

The microstructural studies also revealed that all operated buckets exhibited various degrees of surface depletion that appeared to be related to the operating time. An example of a depletion zone is shown in figure 14(a). Occasionally, needle-like structures (possibly chromium nitrides) were noted in the depletion zones, as shown in figure 14(b).

## DISCUSSION OF RESULTS

### Performance of Different Groups of Buckets

The results of the engine evaluation of the different groups of buckets show that both the forging temperature and the solution-treating temperature significantly influence bucket performance. Of the two forging temperatures used in this study, the higher temperature (2225° F) proved superior to the lower temperature (2100° F). For example, the buckets forged from 2225° F and aged had more than three times the median life of the buckets forged from 2100° F and aged (lot 5 against lot 1).

Further evidence of the superiority of the higher forging temperature may be observed in comparing the performance of lots 6 and 4. Like lots 5 and 1, lots 6 and 4 were forged at two different temperatures. However, subsequently they both received identical high-temperature solution treatments and aging. While the solution treatment improved the performance of both lots over groups 5 and 1, the buckets forged at the higher temperature still showed performance superior to the buckets forged at the lower temperature (lot 6 better than lot 4).

The relative effectiveness of the two solution treatments may be discerned by comparing the performance of lots 1, 2, and 4. The performance of lot 2 buckets (solution-treated at 2150° F) was superior to that of the lot 1 buckets (not solution-treated). An even greater improvement in performance was obtained for the lot 4 buckets, which were solution-treated at 2275° F; however, the aging treatment following the high-temperature solution treatment differs slightly from that following the low-temperature solution treatment. Although it might be argued that this difference in aging could account for the improvement in performance attributed to the high-temperature solution treatment, the authors believe that the solution treatment has a far greater influence on the stress-rupture properties of the material than the interposed 2000° F aging treatment; and, on this assumption, it is concluded that the high-temperature solution treatment is preferred.

To appreciate fully the potentialities of Inconel 700, it is worthwhile to compare its performance with that of materials that are now commonly used in jet engines. One of the materials commonly used is S-816. In a J33-9 engine (similar to that used for the investigation reported herein) operated under cyclic conditions at 1500° F, the average life of S-816 buckets ranged from 148 to 345 hours (refs. 4 and 5). In comparison, the best lot of Inconel 700 buckets operated at 125° F higher temperature (1625° F) for more than 447.5 hours. Thus, this material should be suitable for use in engines designed for advanced-temperature operation.

## Metallographic Studies

Metallographic studies of the buckets offer some assistance in understanding the effects of the different forging temperatures and solution treatments on the bucket performance. The microstructures of as-forged buckets, even those forged from a temperature of 2225° F, showed evidence of cold-working in the form of elongated grains (figs. 9(a) and (e)). More severe grain elongation was present in the buckets forged from a temperature of 2100° F, indicating that these buckets received a greater degree of cold-working.

Solution-treating the buckets at either temperature (2150° or 2275° F) removed all the visual evidence of cold-working irrespective of the forging temperature. This does not preclude the possibility, however, that some deleterious effects that may result from the cold-working would still remain in the buckets.

The microstructural studies did not reveal any general matrix precipitate of the principal hardening phase after the aging treatments. However, with engine operation or with additional aging, the evidence of precipitates becomes plainly visible, and in some cases the precipitates agglomerated. The presence of the precipitates did not cause any significant change in the hardness.

The unusual form of the precipitates and microstructural configurations shown in figure 11 could not be related to the performance of any of the groups of buckets.

## Bucket Elongation

Actual measurements at various times during the test showed that the maximum bucket elongation never exceeded 1.22 percent (table III). This value is considerably below the 3 to 16 percent shown in table IV, which had been obtained from the stress-rupture tests. This low elongation (1.22 percent) might imply that the material may be brittle under engine operating conditions; however, factors other than pure centrifugal stress (e.g., fatigue, etc.) may reduce the final elongation and creep rate of the buckets. This low elongation is not unusual; it has been noted in other engine evaluations with different alloys (refs. 6 and 7).

## Hardness

The evidence of cold-working observed metallographically in the as-forged and aged buckets may also be substantiated by the hardness results presented in table V. The hardness of the as-forged and aged buckets was significantly greater than that of the solution-treated and aged buckets. The greater hardness probably results from the internal stresses that were introduced by the cold-working during forging but not relieved during the aging treatment.



## Grain Size

A relation between grain size and engine performance was noted; that is, engine performance improved as grain size increased. Since the grain size increased as the temperature of the solution treatment increased, it cannot be determined whether the improved engine performance resulted directly from the larger grain size or whether the apparent effect was purely coincidental.

## Failure Mechanisms

Experience has shown that factors other than centrifugal stress act on the buckets during engine operation and may lead to bucket failure. In previous investigations, vibratory stresses have been shown to be of considerable importance in reducing bucket life in J33 engines (refs. 1 and 7). Reduction in life may sometimes be as much as 70 to 90 percent of the predicted life based on stress-rupture considerations alone (ref. 1). Thermal fatigue may also become important in the J33 engine as the operating temperature is raised. However, periodic examinations of the buckets revealed no conclusive evidence of thermal-fatigue damage.

Often the mechanism of failure in a bucket can be determined from the location of failure and the appearance of the fracture surfaces (ref. 1). A simple stress-rupture failure will be located near the critical cross section and will have a rough, intergranular fracture surface. A simple fatigue failure frequently will be located away from the critical cross section and will have a transgranular fracture with a concentric-ring or conchoidal appearance.

In this investigation, the location of the fractures indicated that centrifugal stress alone could not account for most of the bucket failures. Most of the fractures occurred in regions in the buckets where the predicted life was several times the maximum predicted life at the critical cross section. The occurrence of indications of fatigue on a few buckets shows that vibrational stresses were acting on the buckets. These vibrational stresses would tend to decrease the life of the buckets and could account for the displacement of the fractures from the critical cross section.

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Even with the possible detrimental effects of vibratory stress, the performance of the best lot of the Inconel 700 buckets was good compared with the expected life. The best lot had operated 447.5 hours with only one failure, which is nearly 50 percent of the predicted life of 960 hours.

## SUMMARY OF RESULTS

The investigation into the effect of forging temperature and heat treatment on the engine performance of Inconel 700 bucket disclosed the following:

1. Both the forging temperature and the solution-treating temperature significantly influenced the performance of Inconel 700 buckets. Best results were obtained with a combination of high forging and high solution-treating temperatures.

2. Of the two forging temperatures used in this study, the higher temperature (2225° F) proved superior to the lower temperature (2100° F). The median lives of buckets were approximately 240 hours for those forged at the higher temperature and 70 hours for those forged at the lower temperature.

3. Of the two solution-treating temperatures used in this study, the higher temperature (2275° F) proved superior to the lower temperature.

4. The better than 447.5-hour performance at 1625° F for the best lot of Inconel 700 buckets indicated that this material should be suitable for use in engines designed for advanced-temperature operation. In comparison, the average J33-9 engine life of S-816 buckets ranges from 148 to 345 hours at 1500° F.

5. The microstructures of the as-forged buckets, even those forged from a temperature of 2225° F, showed evidence of cold-working in the form of elongated grains. Solution-treating the buckets at either temperature (2150° or 2275° F) removed all the visual evidence of the cold-working irrespective of the forging temperature. This does not

preclude the possibility that some deleterious effects that may result from the cold-working would still remain in the buckets.

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TABLE I. - FORGING TEMPERATURES AND HEAT TREATMENTS USED IN PRODUCING INCONEL 700 TURBINE BUCKETS

| Lot | Forging temperature, °F | Solution treatment | | Preliminary aging | | Aging | |
|---|---|---|---|---|---|---|---|
| | | Temperature, °F | Time, hr | Temperature, °F | Time, hr | Temperature, °F | Time, hr |
| 1 | 2100 | ---- | - | ---- | - | 1600 | [a]4 |
| 2 | | 2150 | 2 | ---- | - | 1600 | [a]4 |
| 3 | | | | | | | 4 |
| 4 | | 2275<br>Furnace-cool to 2175, air-cool | 2 | 2000 | 1 | 1600 | [a]4 |
| 5 | 2225 | ---- | - | ---- | - | 1600 | [a]4 |
| 6 | | 2275<br>Furnace-cool to 2175, air-cool | 2 | 2000 | 1 | 1600 | [a]4 |

[a]Buckets given an additional treatment after finishing - a heat-treatment at 1600° F for 7 hours. This treatment was intended to stress-relieve the surfaces of the materials, and to crack any buckets that had high residual stresses. Two buckets cracked during this heat treatment and they were discarded.

TABLE II. - ORDER OF FAILURE, ORIGIN OF FAILURE, AND FAILURE TYPES OBTAINED DURING ENGINE OPERATION OF INCONEL 700 BUCKETS

| Group | Time to failure, hr | Type of failure (a),(b) | Location of failure with reference to base and edges, in. (c) |
|---|---|---|---|
| 1 | 65.0 | SR | $2\frac{5}{8}$ M.C. |
| | 68.5 | SR | $2\frac{3}{4}$ L.E. |
| | 69.2 | SR | $2\frac{9}{16}$ M.C. |
| | 69.2 | SR-C | $2\frac{5}{8}$ L.E. |
| | 69.2 (median) | ↓ | $2\frac{3}{4}$ L.E. |
| | 69.2 | ↓ | $2\frac{3}{4}$ L.E. |
| | 69.2 | ↓ | $2\frac{3}{4}$ L.E. |
| | 69.2 | ↓ | $2\frac{7}{8}$ L.E. |
| | 69.2 | ↓ | $2\frac{7}{8}$ L.E. |
| 2 | 73.1 | SR | $2\frac{13}{16}$ L.E. |
| | 96.5 | SR | $2\frac{15}{16}$ L.E. |
| | 115.2 | SR | 3 L.E. |
| | 130.8 | SR | 3 L.E. |
| | 147.2 (median) | ---- | |
| | 163.6 | Damage | |
| | 166.8 | SR | $2\frac{7}{8}$ L.E. |
| | 289.5 | SR | $2\frac{7}{8}$ L.E. |
| | >447.5 | Unfailed | |
| 3 | 105.3 | SR | $2\frac{11}{16}$ L.E. |
| | 116.0 | SR | $2\frac{3}{4}$ L.E. |
| | 117.4 (median) | ---- | |
| | 118.8 | SR-C | $2\frac{23}{32}$ L.E. |
| | 368.0 | SR | $2\frac{7}{8}$ L.E. |
| 4 | [d]163.6 | Damage | -------- |
| | 245.2 | SR | $2\frac{7}{8}$ L.E. |
| | 276.2 | SR | 3 L.E. |
| | 276.2 | Damage | |
| | 365.8 | SR | $2\frac{5}{8}$ L.E. |
| | 411.8 | SR | $2\frac{27}{32}$ L.E. |
| | 421.0 (median) | SR | $2\frac{1}{2}$ M.C. |
| | >447.5 (5 buckets) | Unfailed | |
| 5 | 195.2 | SR | $1\frac{15}{16}$ T.E. |
| | 213.5 | SR | 2 T.E. |
| | 214.0 | SR | $2\frac{1}{32}$ T.E. |
| | 216.0 | SR | $2\frac{1}{8}$ T.E. |
| | 227.5 | SR | |
| | 233.8 | SR→F | $1\frac{7}{8}$ T.E. |
| | 238.2 (median) | ---- | |
| | 242.5 | SR | 2 T.E. |
| | 246.0 | Damage | |
| | 248.5 | SR→F | $1\frac{7}{8}$ T.E. |
| | 250.5 | SR→F | $1\frac{7}{8}$ T.E. |
| | 258.2 | SR→F | $1\frac{15}{16}$ T.E. |
| | 280.2 | SR→F | 2 T.E. |
| 6 | 105.0 | SR | $2\frac{7}{8}$ L.E. |
| | >447.5 (8 buckets) (median) | Unfailed | |

[a]Based upon macro-examination.

