FAILURE INVESTIGATIONS
OF
LARGE LIQUID PROPELLED
ROCKET ENGINE
COMPONENTS

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ABSTRACT

Case histories of seven typical failures in large liquid propelled rocket engine components have been prepared. Quite simple to complex investigations are presented covering a variety of failure modes in a variety of materials. Included are successful solutions to the failure problems investigated.

INTRODUCTION

This work was prepared to show primarily how failure analyses are conducted. what metallurgical tools are used to get conclusive answers and how failure problems are solved.

Over a period of time, several service failures have been investigated on liquid rocket engine components. Presented here is a select group of case histories of typical failure analyses. Simple investigation requiring only a good "eyeball" look to complex analyses involving the use of electron microscopes and the microprobe are covered.

These investigations cover failure modes such as stress corrosion cracking, fatigue and changes in base metal structure due to environmental conditions. The materials involved are aluminum alloys, steel, high temperature alloys and the noble metals. Plastic parts are also included in that under certain conditions, the plastic materials act similar to metallic materials in their failure modes.

Also included in this report are successful solutions to the failure problems investigated.

STRESS CORROSION CRACKING OF LOX DOME

Problem: During a leak check of an engine, a leak was detected in the LOX inlet elbow of the dome. The dome was removed from the engine and submitted for a failure investigation. The dome was made from a 7079 aluminum die forging heat treated to the T6 condition. This was the second failure of this type investigated

Failure Investigation Results: After removal from the engine, the dome was examined and the crack shown in Figure 1 and Figure 2 was observed. The metallurgical examination revealed the crack was parallel to the grain direction in the inlet area and therefore, the crack was in the weakest orientation and in the direction most susceptible to stress corrosion cracking. A metallographic examination of the crack, Figure 3 and Figure 4, revealed a intergranular "tree root" crack pattern typical of stress corrosion cracking. Stress corrosion test bars were removed from the dome inlet near the original crack and subjected to an alternate immersion test in 3-1/2% salt solution. The bars were stressed at 75% of yield strength and failed in 2 to 11 days.

From the results of the investigation, it was concluded that the failure was due to stress corrosion cracking. The stress being due to a combination of residual stress and additional stress due to installation of the connecting component to the inlet.

Solution: Three things were done to prevent the reoccurrence of the dome cracking problem. The material was changed to 7075 aluminum heat treated to the T73 temper. This is a slightly overaged condition and is virtually free from stress corrosion. The forging process was changed so that the grain direction in the inlet would always be parallel to the inlet centerline. This would preclude the possibility of stress across the short transverse direction. In addition, the dome was shot peened to place the surface in compression to reduce susceptibility to stress corrosion cracking.

Since the changes have been incorporated about sixty domes have been built and tested with no sign of stress corrosion problems.

