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Failure Analysis of a Stirling Engine Heat Pipe

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E-4561

SUMMARY

Failure analysis was conducted on a heat pipe from a Stirling Engine test rig which was designed to operate at 1073 K. Premature failure had occurred due to localized overheating at the leading edge of the evaporator fin. It was found that a crack had allowed air to enter the fin and react with the sodium coolant. The origin of the crack was found to be located at the inner surface of the Inconel 600 fin where severe intergranular corrosion had taken place.

INTRODUCTION

In September 1987, the evaporator portion of a finned cylinder sodium (Na) heat pipe from a Stirling Engine test rig was submitted to NASA Lewis Research Center for failure analysis. Premature failure had occurred in the evaporator which was designed to operate at 1073 K. Glowing at the leading edge of the fin, which was observed during the run, made it apparent that localized overheating was a primary problem. A preliminary examination of the failed heat pipe showed that a crack which had developed near the leading edge allowed air to leak through the fin wall into the heat pipe and react with the Na coolant.

Because of the gross overheating problem, severe liquid metal corrosion was anticipated at the leading edge of the fin. Devan (ref. 1) has reported a marked temperature dependence of mass transfer for a Ni-base alloy in a forced convection Na loop system, and Thorley and Tyzack (ref. 2) reported a rapid corrosion rate increase with temperature in a stainless steel pumped Na loop.

In this investigation, the failed heat pipe was subjected to macro- and micro-examination. The objective was to determine the nature of the crack and its origin. Corrective actions which were taken to alleviate the overheating problem are mentioned along with cautions about inherent intergranular corrosion considerations for heat pipes.

HEAT PIPE FABRICATION AND OPERATION

The finned cylinder heat pipe system was fabricated from Inconel 600 material. The evaporator portion is shown in figure 1. On the inside of the 0.8 mm thick Inconel 600 fin, Type 316 stainless steel wick materials were positioned as shown in figure 2, as follows:

(1) Three layers of 80 mesh screen in contact with the fin wall

(2) Two layers of 150 mesh screen in contact with the 80 mesh screen

(3) Two layers of 5 mesh woven wire at the center

Gas tungsten arc (GTA) welds were made at the leading and trailing edges of the fin. As is shown in figure 2, location B, the welds penetrated into the wick materials which extended to the edge of the fin. The open side of the fin was inserted into a 6.5 mm wide gap in the 1 mm thick wall, cylindrically shaped member. As shown in figure 1, a GTA fillet weld was used to join the fin to the cylinder.

The Na used in this heat pipe was 99.8 percent pure (nominal). Prior to filling, the heat pipe was subjected to a vacuum bakeout and then cooled. Next, the heat pipe was filled with Na vapor which was generated from an external evaporator. After the filling operation, the connection tube was crimp-sealed and the evaporator was removed.

In operation, the axis of the cylinder was in a horizontal position, as shown in figure 1. The fin was located in flue gas heated with a natural gas flame with 20 percent excess air. On the basis of calculations, the temperature of the gas impinging on the leading edge of the fin was about 1820 K. During the run, the temperatures measured at pads 1, 2, and 3 (1076, 1065, and 1065 K, respectively) were very close to the 1073 K design temperature. A bright glow confined to the leading edge, however, indicated localized gross overheating to perhaps 1350 K. Estimated internal pressure within the heat pipe was about one half of atmospheric pressure (55.2 kPa). The power output during the run was between 2.0 and 2.2 kW and the heat flux at leading edge of the fin was in the range of 500 to 600 kW/m^2. Under the conditions described above the heat pipe system failed after only 2 hr due to a through-the-wall crack near the leading edge of the evaporator fin.

EVALUATION PROCEDURES

On receipt, the failed heat pipe was submerged in flowing tap water and then thoroughly rinsed in tap water to remove all traces of free Na products. Samples for chemical analysis of the wick and fin materials were taken where no macro-corrosion was evident (near location C in fig. 1). Specimens for macro- and micro-examination were obtained from locations A, B, C, and D as shown in figure 1. The arrows point to the cut edges which were to be viewed. At location D, the viewing direction was normal to the through-the-wall crack in the fin.

RESULTS AND DISCUSSION

Chemical Analysis

Single chemical analysis determinations indicated that the fin material was made from the Inconel 600 alloy and that the wick material was Type 316 stainless steel. Minor deviations from the specified composition ranges were observed, however, as shown in table I. The Cr content of the fin (13.8 percent) was just below the 14.0 percent minimum for Inconel 600. For the wick screen material, Ni at 8.8 percent (10.0 percent minimum) and Mo at 1.3 percent (2.0 percent minimum) were low. As was stated in the Evaluation Procedures section, Inconel 600 and Type 316 stainless steel analysis samples were taken from regions which showed no macro-corrosion. Micro-corrosion effects, however, may have affected the chemistry. Without further chemical analysis data of starting materials, and of materials with various degrees of corrosion, the possibility of micro-corrosion affecting material chemistry is uncertain. In any event, it is believed that the overall behavior of the Inconel 600 and Type 316 stainless steel would not be adversely affected even if these minor deviations were present in the starting materials.