[b]SR = Stress-rupture.
SR-C = Stress-rupture cracks (bucket did not fracture).
SR→F = Stress-rupture followed by fatigue.

[c]L.E. = Leading edge.
M.C. = Midchord
T.E. = Trailing edge.

[d]Omitted in determining median.

TABLE III. - FINAL ELONGATIONS OBSERVED IN INCONEL 700 BUCKETS PRIOR TO FAILURE

[Refer to fig. 4 for location of "position."]

| Lot number | 1 | | 2 | | 3 | | 5 | | 4 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time of last reading, hr | 65.0 | | 99.2 | | 99.2 | 150.0 | 182.7 | 219.0 | 354.2 | | 354.2 | |
| Percent elongation at position | | | | | | | | | | | | |
| 1 | 0.24 | 0.25 | <0.2 | 0.31 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 |
| 2 | .58 | .48 | <.2 | <.2 | <.2 | .21 | .39 | .33 | <.2 | <.2 | <.2 | <.2 |
| 3 | .91 | 1.07 | <.2 | <.2 | <.2 | <.2 | .71 | .56 | .21 | .41 | <.2 | <.2 |
| 4 | .34 | 1.22 | <.2 | <.2 | <.2 | .44 | .44 | .02 | <.2 | <.2 | <.2 | <.2 |

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TABLE IV. - STRESS-RUPTURE LIFE OF INCONEL 700 BUCKET SPECIMENS AT 1600° F

| Lot | Stress, psi | | | | | |
|---|---|---|---|---|---|---|
| | 30,000 | | 25,000 | | 20,000 | |
| | Life, hr | Elongation in 1/2-in. gage length, % | Life, hr | Elongation in 1/2-in. gage length, % | Life, hr | Elongation in 1/2-in. gage length, % |
| 1 | 36.9 | (a) | [b]83.6 | 8 | 168.3 | 8 |
| | | | | | [b]217.8 | -- |
| 2 | 49.7 | (a) | 126.0 | 16 | 399.9 | 16 |
| | | | | | [c]>337.3 | -- |
| 4 | [b]74.3 | 10 | [c]>54.8 | -- | [c]>560.0 | [d]4 |
| | | | | | [b]72.2 | 10 |
| 5 | 51.9 | (a) | 219.0 | -- | 568.0 | 8 |
| | | | | | 364.8 | 3 |
| 6 | 86.3 | 6 | 262.3 | 10 | 1397.5 | 10 |
| | | | | | 237.7 | [e]42 |

[a]Gage marks obliterated.

[b]Specimens may have been tested under a bending moment.

[c]Specimens slipped from grips at time noted.

[d]Approximate reading; specimen bent.

[e]Meaningless; excessive grain separation.

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TABLE V. - HARDNESS OF INCONEL 700 BUCKETS BEFORE AND AFTER OPERATION IN J33-9 ENGINE

[Rockwell A hardness was taken and converted to Rockwell C.]

| Lot | As-received hardness | | First failure hardness | | | Last failure hardness | | |
|---|---|---|---|---|---|---|---|---|
| | Rockwell A | Rockwell C | Time at rated speed, hr | Rockwell A | Rockwell C | Time at rated speed, hr | Rockwell A | Rockwell C |
| 1 | 68.8 | 36.6 | 65.0 | 69.0 | 37.0 | 69.2 | 69.5 | 38.0 |
| 2 | 66.0 | 31.0 | 73.1 | 68.3 | 35.6 | 289.5 | 68.0 | 35.0 |
| 3 | 66.0 | 31.0 | 105.3 | 66.5 | 32.0 | 368.0 | 67.3 | 33.6 |
| 4 | 66.6 | 32.2 | 245.2 | 65.7 | 30.4 | 421.0 | 67.0 | 33.0 |
| 5 | 68.2 | 35.4 | 195.2 | 69.0 | 37.0 | 280.2 | 71.0 | 41.0 |
| 6 | 65.2 | 29.4 | 105.0 | 66.3 | 31.6 | ----- | ---- | ---- |

TABLE VI. - GRAIN SIZES

| Lot | ASTM grain size |
|---|---|
| 1 | 5 to 6 |
| 2 | 0 to 3 |
| 3 | 0 to 3 |
| 4 | -1 to 2 |
| 5 | 1 to 4 |
| 6 | -2 to 1 |

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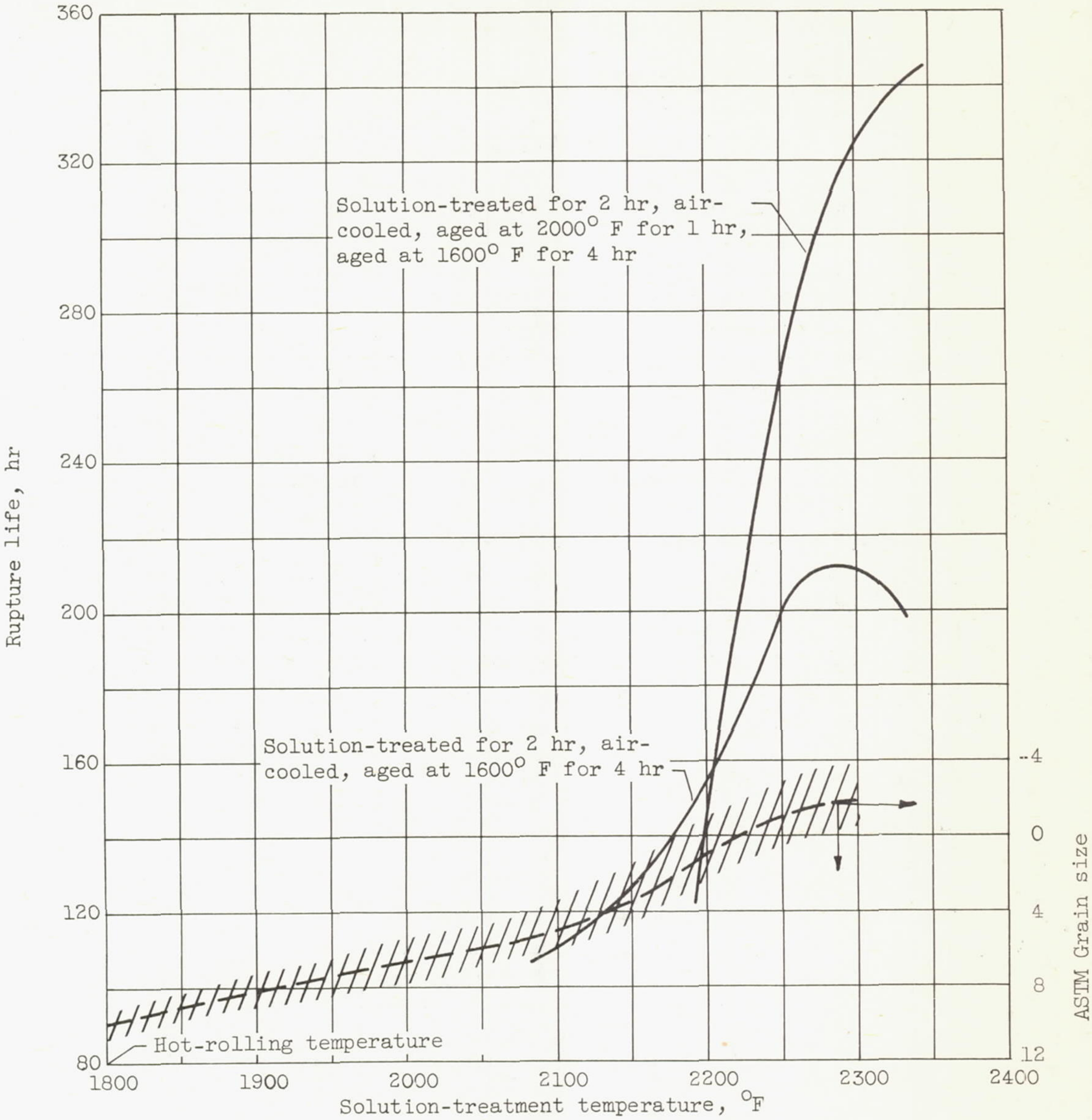


Figure 1. - Effect of solution treatment and aging on the rupture life of Inconel 700 at 1600° F and 25,000 psi, and effect of solution-treatment temperature on grain size.

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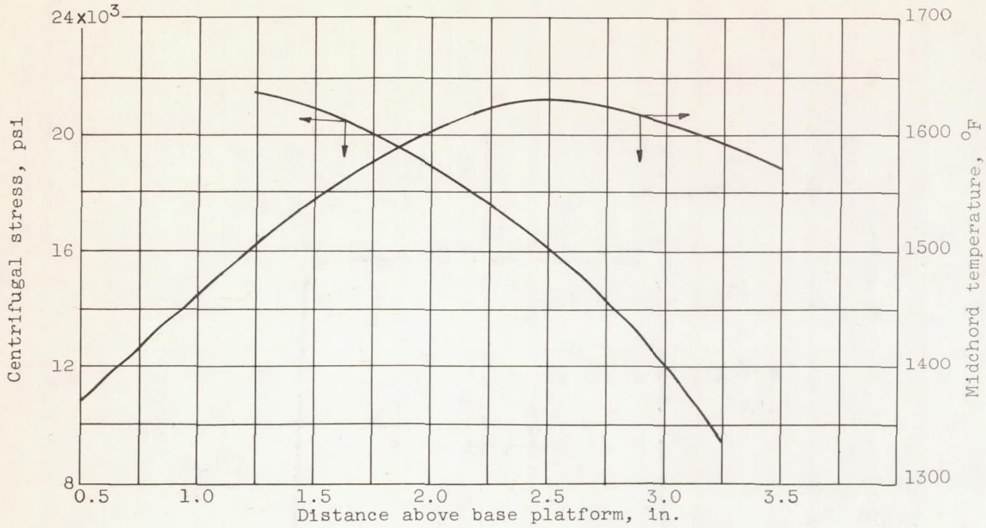


Figure 2. - Centrifugal-stress and midchord-temperature distributions in Inconel 700 turbine buckets during rated-speed operation (11,500 rpm) in J33-9 turbojet engine. Total airfoil length, 4 inches.