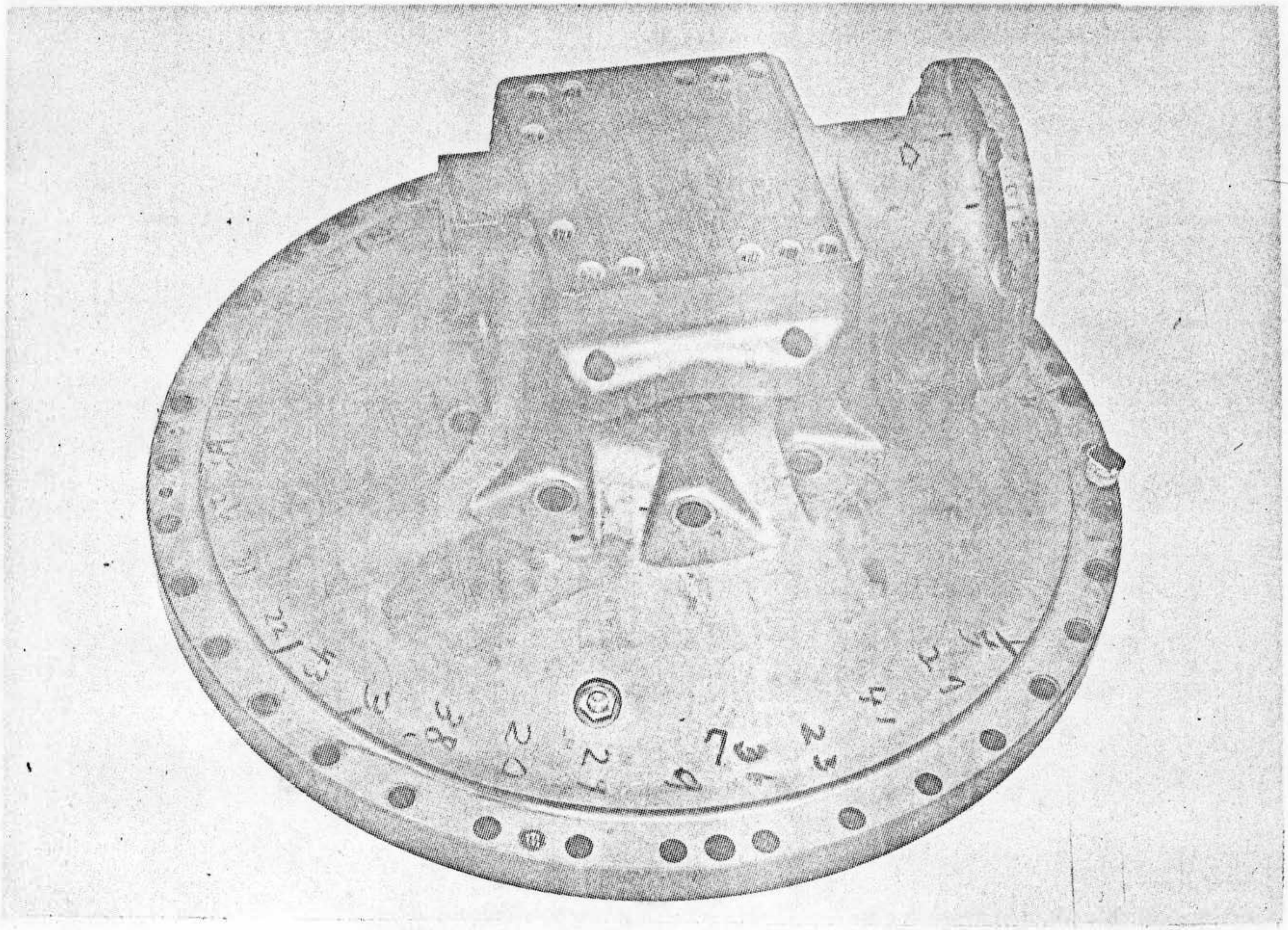


FIGURE 1. Crack in Dome Inlet

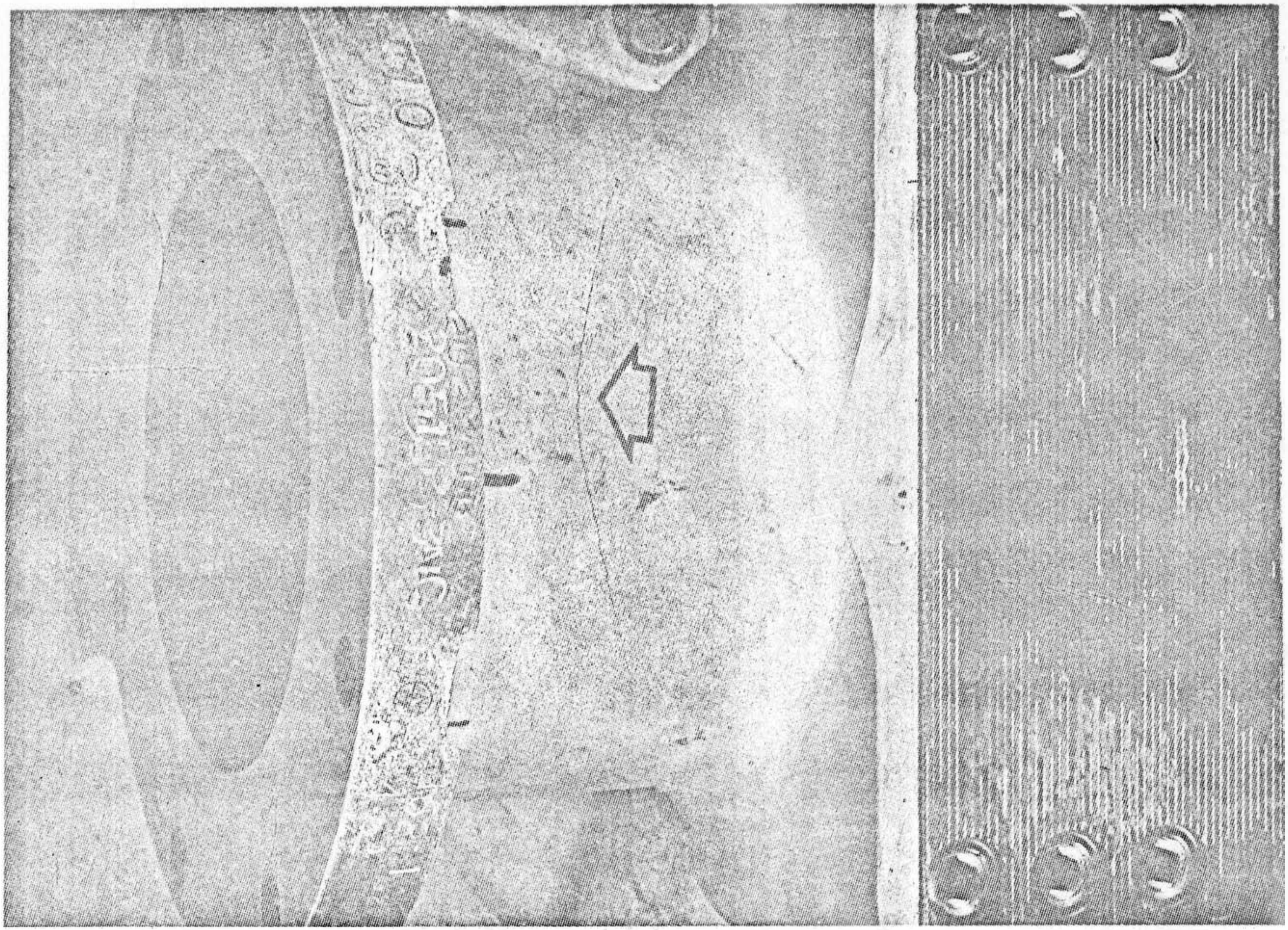


FIGURE 2. Crack in Dome Inlet

FIGURE 3. OD Start of Crack 500X

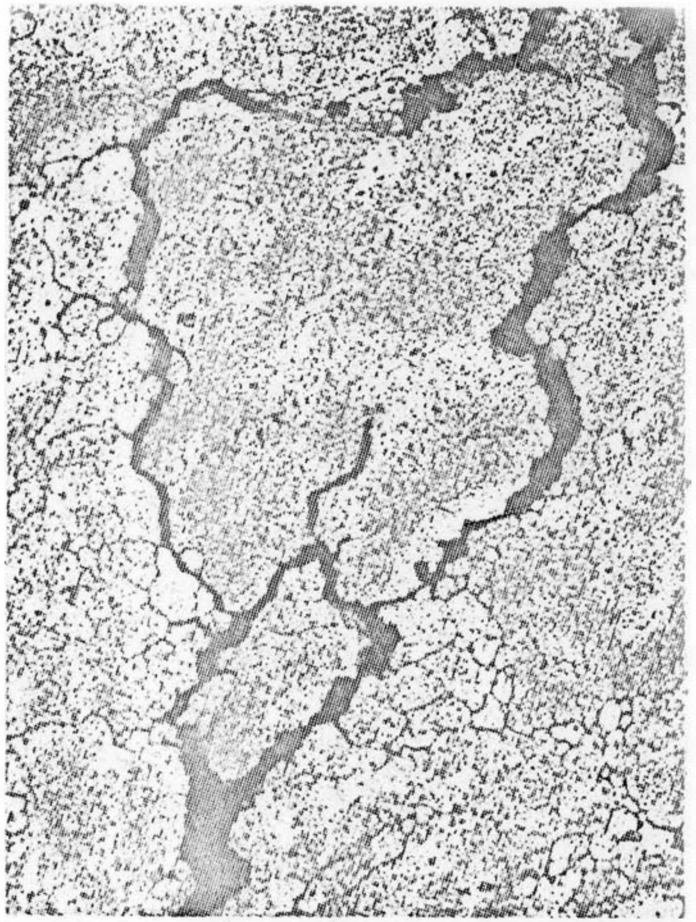


FIGURE 4. End of Crack 500X

CRACKING OF FUEL INLET ELBOW

Problem: During a routine inspection of an engine fuel inlet duct, two small cracks were observed in one of the four vanes, Figure 5 and Figure 5A. The elbow is a Tens 50 aluminum casting heat treated to the T60 condition. The failed component was removed from an R & D engine after about 3000 seconds of operation.

Failure Investigation Results: A visual examination of the crack area revealed that the hand finishing of the fillet area was very rough and irregular. A strip from the defective vane was removed and fractured in the cracked areas. Visual and electron fractographs verified the crack was due to cyclic fatigue. Figure 6 shows a photomacrograph of the crack surface. In castings, particularly aluminum castings, the fatigue markings (beach marks) are not nearly as evident as they are in hardened steels or wrought aluminum alloys. However, the electron microscope fractograph, Figure 6, reveals the fatigue striations clearly.

Solution: The solution to the fatigue problem was two-fold; first, the quality of the blend radius was improved and secondly, the inside of the elbow assembly was shot peened to have the surface in compression.

Since the changes were incorporated, no further cracking of the inlet vane has been observed.

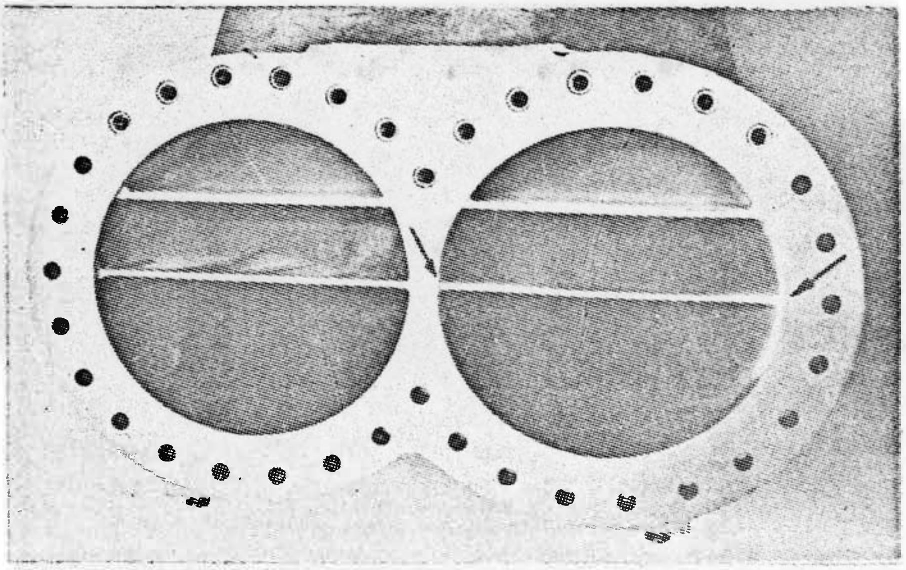


FIGURE 5. The Arrows Indicate the Location of the Fatigue Cracks. Note that the Vane Is Slightly Bulged. 1/4 Scale