Macro-examination

An examination of cross sections of the fin revealed that, at the overheated leading edge, the wick material was disintegrated by corrosion and the interior wall of the fin was also severely corroded. At location A in figure 2, areas of the fin wall that appear white are corroded. The maximum penetration of this general corrosion was about 360 μm near the through-the-wall crack which was parallel to this cross section. The severity of the corrosion progressively decreased as the distance from the leading edge increased. At a distance of 10 mm from the leading edge no macro-evidence of corrosion was observed.

At the trailing edge, location B in figure 2, no corrosion of the wick or fin was evident. Thus, the wick exhibits an as-fabricated appearance. As shown at location C in figure 2, continuity of the wick at the folded edge of the fin permitted complete access of the Na coolant to this region of the fin. No corrosion was evident at location C.

A photograph of the outer surface of the through-the-wall crack (from fig. 1) is shown in figure 3(a). Cracking, which initiated at the inner surface, extended through the thickness to the outer surface about 2.3 mm from the leading edge. The total length of the crack at the outer surface was about 4.3 mm. At cross-section A-A (fig. 3(b)), the crack does not quite extend to the outer surface. But, a little further back from the leading edge it did reach the outer surface and permitted air to enter the heat pipe. The air-contaminated Na coolant and corrosion products leaked to the outer surface and deposited a residue there (fig. 3(b)).

Micro-examination

The intergranular nature of the corrosion cracking is evident in figure 4. The crack developed in the area of general corrosion at the inner surface of the fin and proceeded to the outer surface. Since the pressure within the fin was below atmospheric pressure, a slight tensile stress would be produced at the inner surface and it would contribute to a stress corrosion effect. Severe corrosion of the Type 316 wick materials also occurred near the overheated leading edge of the fin. At location A, shown in figure 5, the intergranular attack resulted in disintegration of the wire screen. It was not surprising to find the severe corrosion of fin and wick materials since the localized area at the leading edge of the fin was estimated to have been operating at about 1350 K. Under these conditions the Na was in the gaseous rather than the liquid state. At much lower temperatures in pumped Na loops, Devan (ref. 1) showed a marked increase in mass transfer between 922 and 1089 K for Ni-base alloys. Thorley and Tyzack (ref. 2) reported a rapid corrosion rate increase in stainless steel with temperature increases from 723 to 998 K.

At location B (fig. 5) at the trailing edge, intergranular corrosion also occurred, but only to a depth of 10 μm in both the Type 316 wire screen and in the Inconel 600 fin. A lesser degree of attack (5 μm deep) took place at the folded side of the fin (see location C in fig. 5). Even though the extent of corrosion is very slight these results show that Inconel 600 and Type 316 stainless steel are susceptible to corrosive attack at the 1073 K design temperature.

SUMMARY OF RESULTS

An investigation of a failed sodium heat pipe which had cracked because of local overheating at the leading edge of an evaporator fin revealed the following:

1. Through-the-wall cracking which occurred near the leading edge of the fin was a result of intergranular corrosion.

2. Cracking initiated at the inner surface of the fin and proceeded to the outer surface.

3. Severe intergranular corrosion took place in the vicinity of the leading edge in both the Inconel 600 fin and the Type 316 stainless steel wick.

4. A minor degree of intergranular corrosion was observed in both fin and wick materials at the cooler trailing edge and at the folded side region of the fin.

CONCLUDING REMARKS

The reason that this heat pipe failed is that the leading edge of the evaporator fin was overheated. The system did not work properly because liquid Na failed to carry a sufficient quantity of heat away from the leading edge. This problem has been largely solved in more recently fabricated Type 321 stainless steel heat pipes in which higher capillary pressure was produced by changing the internal design of the heat pipes.

The fact that some evidence of intergranular corrosion was found in the cooler regions of the fin in both Inconel 600 and Type 316 stainless steel indicates that corrosion must be considered a potential failure mode in long time service at 1073 K.

Devan (ref. 3) suggests that Ni-base alloys and stainless steels can be suitable for heat pipe applications if the surface area of the wick is very high and extreme precautions are taken to keep impurities (mainly oxygen) at low levels. Devan sees little difference between Ni-base and Fe-base alloys for heat pipe applications.

REFERENCES

1. DeVan, J.H.: Corrosion of Iron- and Ni-base Alloys in High Temperature Sodium and NaK. Alkali Metal Coolants, International Atomic Energy Agency, Vienna, 1966, pp. 643-661.