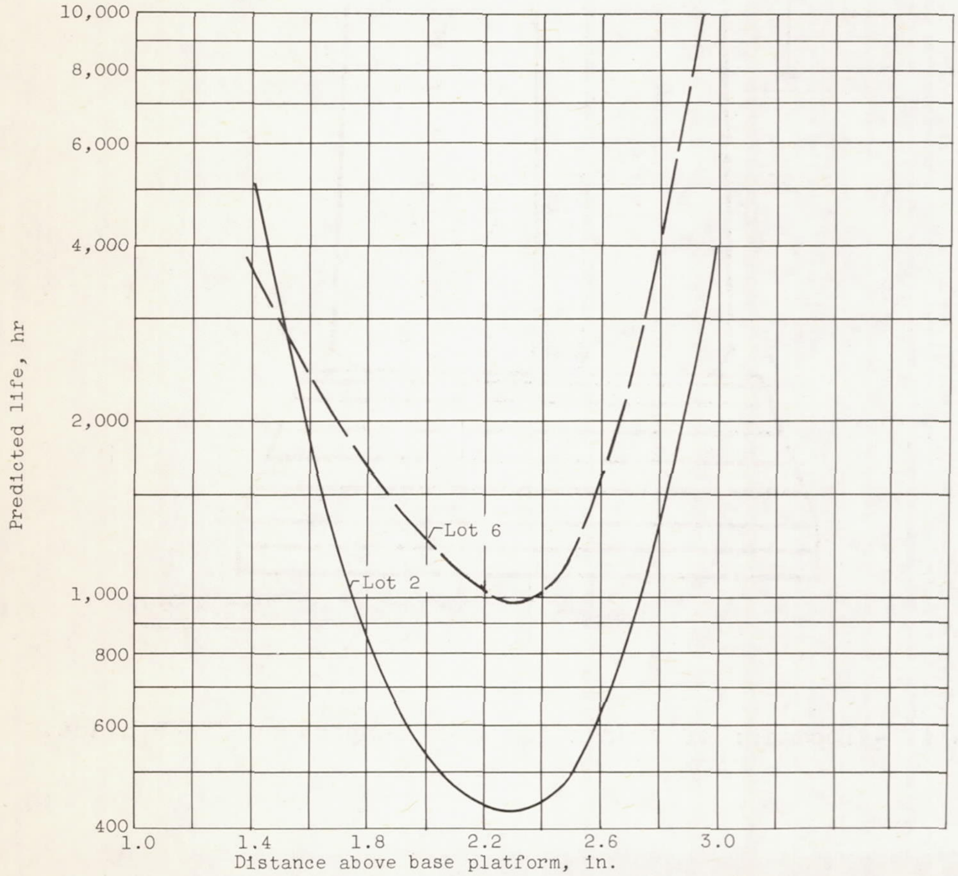


Figure 3. - Predicted engine life of lot 2 and lot 6 buckets if centrifugal stress and temperature were the only factors causing bucket failure.

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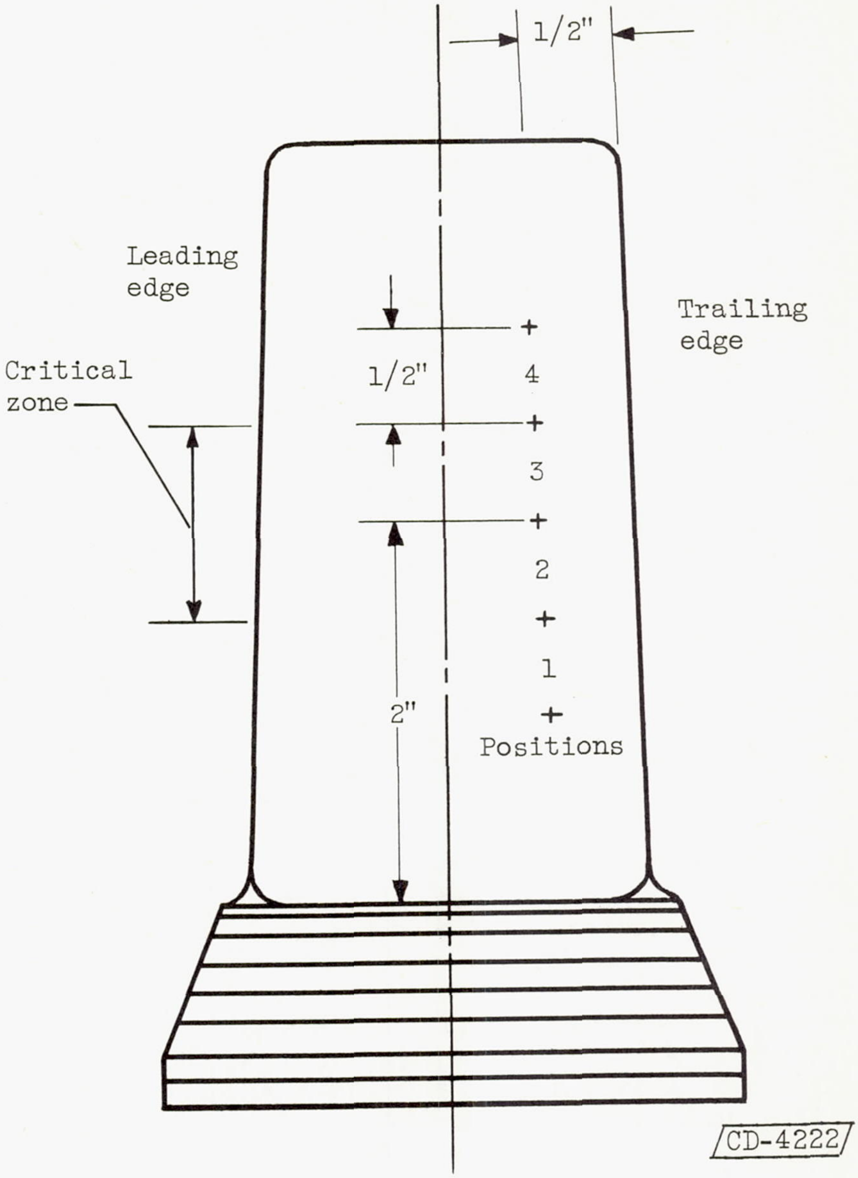



Figure 4. - Location of elongation gage lengths in J33-9 blade.

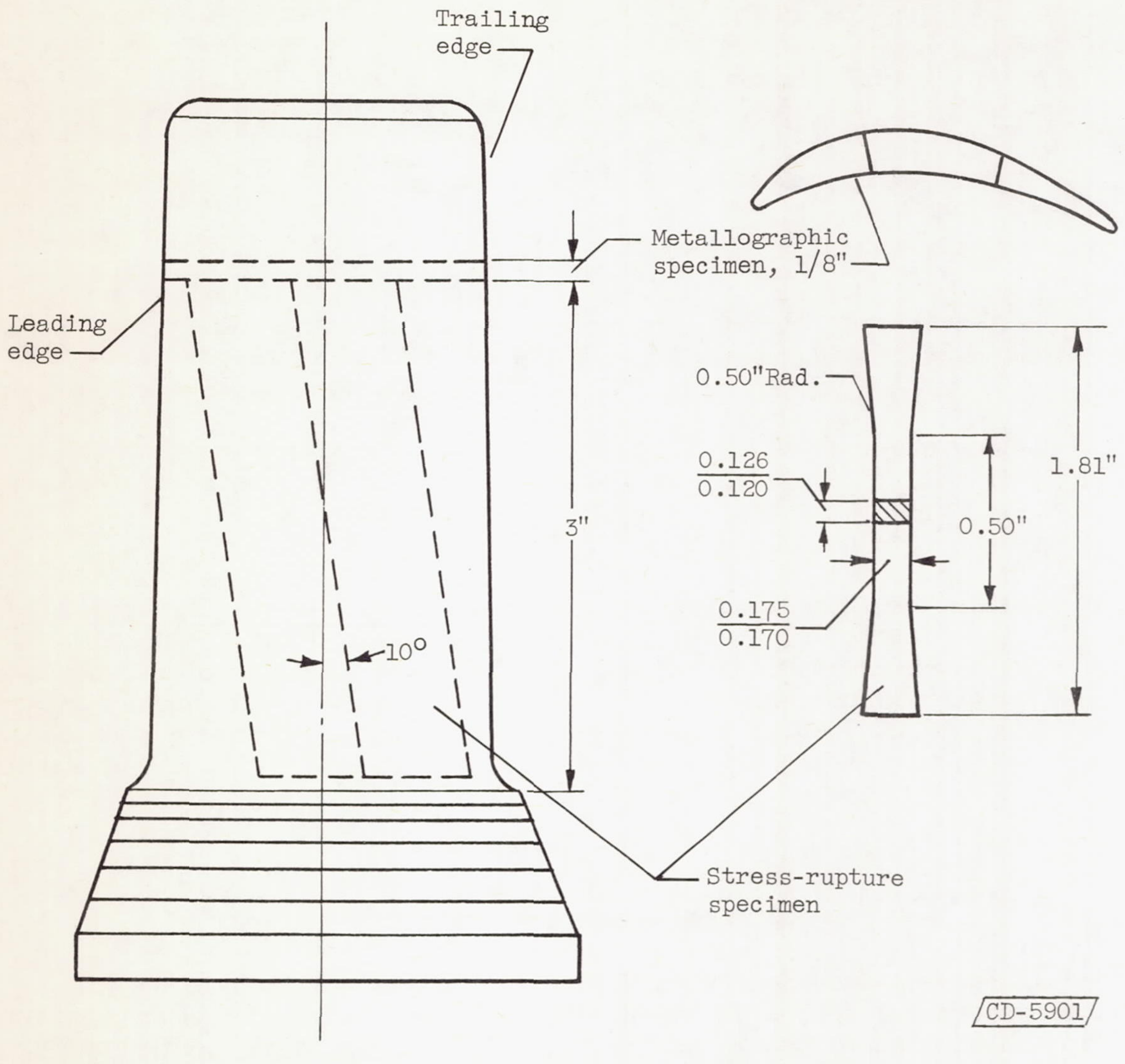



Figure 5. - Metallographic and stress-rupture specimens and the zones from which they were obtained.