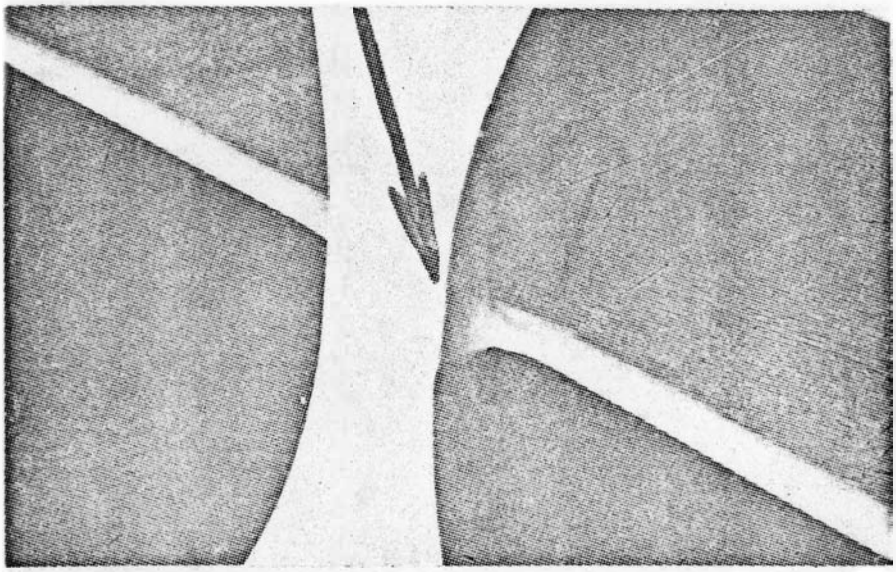
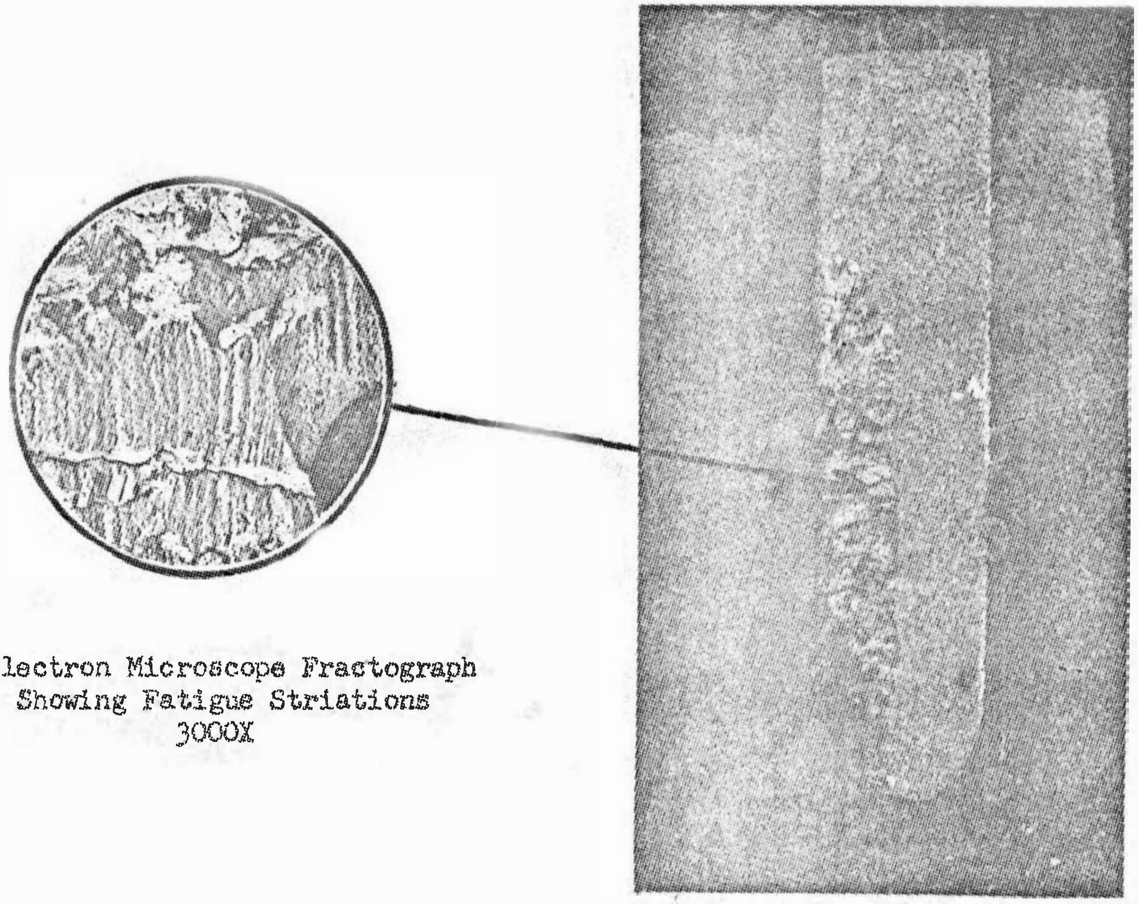


FIGURE 5A. Enlargement of the Photo Above. 1X



Electron Microscope Fractograph
Showing Fatigue Striations
3000X

Photomacrograph of the Fracture
2X

FIGURE 6.

PUMP INDUCER FAILURE

Problem: A failure occurred on an engine fuel turbopump inducer made of 7075 aluminum heat treated to the T73 temper. The inducer failed after approximately 2300 seconds of R & D operation. About one-half of the run time was under off-flow conditions in which various trim configurations were being investigated on the pump impeller. The pumped fluid is RP-1 fuel. Figure 7 is an overall view of the failed inducer.

Failure Investigation Results: The metallurgical investigation revealed that the inducer failed in fatigue due to vibration of the blades. The fatigue cracks which precipitated the failure proceeded across the thickness of the blade on one side according to Figure 8 and on the other side approximately 180° from the first failure. The strength of the material met the requirements of the specification. There was no stress corrosion cracking evident.

Figure 8 shows the typical fatigue markings (bench marks) which were not nearly so evident in the previous investigation of the casting fatigue failure.

Solution: The off-flow conditions experienced by this inducer caused the premature failure. These operating conditions created a large pressure change across the inducer which caused excessive cyclic bending of the blades which led to the fatigue fracture. Under normal flow conditions, failures have not been experienced in this component.

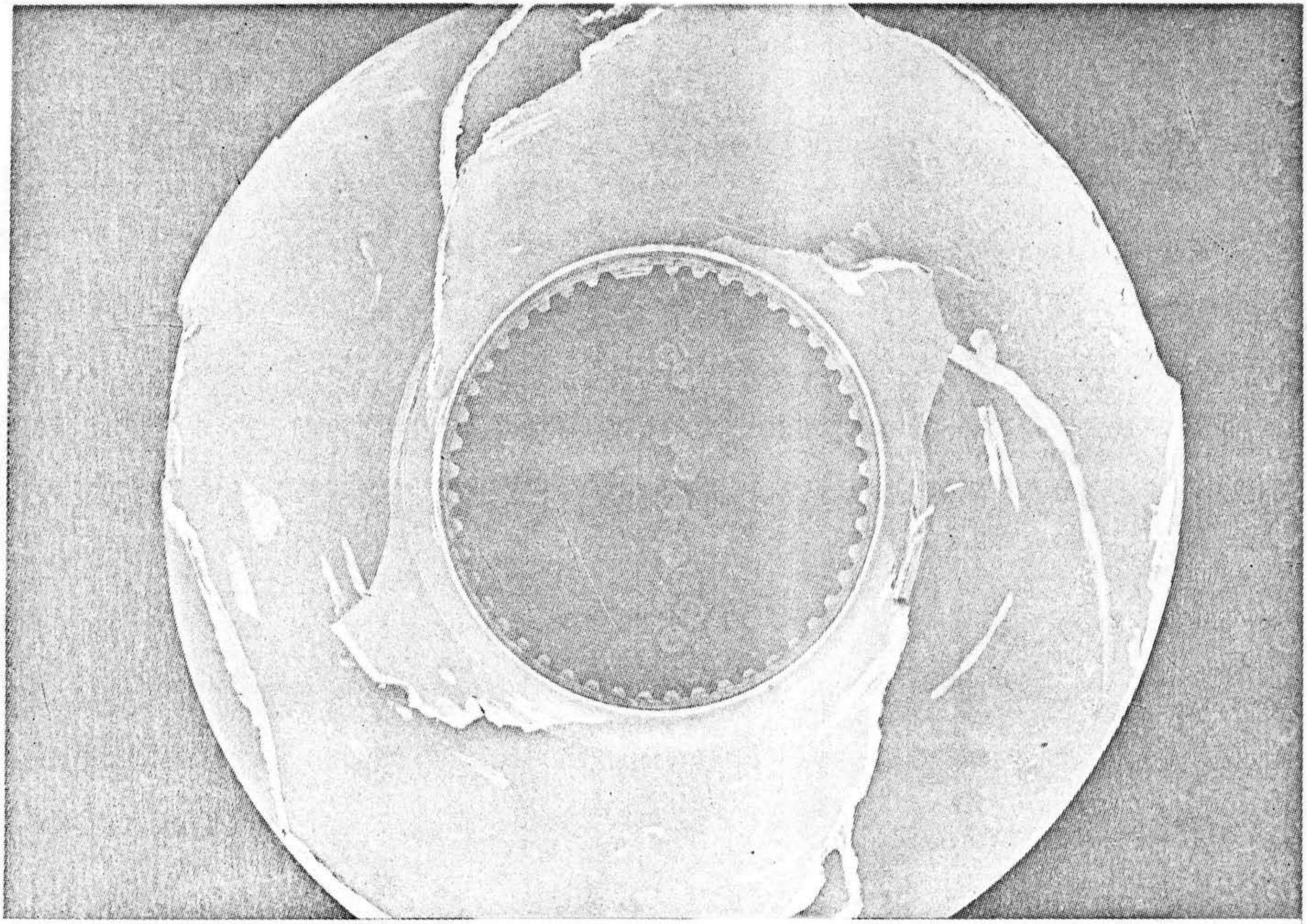


FIGURE 7. Overall View of Inducer 1/2X

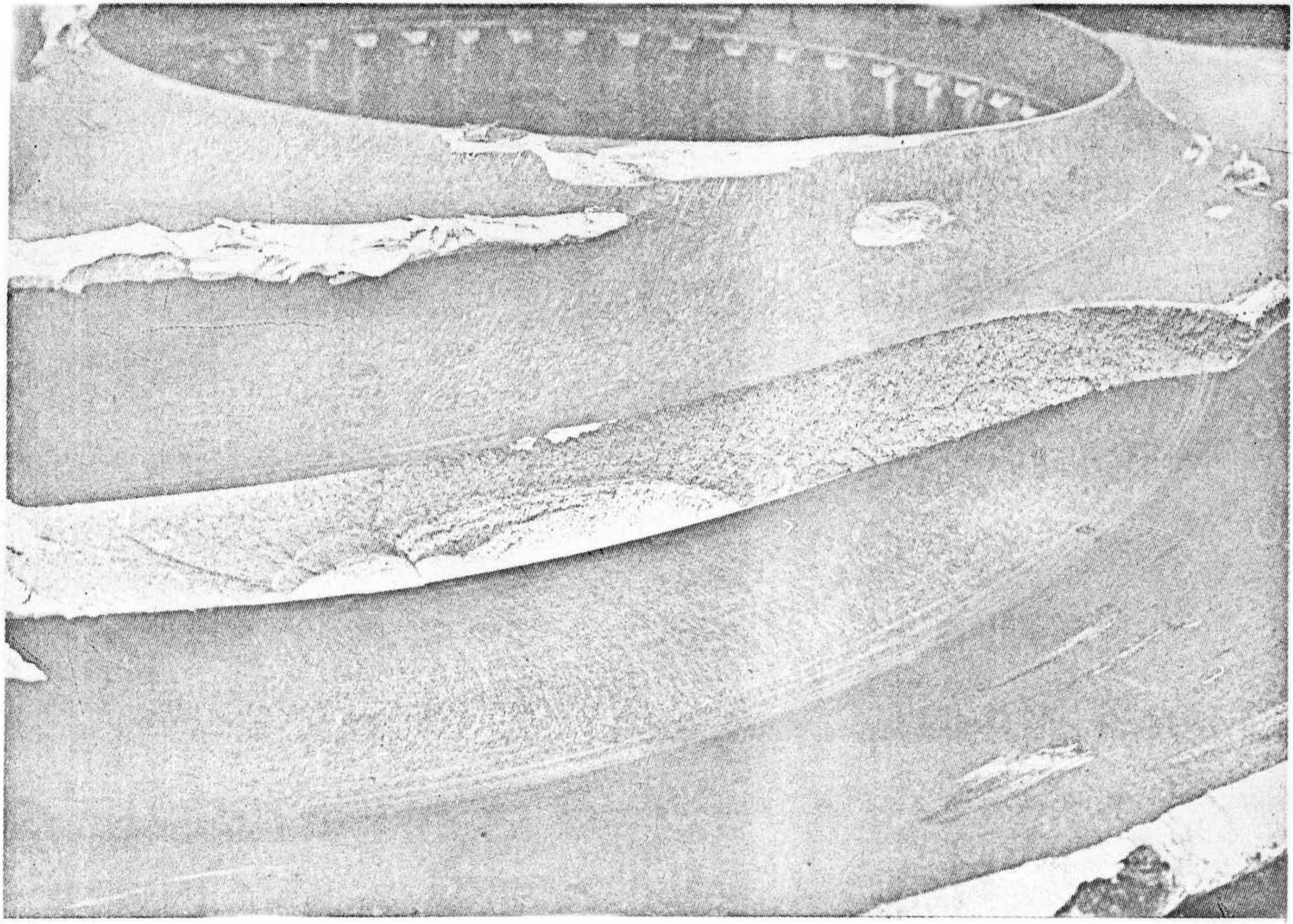


FIGURE 8. Fatigue Beach Marks on Inducer Blade 1X

FAILURE OF ENGINE NOZZLE EXTENSION SHINGLES

Problem: The engine nozzle extension under disucssion consists of approximately one thousand pieces of Hastelloy C sheet joined to form a conical section. These Hastelloy C pieces each about 4" x 6" are spot welded in a shingle-like configuration to a series of hat section rings to form the extension. Comparatively cool turbine exhaust gases pass through the shingle openings to film cool the combustion side of the nozzle extension. A history of failures in the form of shingle erosion and cracking during engine testing precipitated this metallurgical investigation to determine the cause of the failure.

Failure and Investigation Results: Several typically damaged shingles were removed from a nozzle extension assembly and subjected to microscopic and metallographic examination. Figure 9 and Figure 10 illustrate degrees of erosion on the combustion side of the shingles and Figure 11 and Figure 12 show melting and coking on the shingle surfaces. The metallographic examination revealed a carburized surface on the shingles, Figure 13.

The turbine exhaust gases are fuel rich and carburizing in nature and the temperature is sufficient to cause carburization. The failures were due to the following sequence of events:

1. During engine firing both surfaces (coolant and combustion sides) of the shingles in the nozzle extension were exposed to a carburizing environment.

2. With time and localized temperature increases, due to carbon build-up and subsequent restricted coolant gas flow, areas of the shingles become carburized.

3. The higher carbon content on the surface of the Hastelloy C sheet lowered the melting temperature of the alloy sufficiently to cause premature surface melting and subsequent erosion. The high carbon skin also resulted in a brittle layer susceptible to cracking on engine starts.

Solution: Up to the present time, a complete solution to the problem has not been found; however, various protective coatings that will prevent or retard carburization are being tested with some success.