| Lot | Forge temperature, °F | Solution treatment | | Aging treatment | | Post-finish aging treatment | | Buckets in wheel |
|---|---|---|---|---|---|---|---|---|
| | | Temperature, °F | Time, hr | Temperature, °F | Time, hr | Temperature, °F | Time, hr | |
| 1 | 2100 | ---- | - | 1600 | 4 | 1600 | 7 | 9 |
| 2 | | 2150 | 2 | 1600 | 4 | 1600 | 7 | 8 |
| 3 | | | | | | ---- | - | 4 |
| 4 | | 2275 Furnace-cool to 2175° F, air-cool | 2 | 2000 Air-cool; re-age 1600° F, 4 hr | 1 | 1600 | 7 | 12 |
| 5 | 2225 | ---- | - | 1600 | 4 | 1600 | 7 | 12 |
| 6 | | 2275 Furnace-cool to 2175° F, air-cool | 2 | 2000 Air-cool; re-age 1600° F, 4 hr | 1 | 1600 | 7 | 9 |

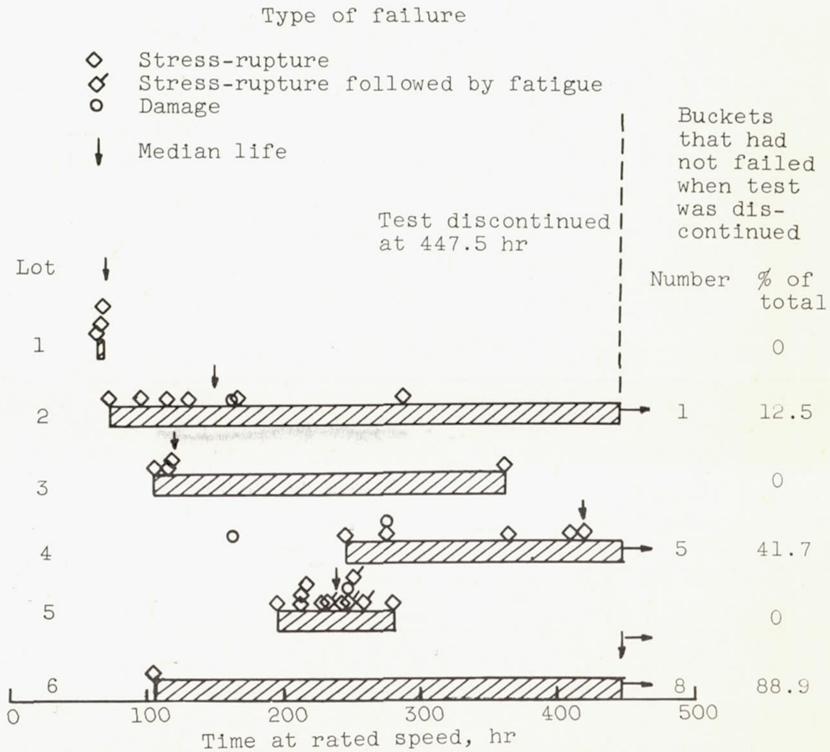



Figure 6. - Effect of forging temperatures and solution treatments on performance of Inconel 700 turbine buckets in a J33-9 engine at material temperature of 1625° F.

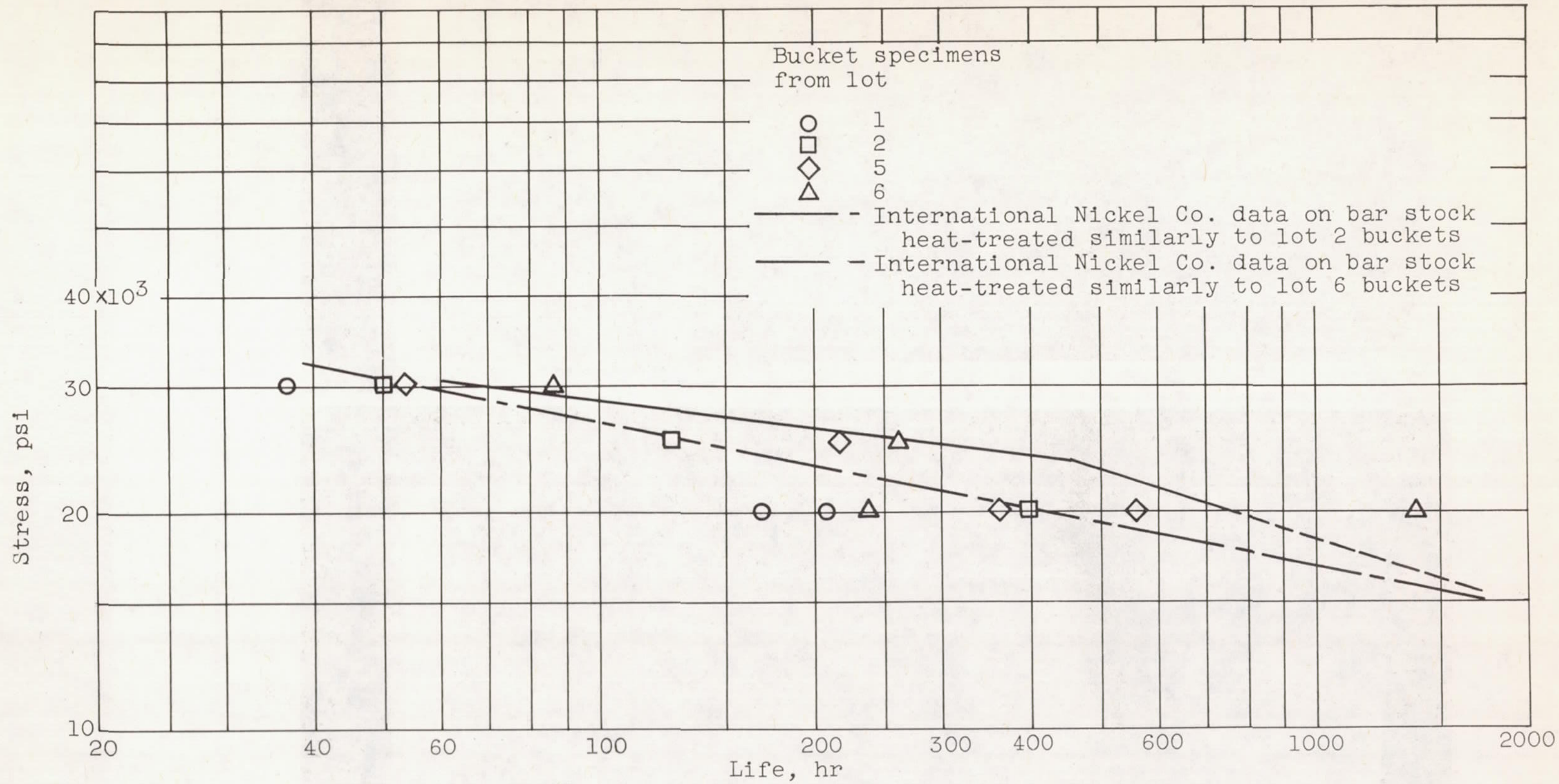
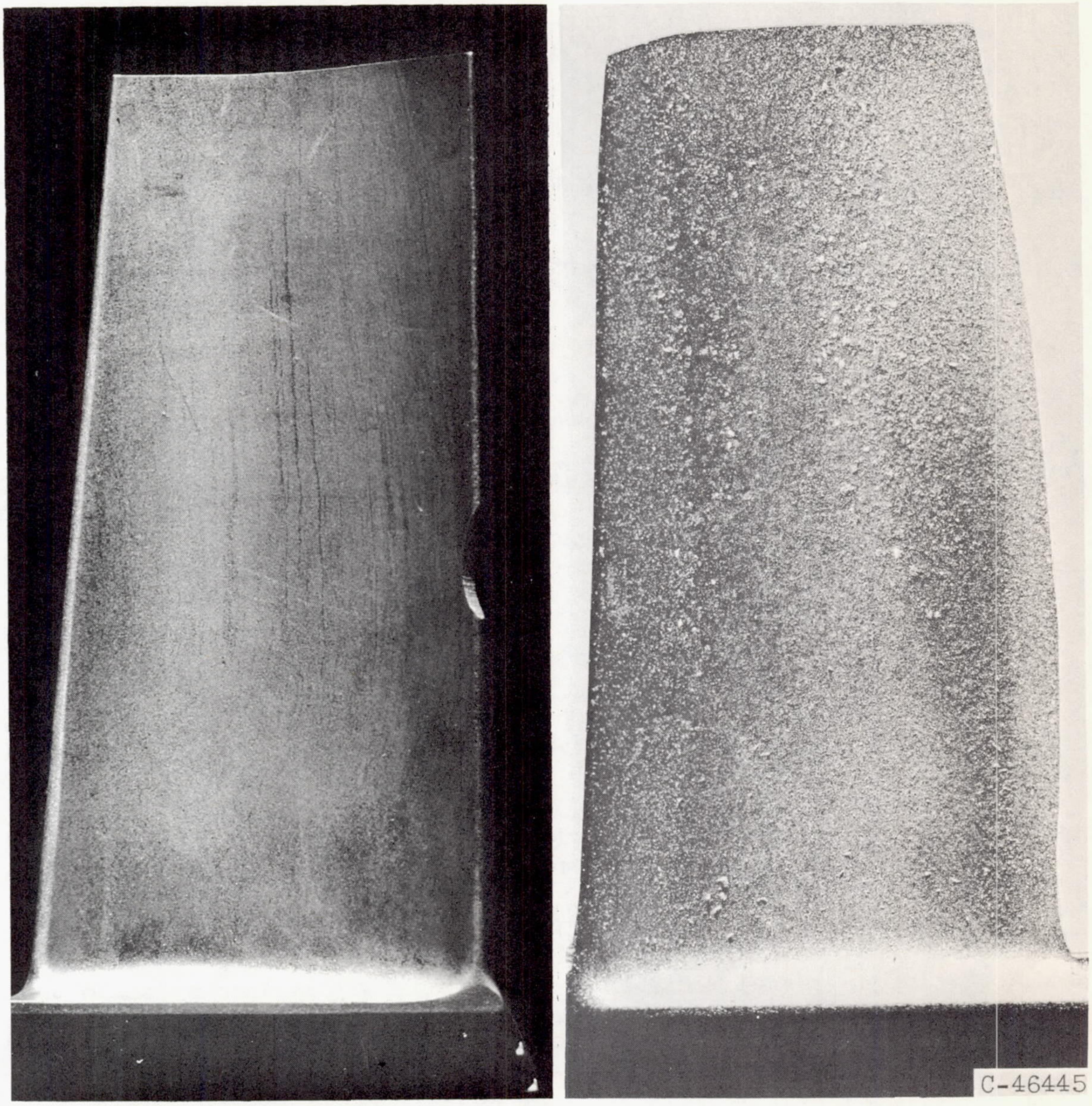
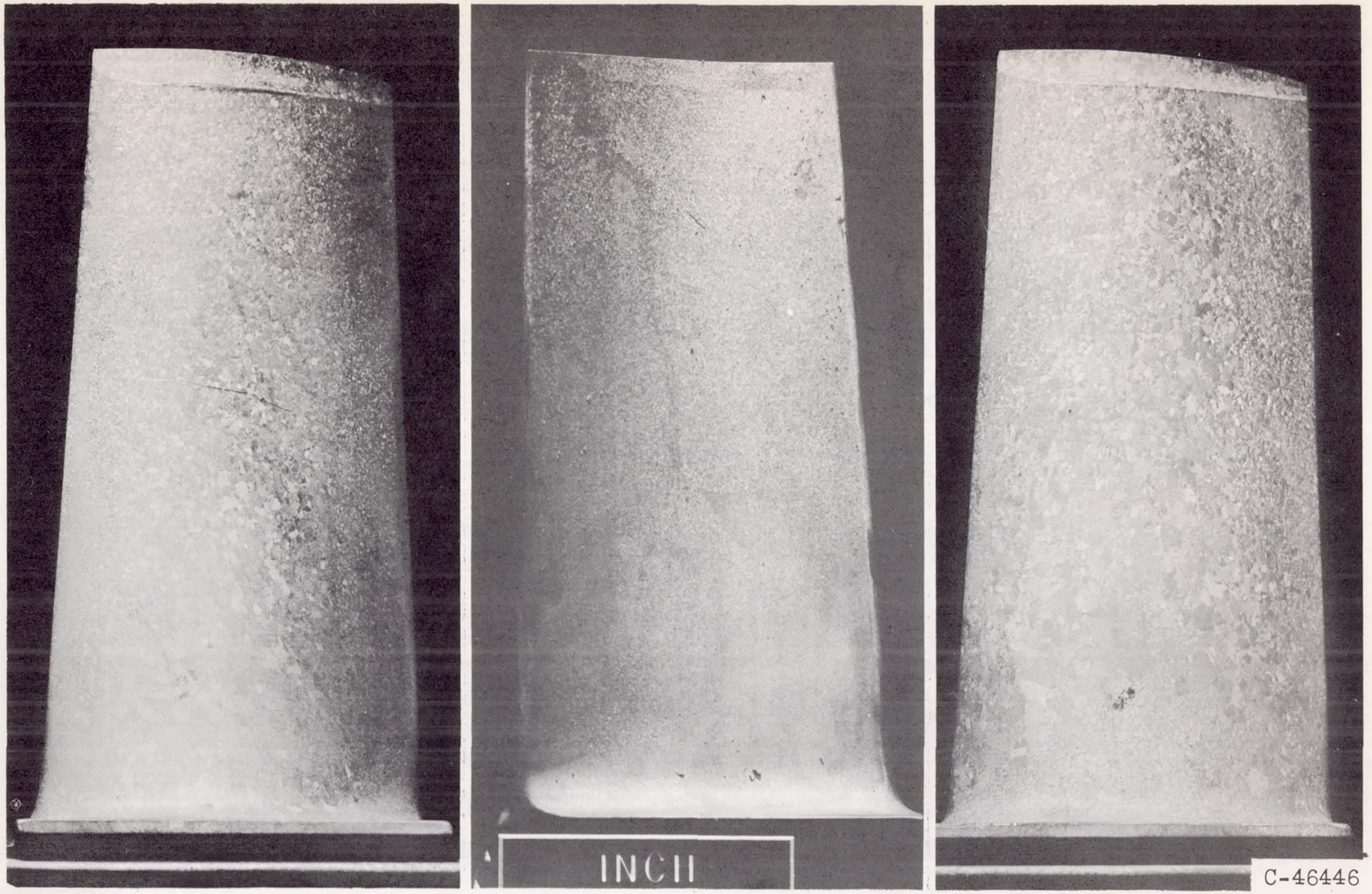



Figure 7. - 1600° F Stress-rupture life of Inconel 700 specimens taken from airfoils of buckets.




Lot 1 Lots 2 or 3

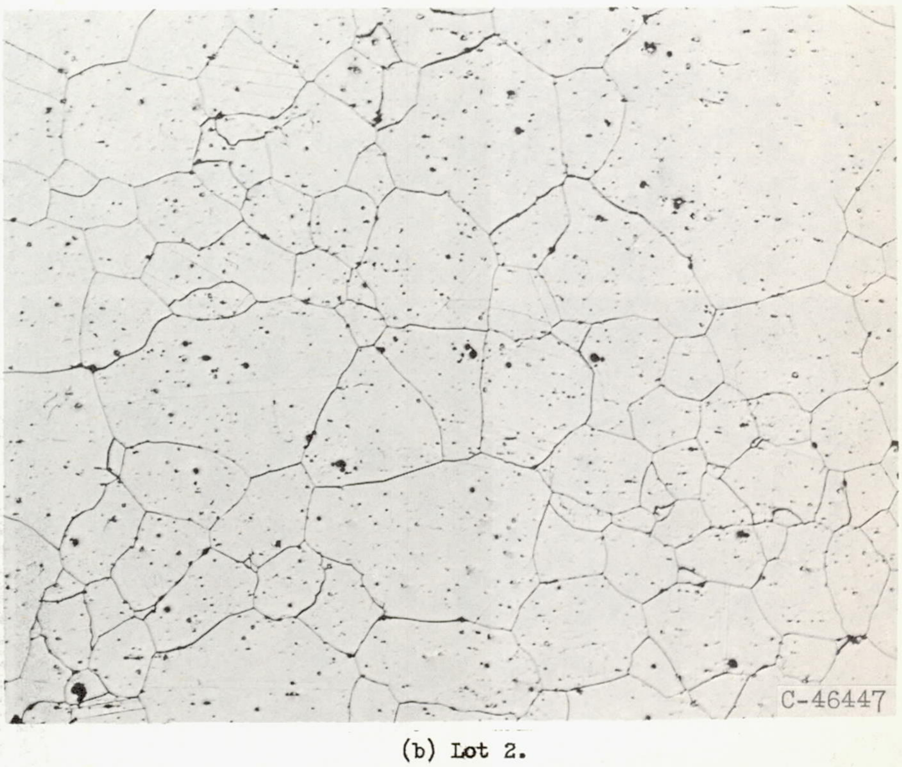
Figure 8. - Comparison of grain sizes of macroetched buckets.




Lot 4 Lot 5 Lot 6

Figure 8. - Concluded. Comparison of grain sizes of macroetched buckets.

(a) Lot 1.




(b) Lot 2.

Figure 9. - Photomicrographs showing grain-size differences among various lots of Inconel 700 buckets. Original magnification, X100.

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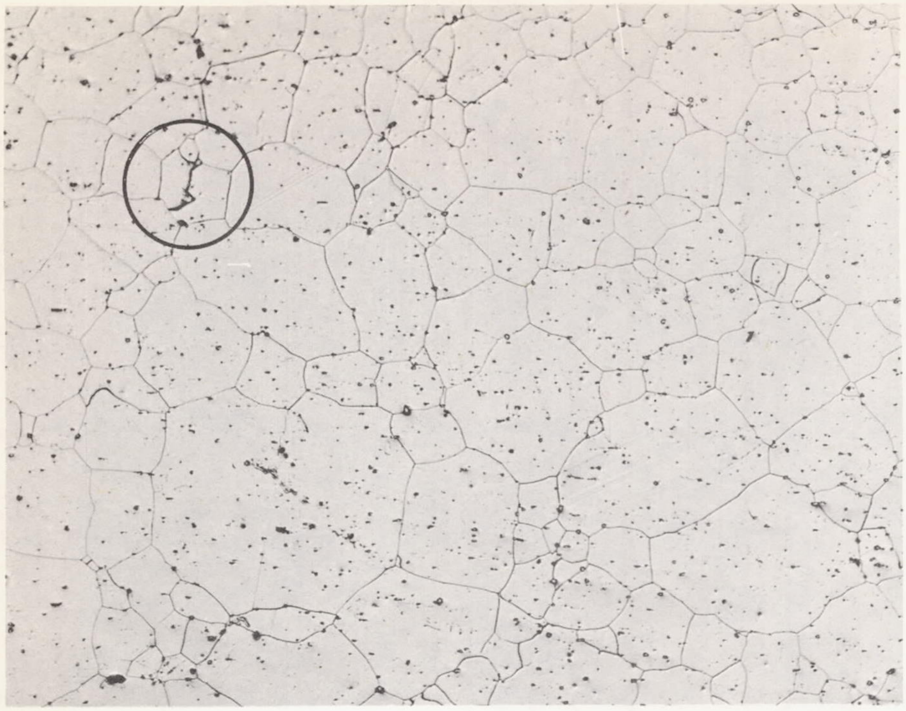
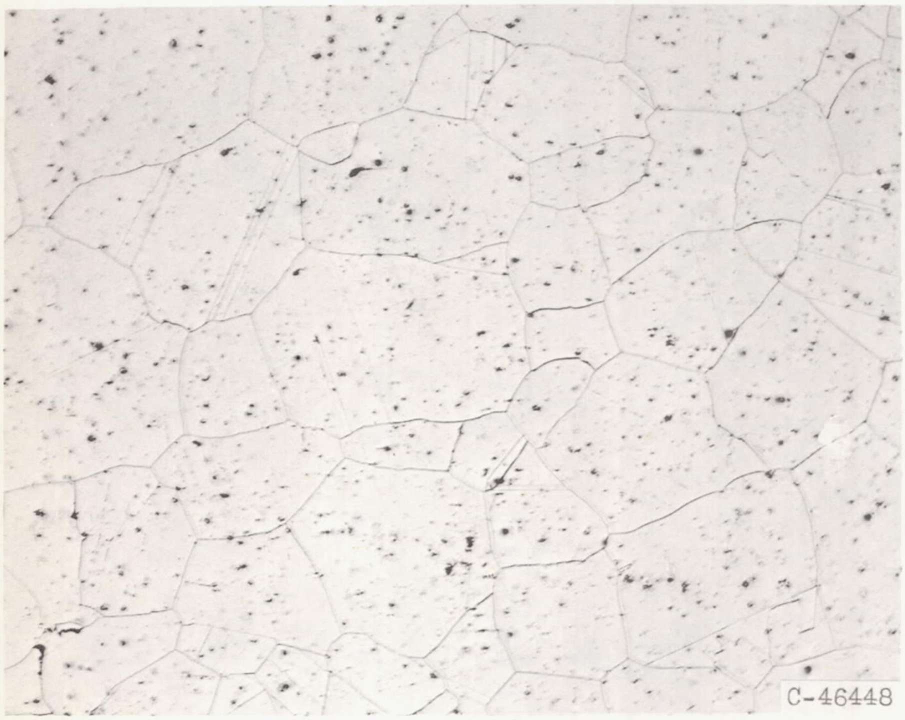