FIGURE 9. Typical Erosion on the Combustion Side of the Shingle. Mag: 4X

FIGURE 10. A More Advanced Degree of Erosion. Mag: 4X

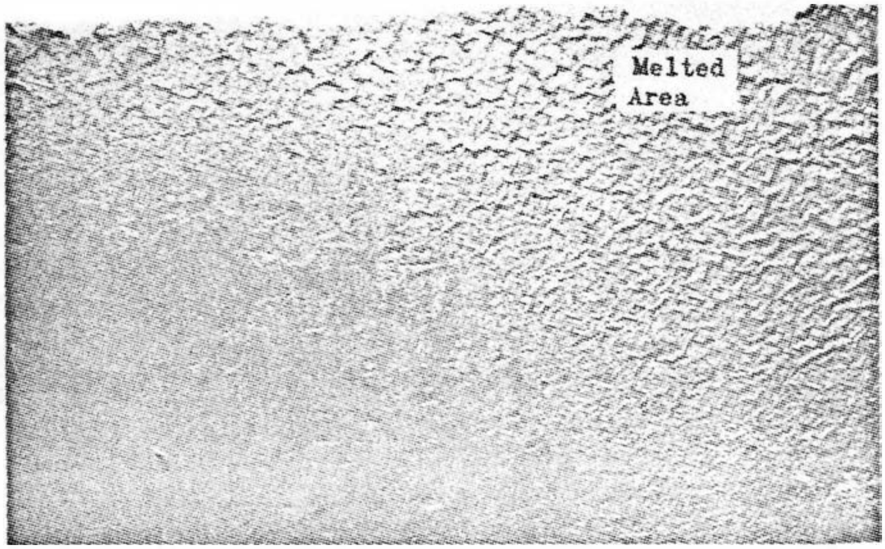
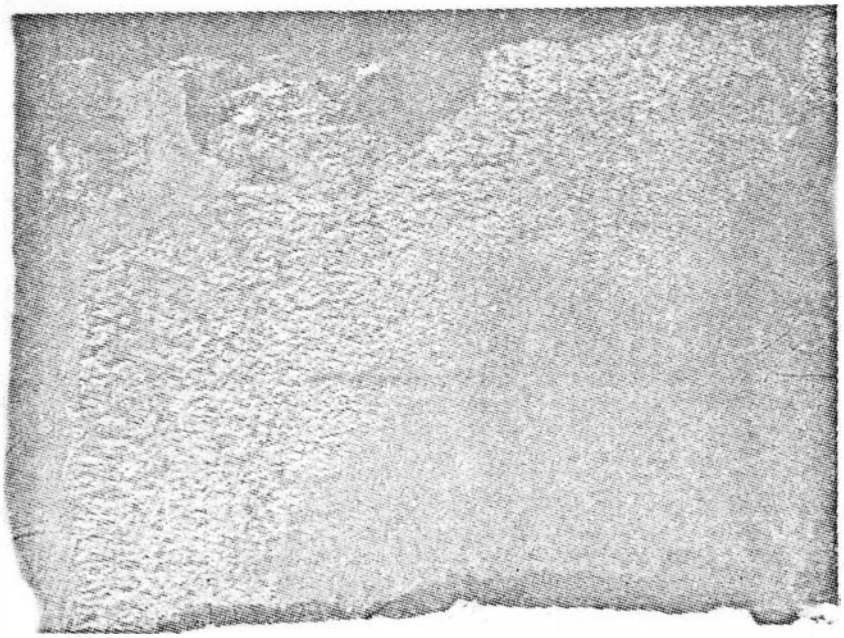


FIGURE 11. Combustion Side of A Shingle. Note the Initial Stages of Surface Melting Prior to Erosion.
Mag: 10X



IGURE 12. Coolant Side of Shingle. Note the Surfa
elting and Coking.
Mag: 10X

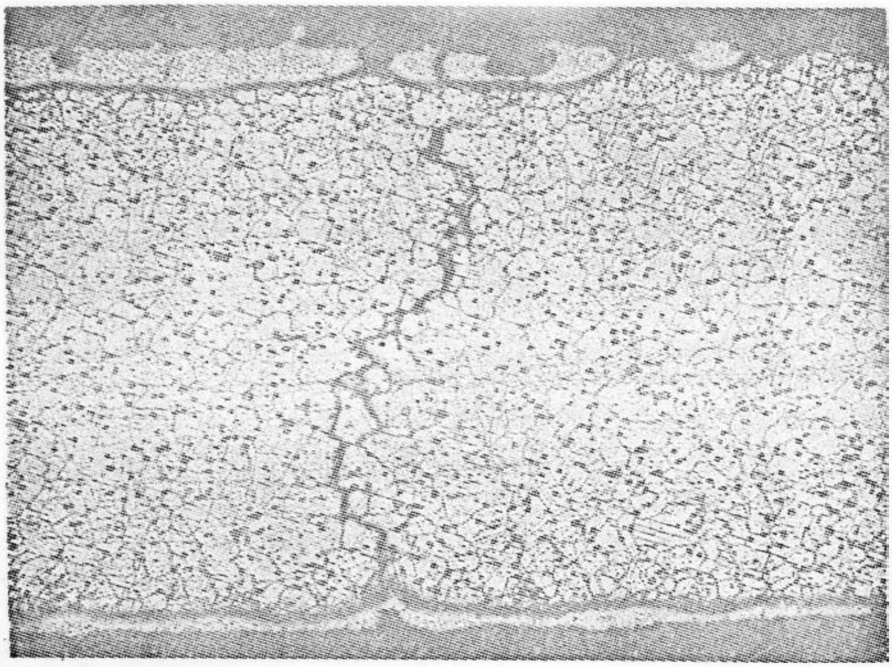


FIGURE 13. Corss-Section through A Cracked Area Showing Carburized Surfaces.

Mag: 100X. Etchant: 2% Chromic (elect)

FAILURE INVESTIGATION OF PLATINUM HOT GAS TEMPERATURE TRANSDUCERS

Problem: Some engines have experienced an unacceptable component failure rate with hot gas temperature transducers used for accurate measurement of gas temperature at various locations on the engine. These temperature probe devices yield a change in electrical resistance which is proportional to and is a measure of a corresponding change in temperature. Unit design requires that the sensing element and integral electrical lead wires to the element be made of precision instrumentation quality platinum wires (at least 99.99% platinum). Component failures have been manifested as platinum wire fractures with resultant erratic component operation or complete loss of electrical continuity through the temperature sensing device. The sensing unit is 1 mil platinum wire and the lead wire is 13 mil platinum wire.

Failure Investigation Results: Figure 14 is a schematic sketch of the transducer showing the location of failures. Figure 15 is a positive enlargement of a x-ray of the transducer showing the failure location so that sections could be cut in the proper location in order not to damage any evidence inside the housing. After disassembly metallographic sections were prepared and examined. Figure 16 shows an intergranular constituent extending completely through the cross section and Figure 17 shows a brittle fracture following the intergranular constituent. A microprobe analysis was conducted on the grain boundary constituent and this revealed the presence of phosphorus. Figure 18 is an electron microprobe readout of the grain boundary area in Figure 16. The x-ray detector was set for selective response only to phosphorus. The light dots indicate phosphorus response from the intergranular constituents. Figure 19 is an electron fractograph of a fracture face. Contour line indications of a solidification reaction are seen. The fractograph illustrates that the fractured surface existed as a liquid phase

Wire failure mode may be described as grain boundary melting at operating temperature caused by formation of intergranular low melting platinum-phosphorus constituent. The resulting metallurgical structure was incapable of withstanding vibrational loading imposed during engine operation. Fracture took place in the assumed semi-molten grain boundary area without ability for plastic deformation.

Further investigation revealed that the phosphorus came from the ceramic cement used in the construction of the probe.

Solution: The transducer has been redesigned to make the ceramic core slightly larger for more strength and the use of ceramic cement has been discontinued. These changes have increased the service life of the probes considerably,