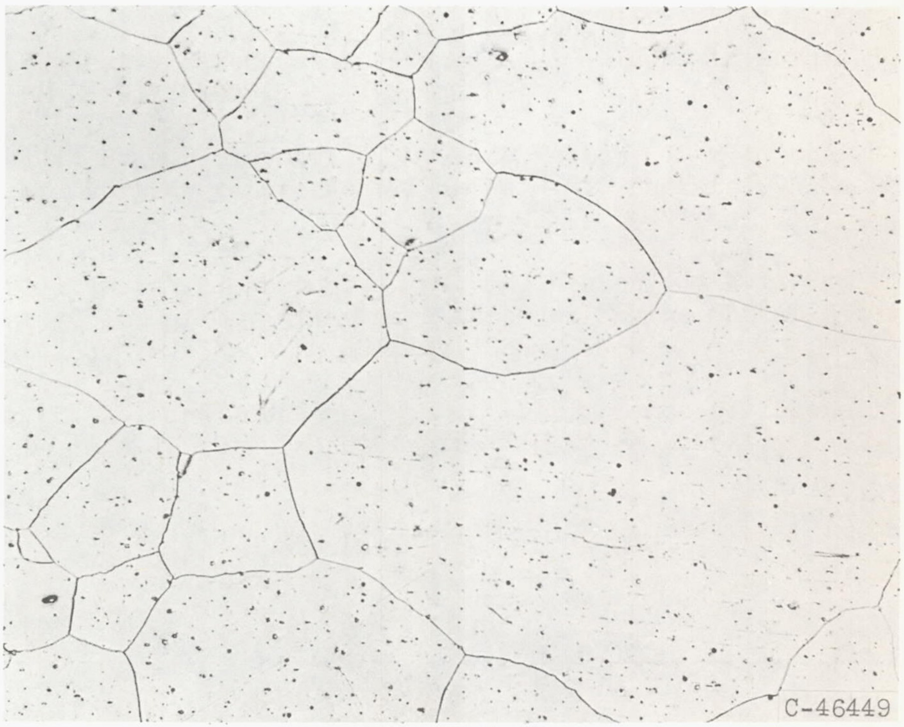
(c) Lot 3.




(d) Lot 4.

Figure 9. - Continued. Photomicrographs showing grain-size differences among various lots of Inconel 700 buckets. Original magnification, X100.

(e) Lot 5.




(f) Lot 6.

Figure 9. - Concluded. Photomicrographs showing grain-size differences among various lots of Inconel 700 buckets. Original magnification, X100.

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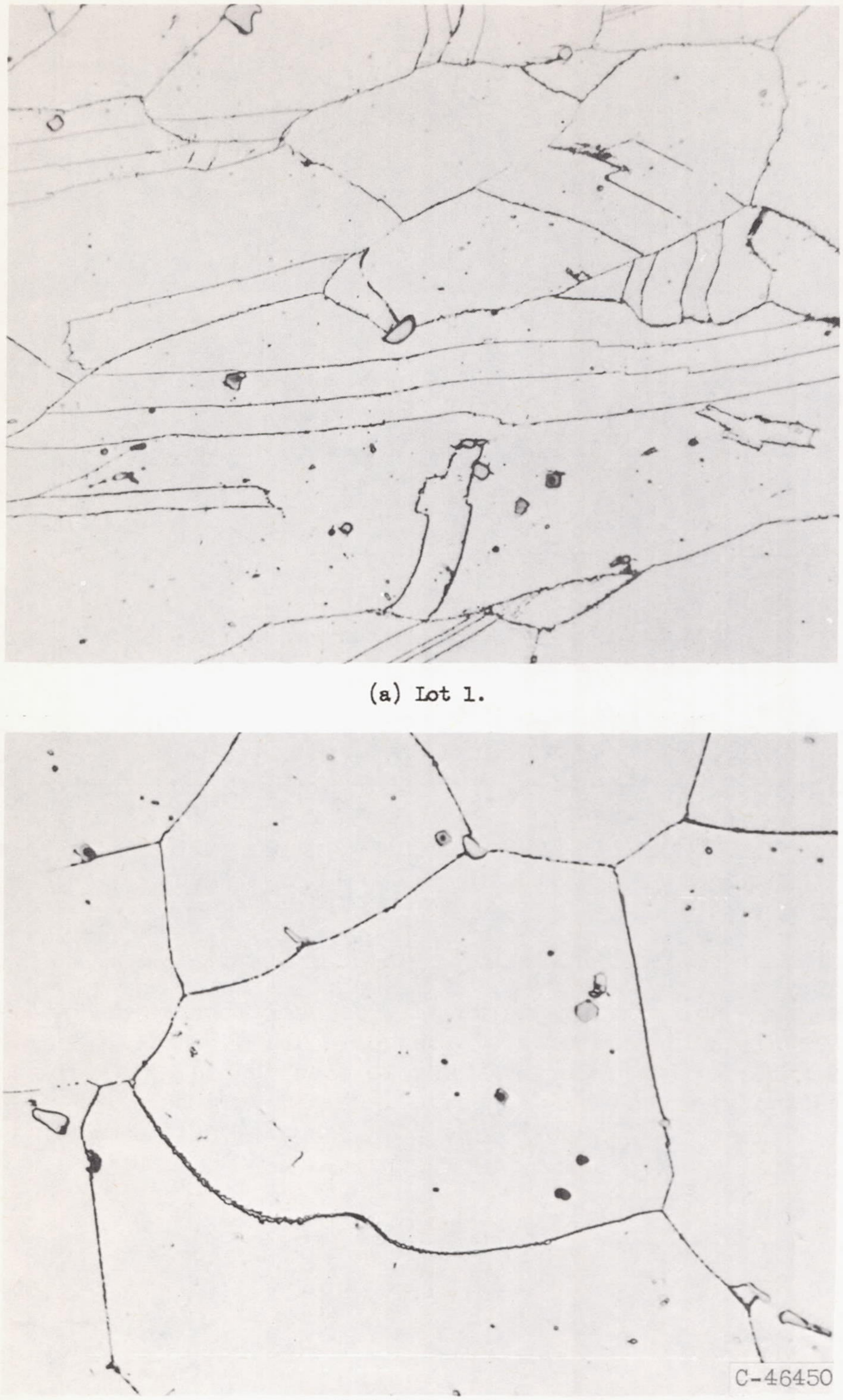
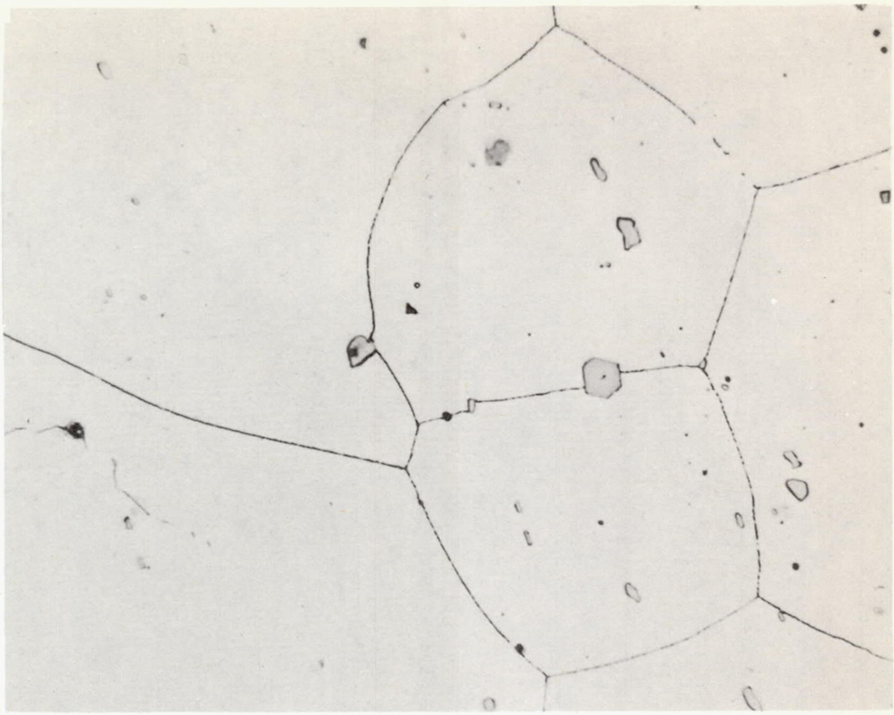



(a) Lot 1.

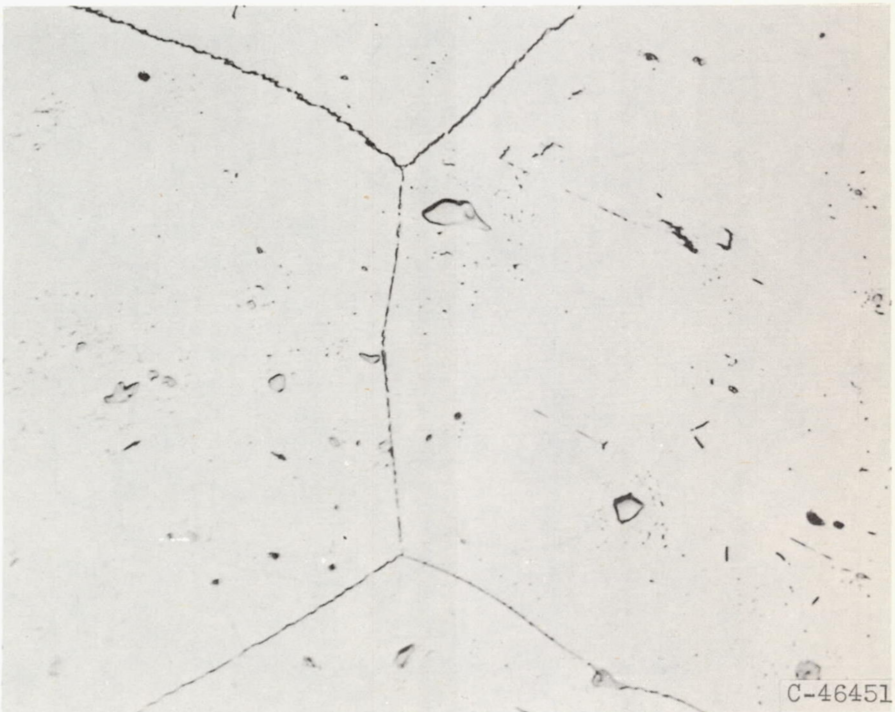
(b) Lot 2.

Figure 10. - Typical as-heat-treated microstructures. Original magnification, X750.

4217



(c) Lot 3.




(d) Lot 4.

Figure 10. - Continued. Typical as-heat-treated microstructures. Original magnification, X750.

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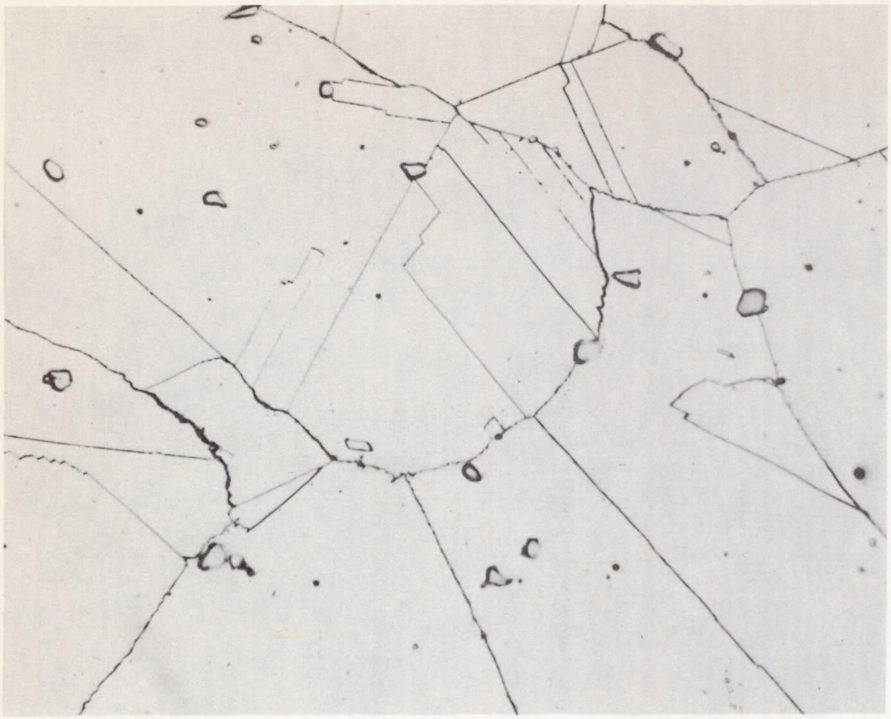
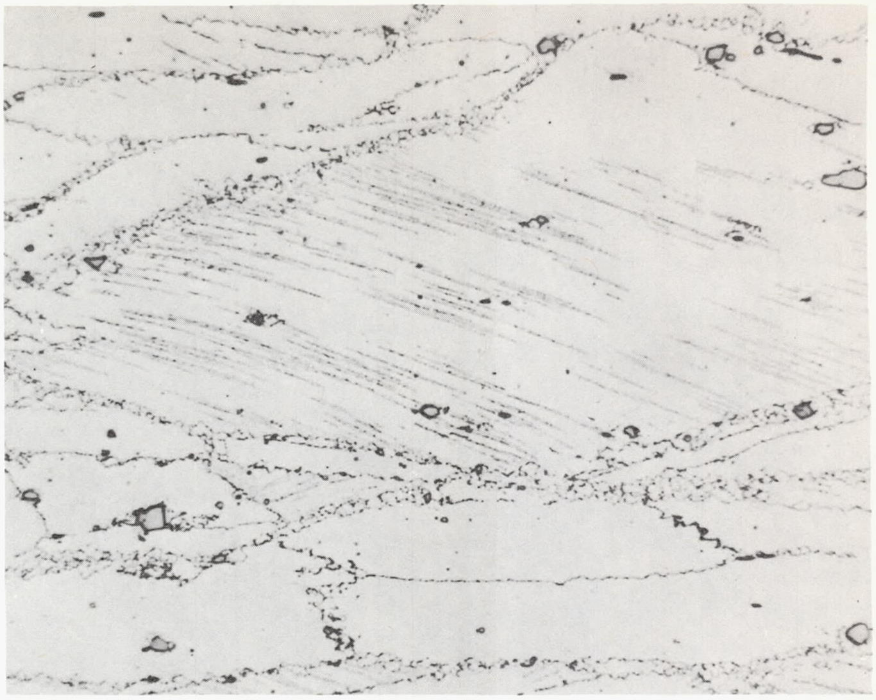


(e) Lot 5.

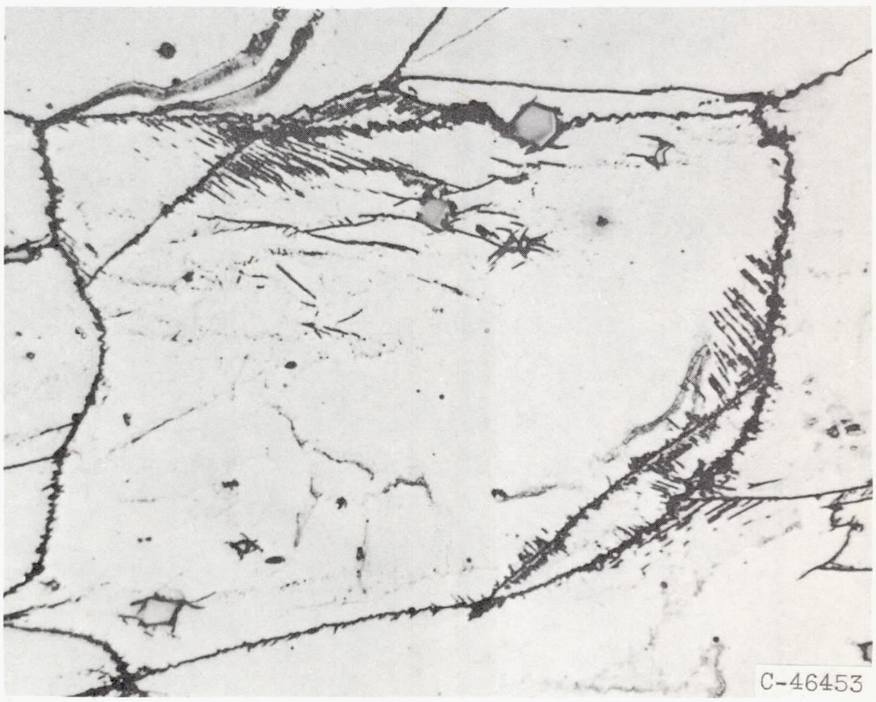

(f) Lot 6.

Figure 10. - Concluded. Typical as-heat-treated microstructures. Original magnification, X750.

4217

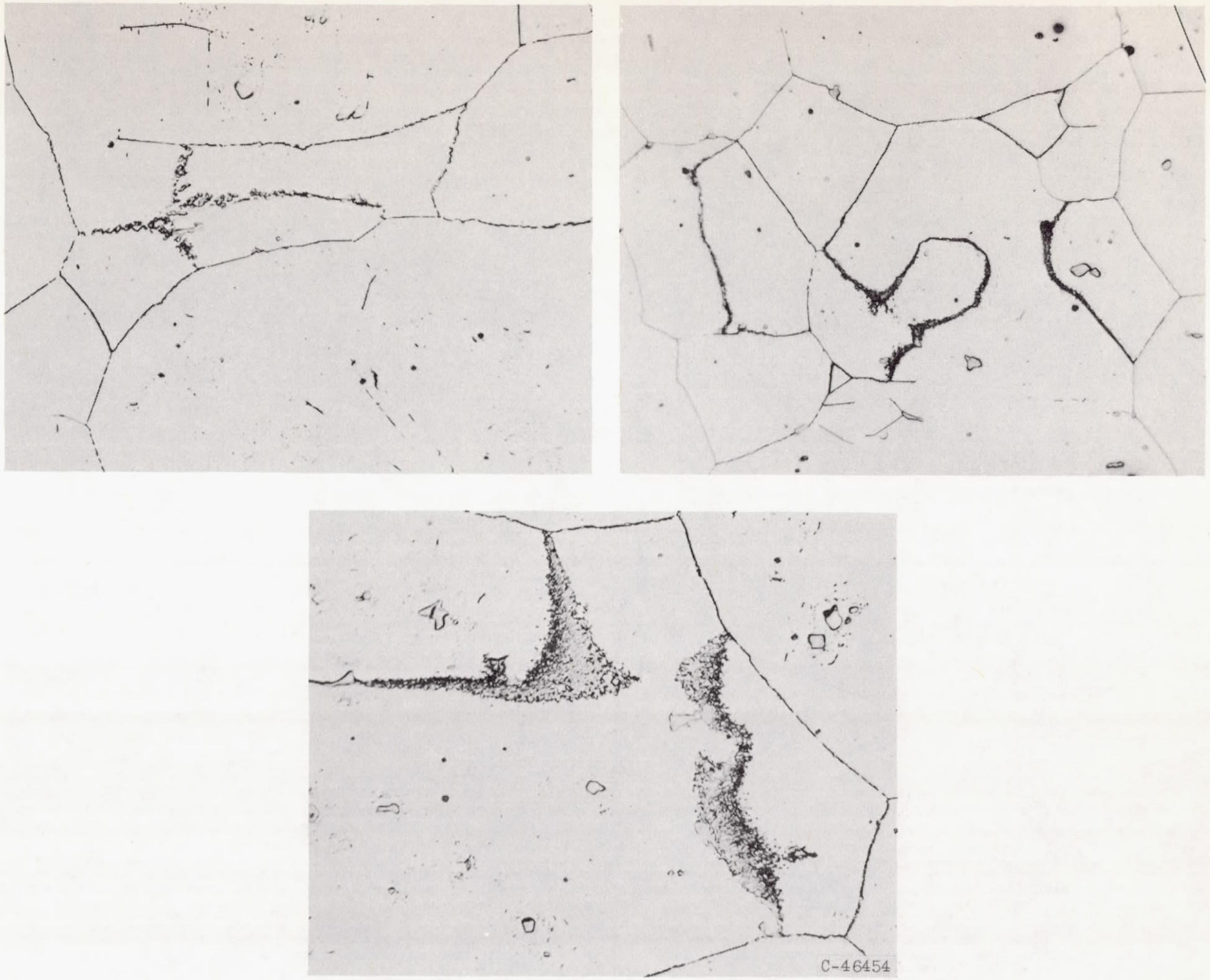


(a) Slipline precipitate found in the leading and trailing edges of lot 1 and lot 5 buckets.




(b) Feathery precipitate found in lot 1 and lot 5 buckets.

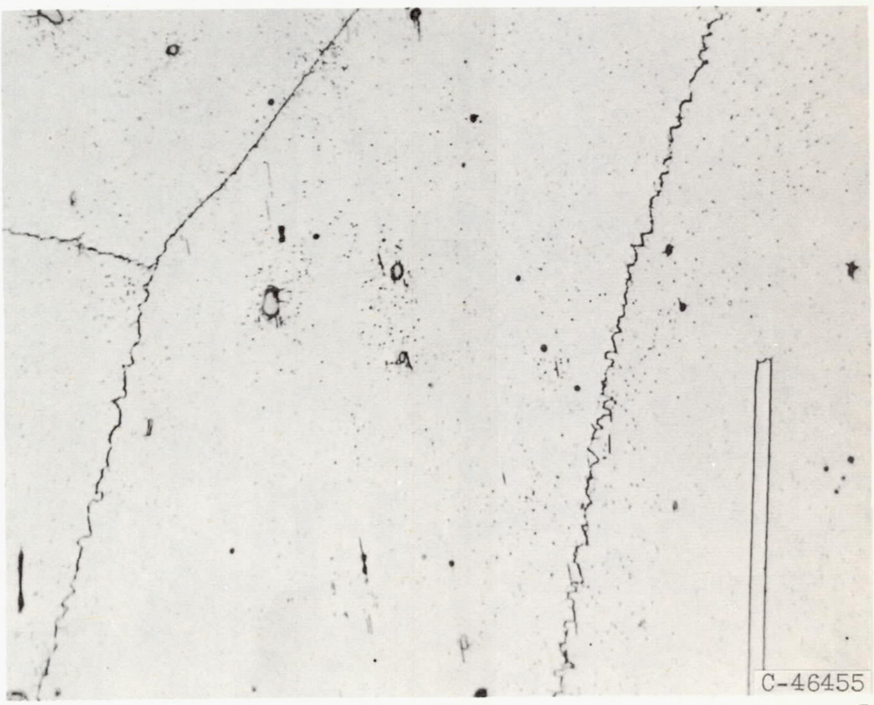
Figure 11. - Microstructure encountered in isolated areas of Inconel 700 buckets. Original magnification, X750.