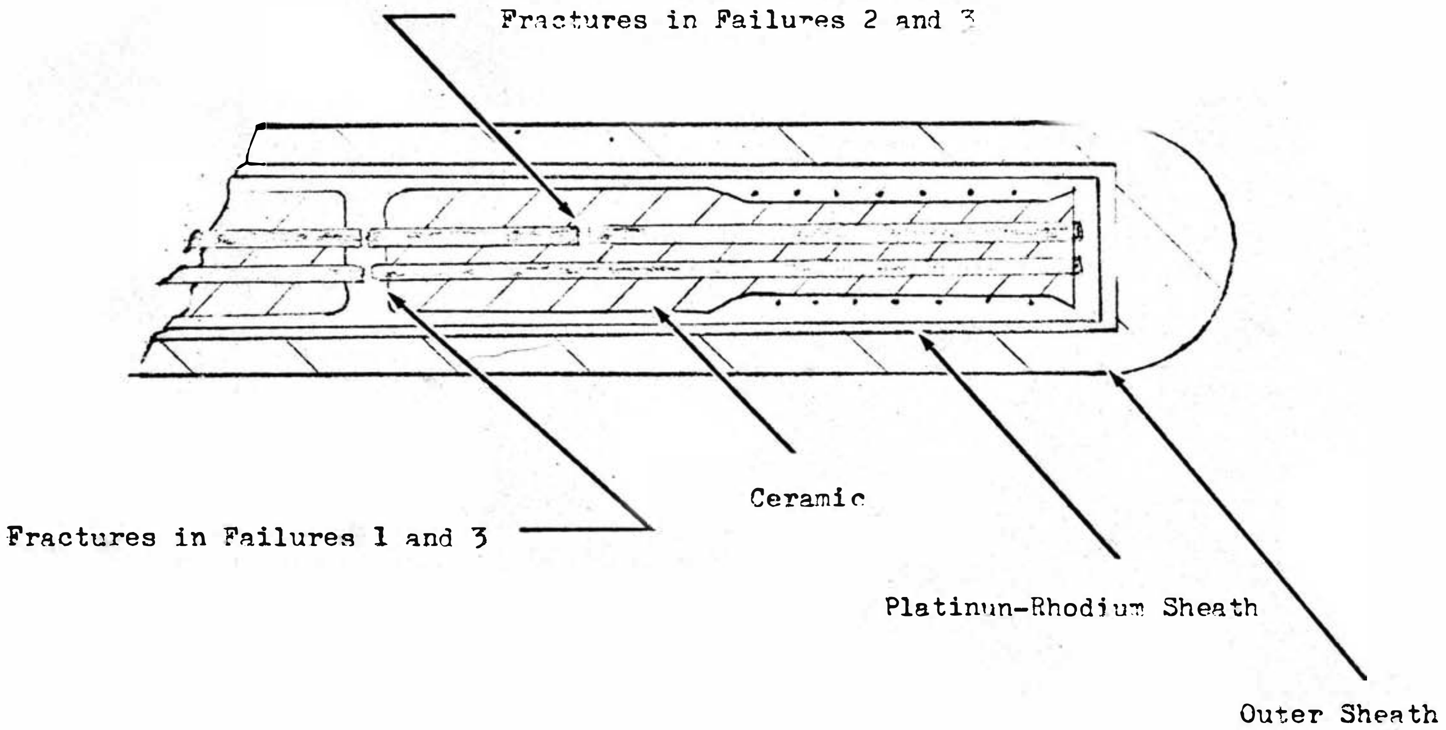


FIGURE 14. Schematic Sketch of Transducer Tip End Showing Approximate Platinum Wire Fracture Locations in each Failure as Designated.

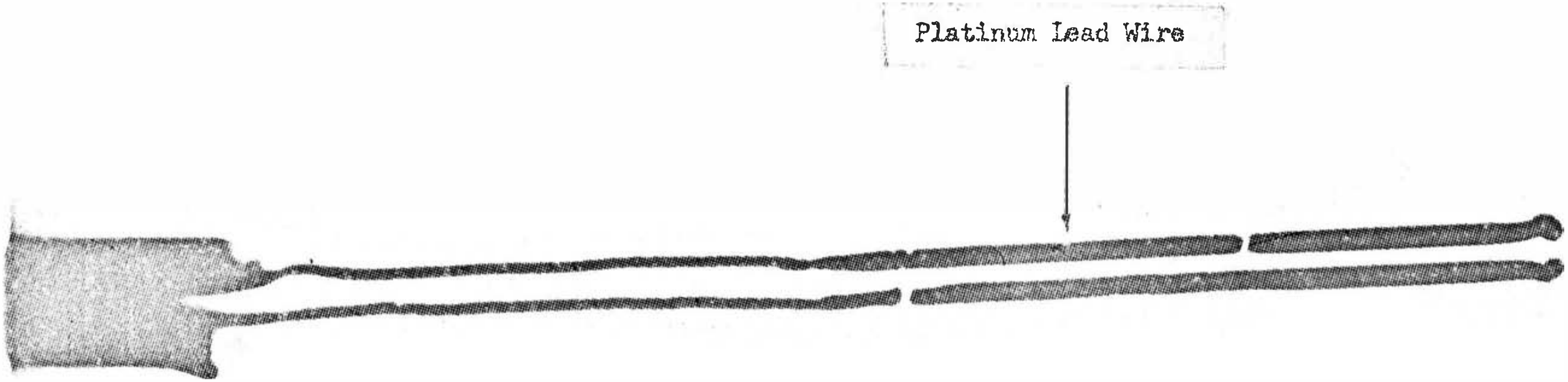


FIGURE 15. X-ray Photograph of Failure Number Three. This Enlarged Photographic Positive Print Reveals that Failure Number Three Experienced Platinum Lead Wire Fracture in Three Locations. The Wire Segment with Two Fractured Ends Was Chosen for Metallographic and Microprobe Analysis.

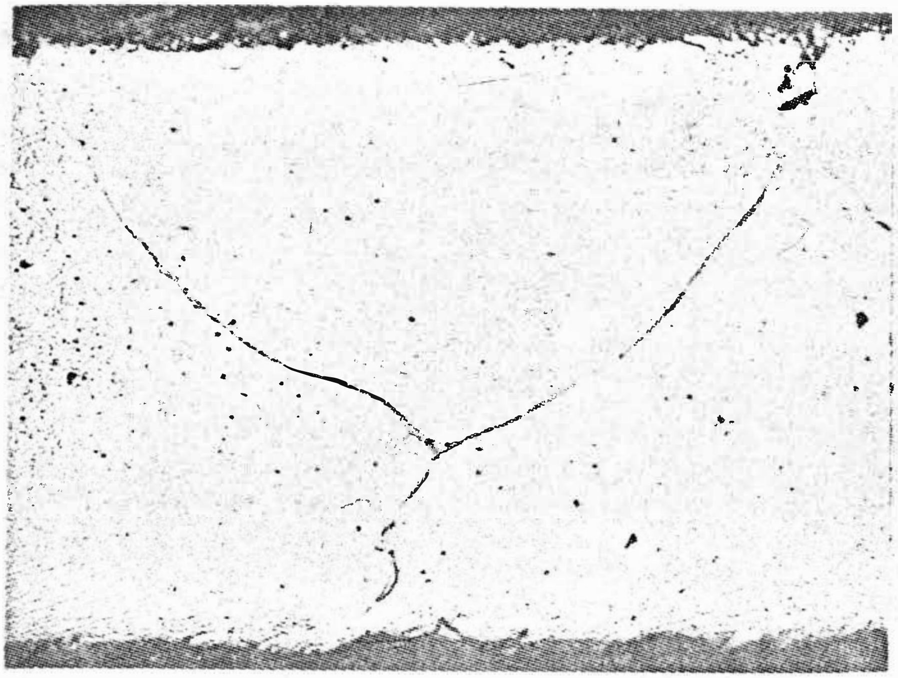


FIGURE 16. Photomicrograph of the Wire Segment Chosen for Investigation from Failure Number Three Showing Presence of a Constituent in the Platinum Grain Boundaries. The Photomicrograph Illustrates How This Intergranular Constituent Extends Completely through Wire Cross-Section.

Mag: 500X Electric Etch
NaCl + HCl

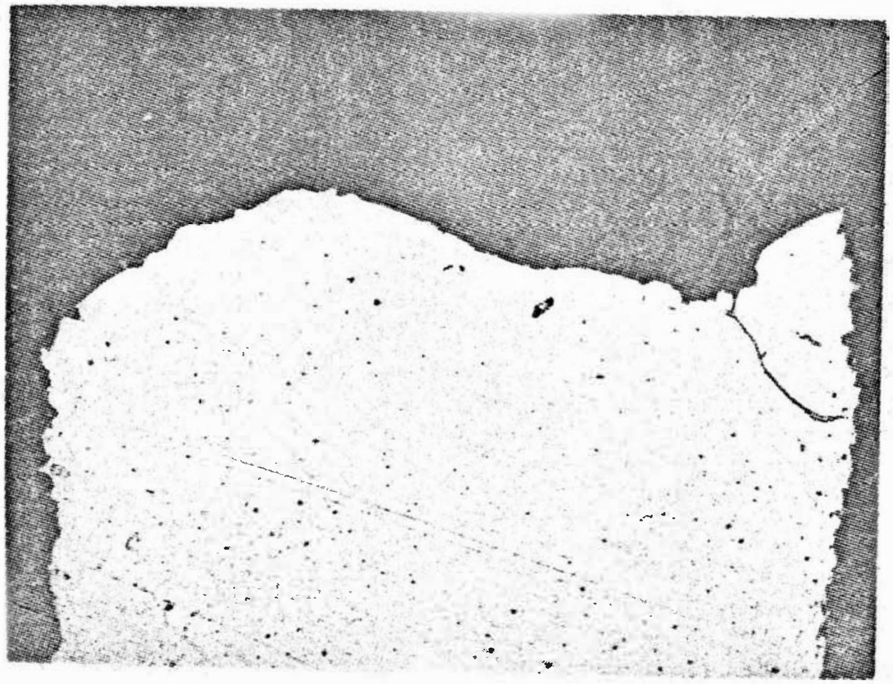


FIGURE 17. Photomicrograph of a Fractured End in the Wire Segment from Failure Number Three Showing Presence of an Intergranular Constituent in the Fracture Surface Vicinity. Note Lack of Plastic Deformation at Fracture Surface.