(c) Types of grain-boundry precipitation found in Inconel 700 buckets.

Figure 11. - Continued. Microstructure encountered in isolated areas of Inconel 700 buckets. Original magnification, X750.


(d) Beginning of void formation in Inconel 700 buckets solution-treated at 2275° F.




(e) Sawtooth grain boundaries found in Inconel 700 buckets.

Figure 11. - Concluded. Microstructure encountered in isolated areas of Inconel 700 buckets. Original magnification, X750.

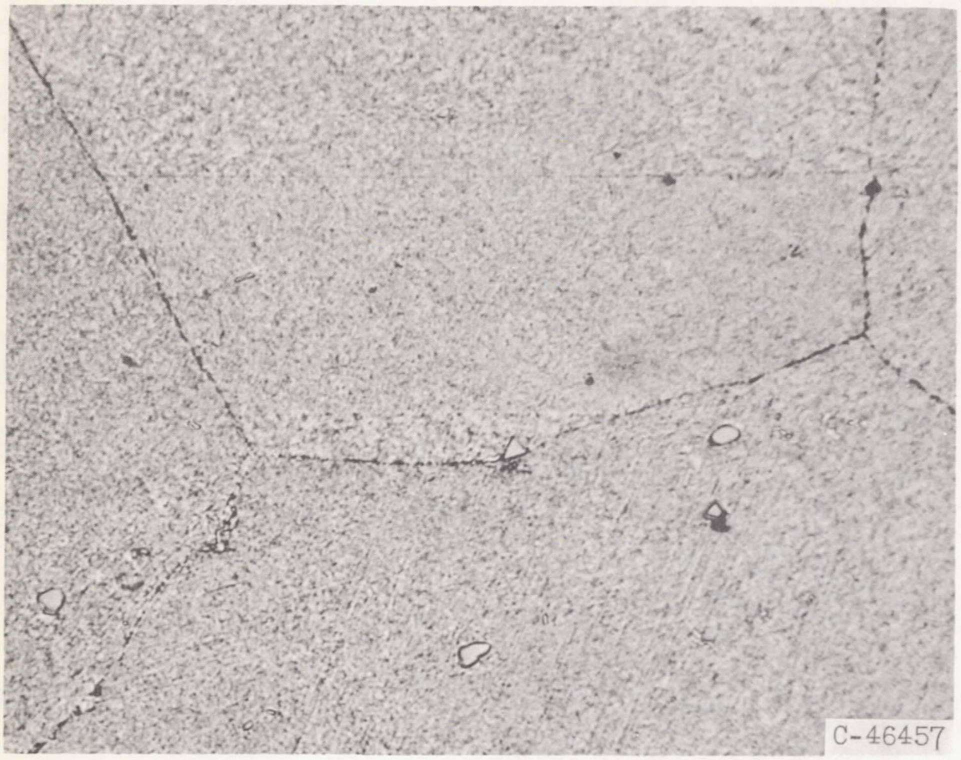


Figure 12. - Typical microstructure of failed buckets. (Lot 3 bucket operated 421 hours.) Original magnification, X750.

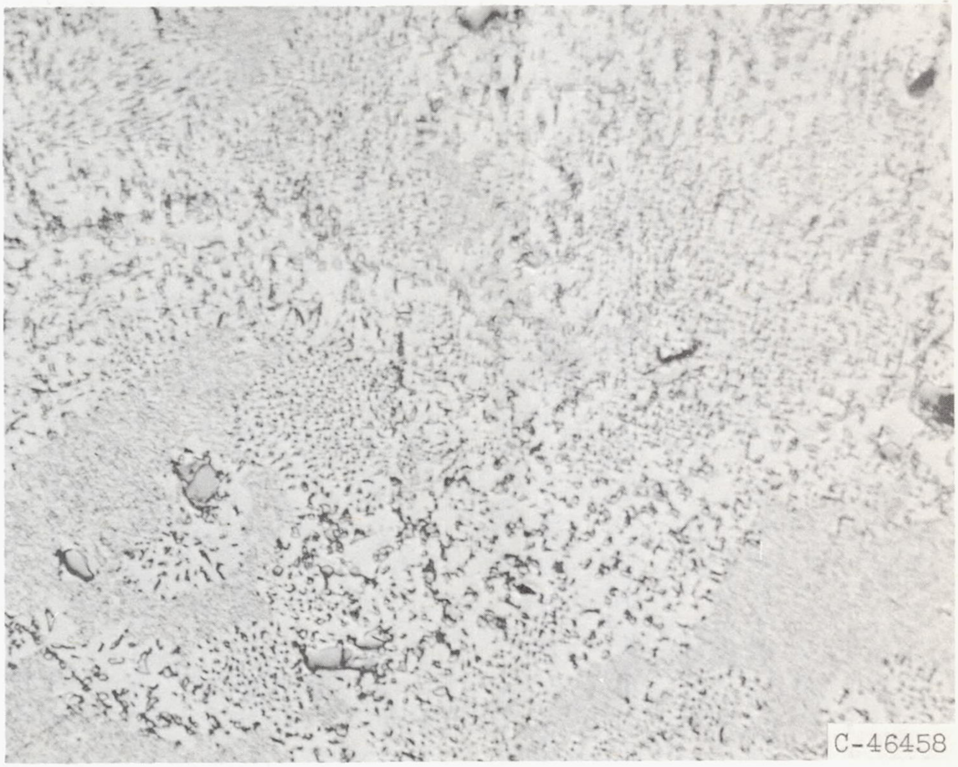
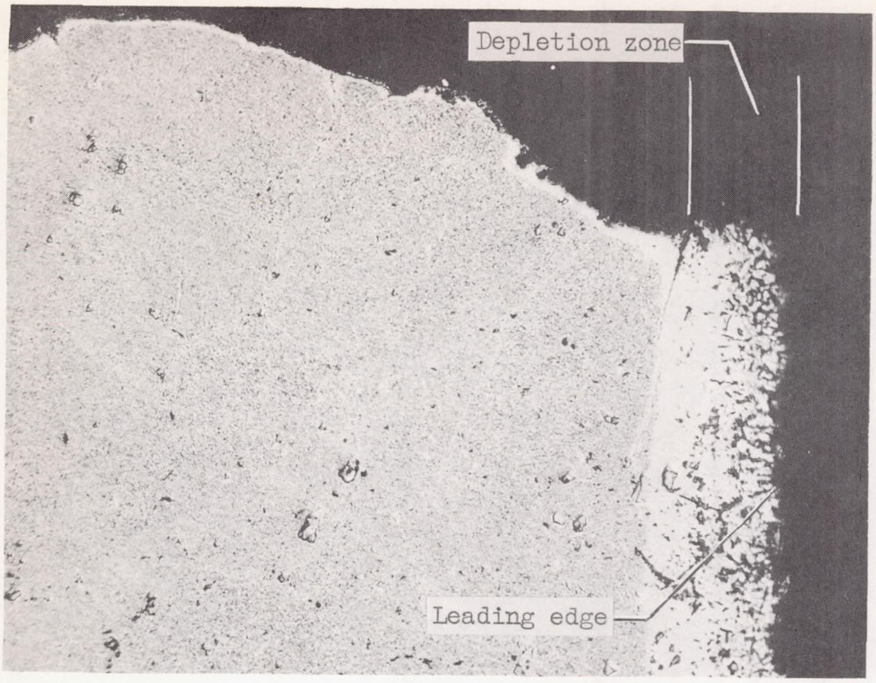
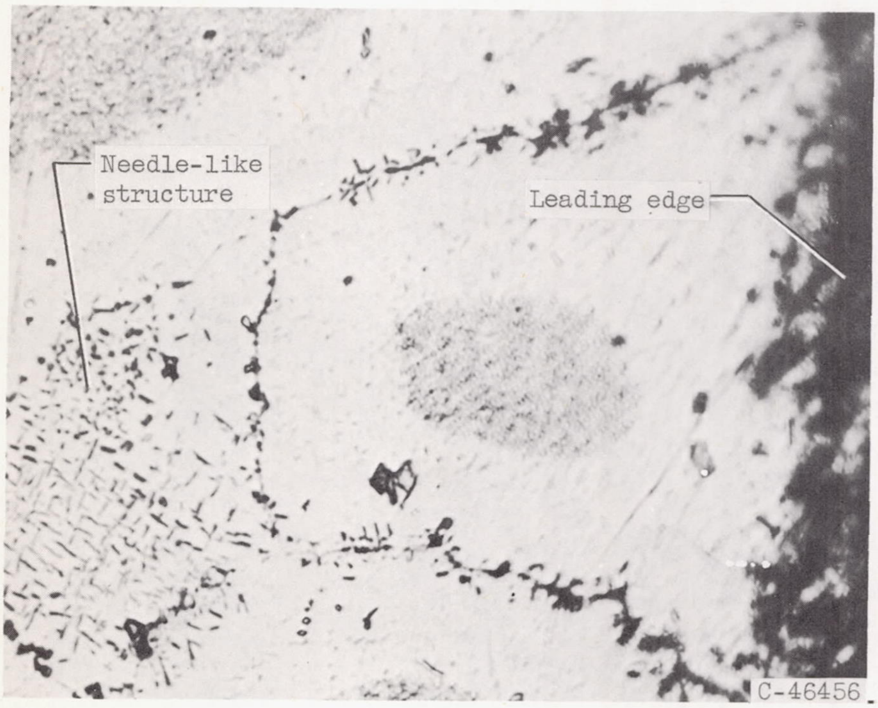



Figure 13. - Agglomeration of precipitates in a failed bucket. Original magnification, X750.




(a) Depletion zone in bucket that fractured after 245 hours of operation. Original magnification, X250.




(b) Needle-like structure associated with the depletion zone of operated buckets. Original magnification, X1000.

Figure 14. - Examples of surface depletion in operated buckets.