Mag: 500X Electric Etch
NaCl + HCl

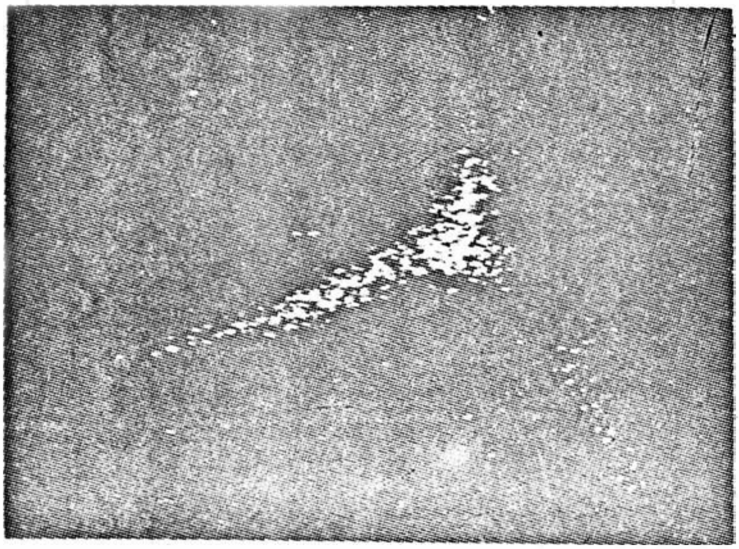


FIGURE 18. Electron Microprobe Readout of Microprobe Analysis Area Illustrated in Figure 16, with X-ray Detector Set for Selective Response Only to Phosphorus. Light Dots Indicat Phosphorus Response from the Intergranular Constituent.

Mag: 3500X

FIGURE 19. Electron Fractograp of Fractured Surface Failure Number Two. Arrows Point to the "Contour Lines" which Are Indicative of a Solidification Reaction. The Fractograph Illustrates that the Fractured Surface Existed as a Liquid Phase.

Mag: 3500X

FAILURE OF ENGINE OUTRIGGER STRUT

Problem: The outrigger strut is one of three pieces of 4135 steel tubing welded into a tripod configuration. A crack about 11" long was detected in one strut at the end of a series of hot fire and environmental tests. The environmental test included 0° stabilized temperature for prolonged periods of time. The purpose of the investigation was to determine the cause of cracking of the strut.

Failure Investigation Results: A metallurgical examination revealed that the material conformed to AMS-6372, 4135 steel tubing and was properly heat treated to 160 - 180,000 psi. The fracture, Figure 20, indicated that the failure was not caused by a defect and was ductile in nature.

The general appearance of the failed area of the strut indicated that failure had occurred from an internal force. When the strut was removed from the engine, it had been noted as being partially full of water. Further examination of the chamber revealed that water could be introduced through holes in the pad and drain between the jacket and eggcrate assembly to the strut in question, Figure 21. An x-ray and ultrasonic examination of a strut adjacent to the failed one showed it to be approximately half full of water.

A strut, identical to the failed part, was removed from a scrap thrust chamber with the clevis and forward support intact.

This assembly was filled with water and placed in a $0^{o}F$ refrigerator overnight. It failed in a manner identical to the subject part, Figure 22.

From the investigation, it was concluded that the fracture was the result of water freezing inside the strut.

Solution: Provisions for removing entrapped water from struts and eliminating entrance holes were made on all chambers. Since this provision was put into effect there have been no strut cracking problems.

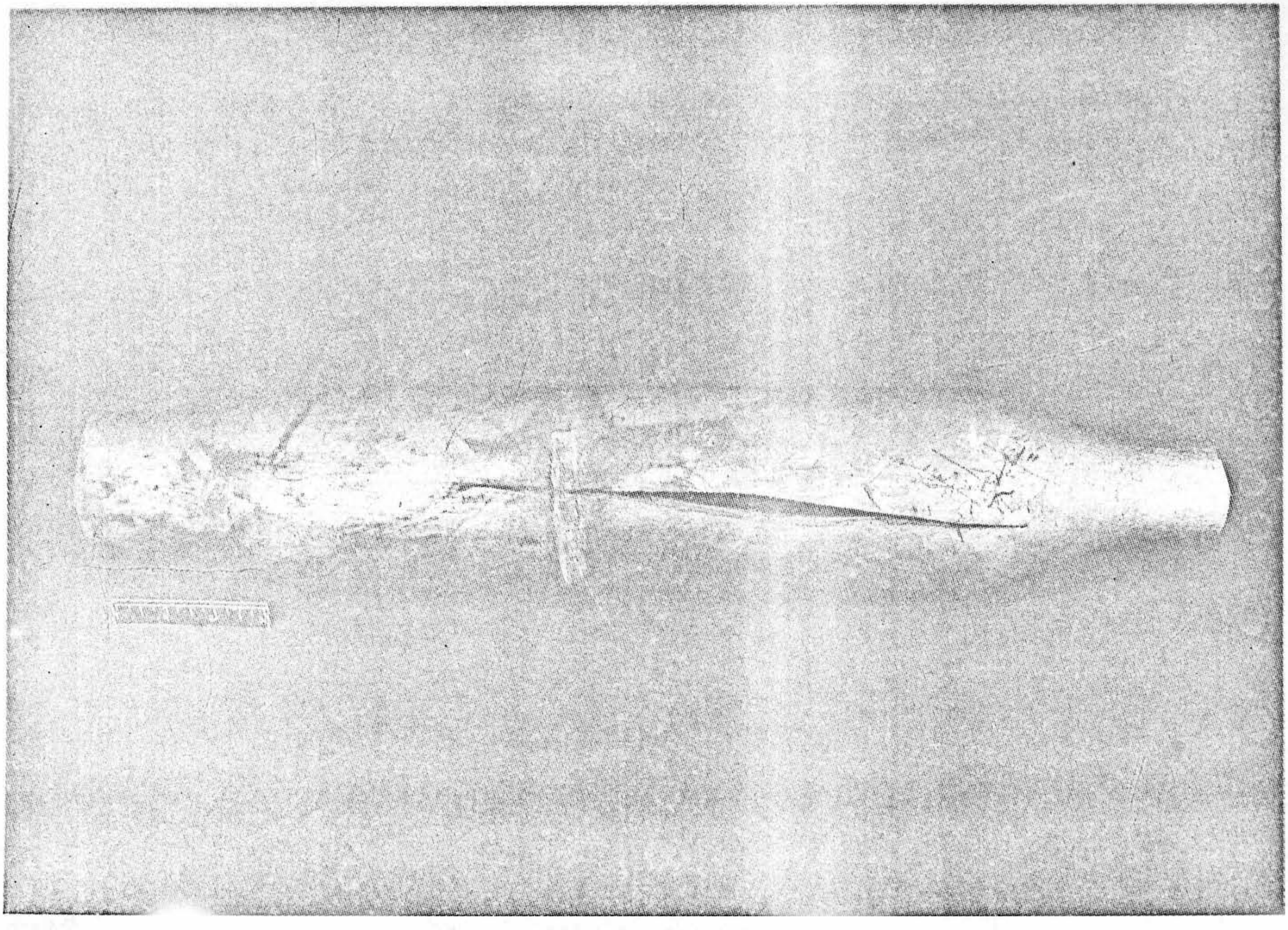


FIGURE 20. Failed Strut

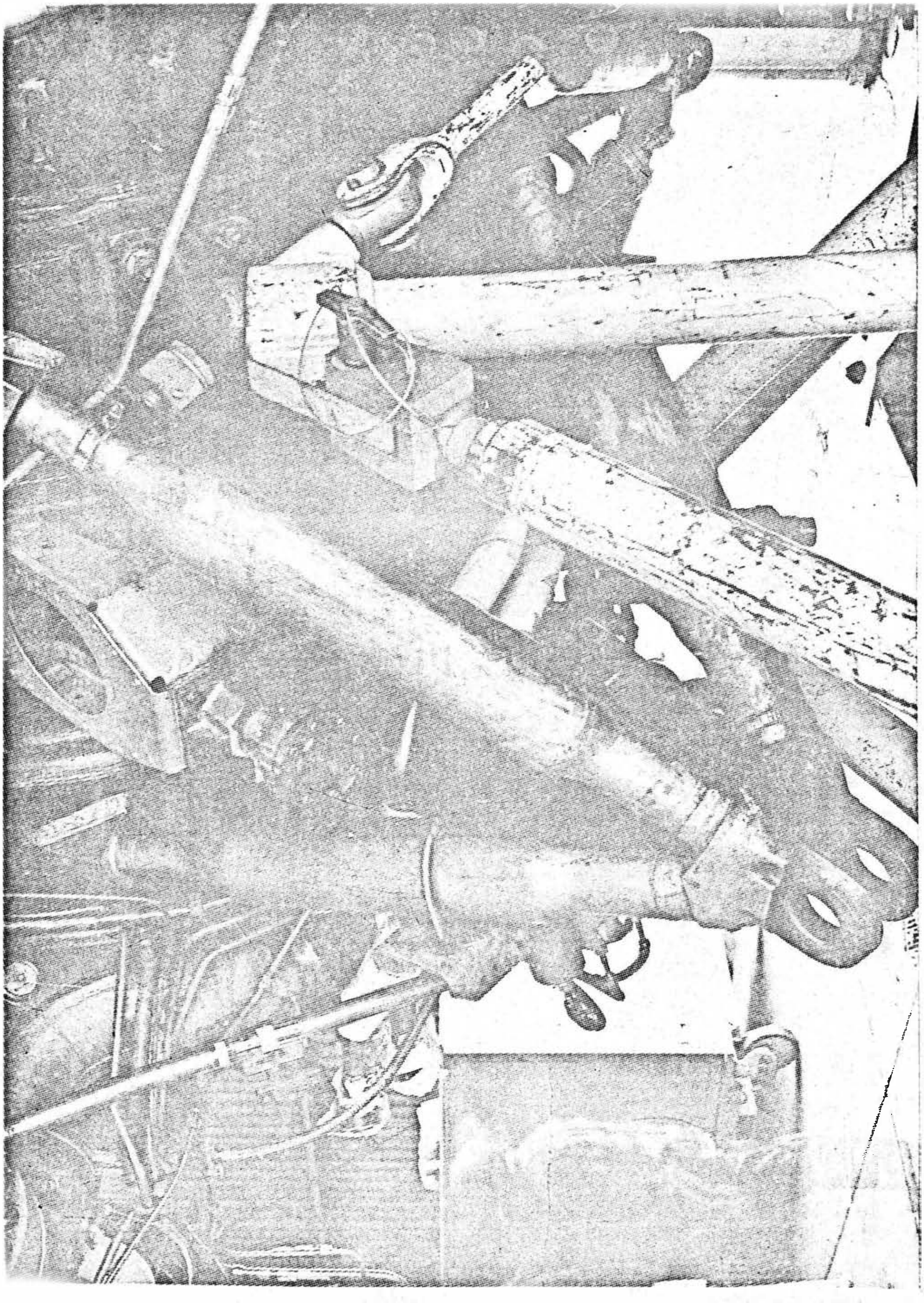


FIGURE 21. Failed Strut on Engine

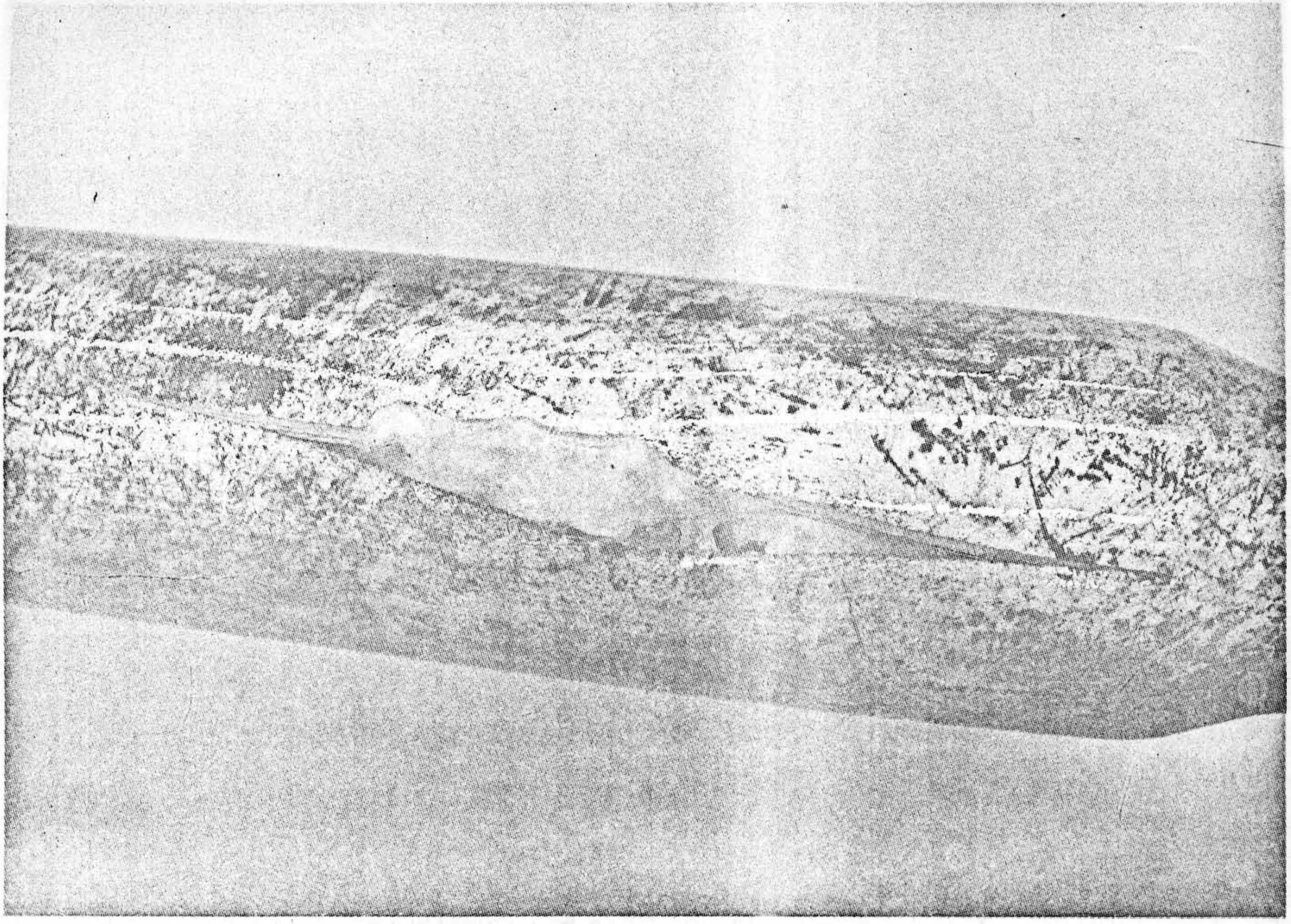


FIGURE 22. Intentionally Failed Strut.

FAILURE OF A TURBOPUMP KEL-F PLASTIC LINER

Problem: A Kel-F plastic liner was used in the inlet of an engine LOX pump. The liner in this investigation ran about 4000 seconds at -297°F in component and engine testing. Inspection of the liner upon disassembly of the turbopump revealed a crack through the thickness of the material on the inside circumferance of the inlet pilot diameter of the liner, Figure 23.

Failure Investigation Results: The mechanical properties of the Kel-F material were to specification requirements. A macroscopic examination of the fracture, Figure 24, revealed typical fatigue "beach marks", such as are commonly seen in fatigue fractures in metals. It was concluded that the liner failed due to vibrational fatigue with the vibration coming from a cavitation condition in the pump inlet.

Substantially, flexural fatigue tests of Kel-F material in LN_2 at -320 revealed typical fatigue "beach marks" in the plastic material similar to those found in metallic materials.

Solution: The solution to the fatigue problem was two-fold. The diameter of the Kel-F liner was increased to produce a tighter fit on the aluminum housing. This helped to dampen vibration. The fillet radius at the area of fatigue initiation was increased to reduce the stress riser effect of the sharp corner of the original design.