2. Thorley, A.W.; and Tyzack, G.: Corrosion Behavior of Steels and Nickel Alloys in High Temperature Sodium. Alkali Metal Coolants, International Atomic Energy Agency, Vienna, 1966, pp. 97-118.

3. DeVan, J.H.: Oak Ridge National Laboratory, Personal Communication to D.L. Alger, NASA Lewis Research Center, Feb. 16, 1988.

TABLE I. - CHEMICAL ANALYSIS OF FIN AND SCREEN MATERIALS (WEIGHT PERCENT)

	Inconel 600 fin material		Type 316 stainless steel wick material		
	Specified composition range	0.8-mm sheet	Specified composition range	80-mesh and 150-mesh screen	5-mesh woven wire
Cr	14.0 to 17.0	13.8	16.0 to 18.0	17.5	17.3
Ni	Balance	Balance	10.0 to 14.0	8.8	9.9
Fe	6.0 to 10.0	7.8	Balance	Balance	Balance
Mn	1.0 max	0.2	2.0 max	0.9	1.0
Si	0.5 max	0.08	1.0 max	0.3	0.6
C	0.15 max	0.014	0.08 max	0.074	0.030
Mo	-----------	-------	2.0 to 3.0	1.3	2.0

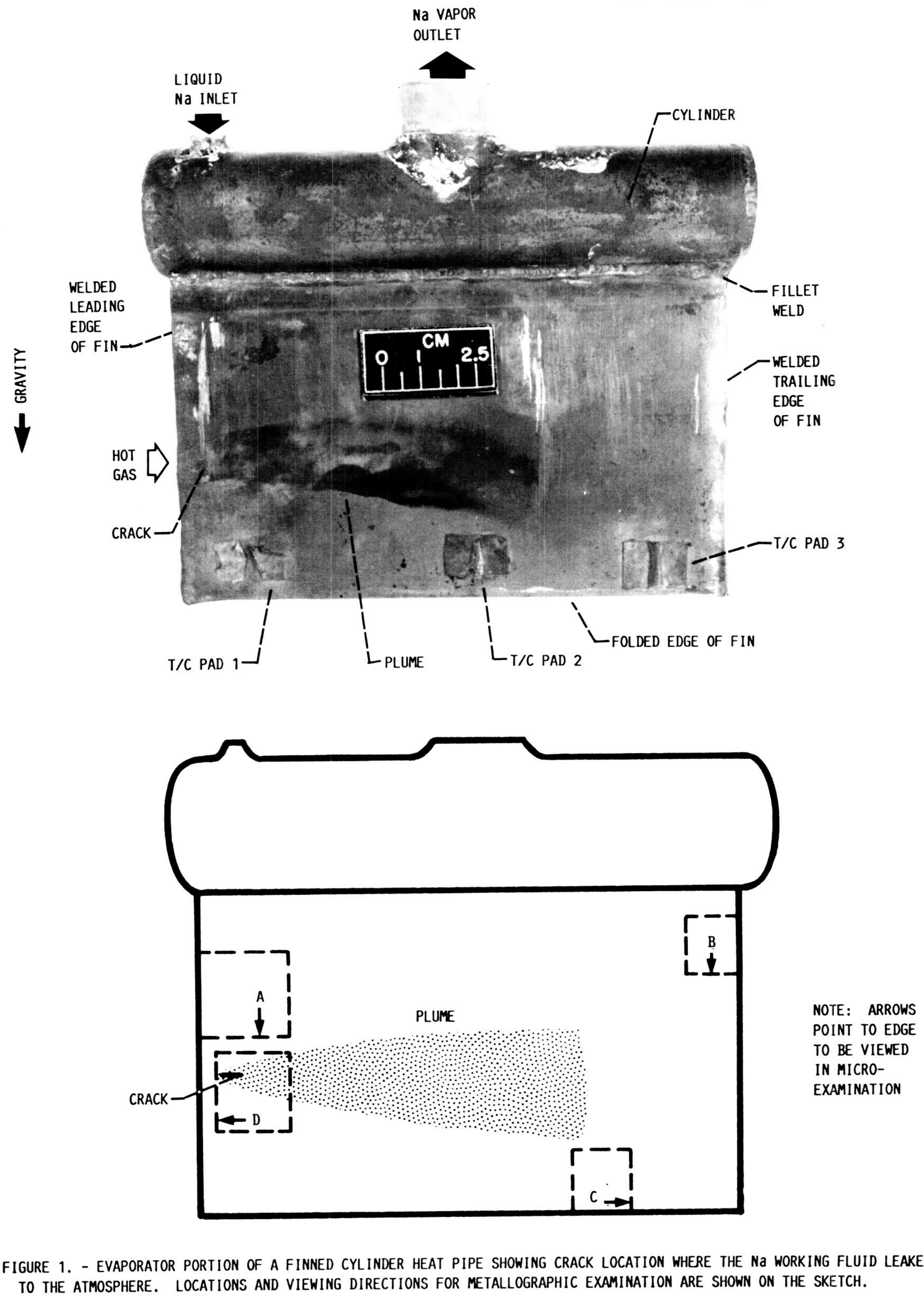

FIGURE 1. - EVAPORATOR PORTION OF A FINNED CYLINDER HEAT PIPE SHOWING CRACK LOCATION WHERE THE Na WORKING FLUID LEAKED TO THE ATMOSPHERE. LOCATIONS AND VIEWING DIRECTIONS FOR METALLOGRAPHIC EXAMINATION ARE SHOWN ON THE SKETCH.

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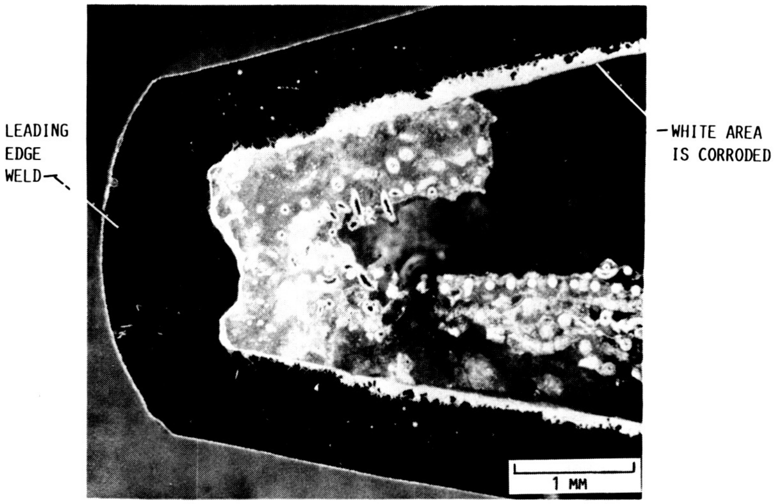
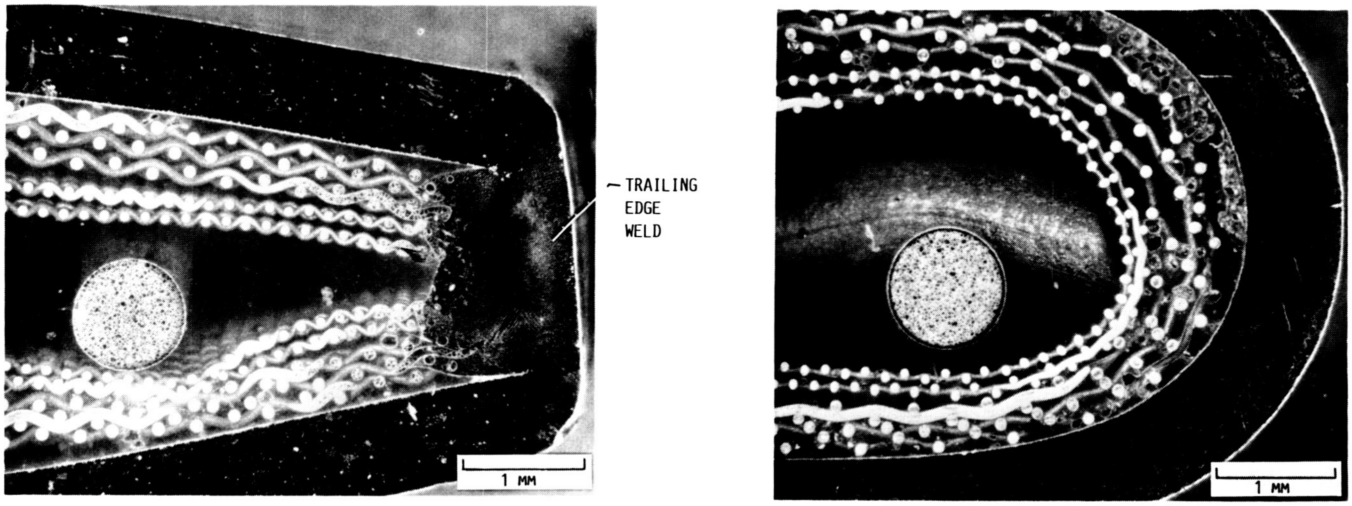


LOCATION A. LEADING EDGE OF FIN NEAR THROUGH-THE-WALL CRACK REGION WHICH WAS PARALLEL TO THIS CROSS SECTION. CORROSION HAS OCCURRED HERE AT THE INNER SURFACE OF THE FIN AND IN THE WICK MATERIAL.



LOCATION B. TRAILING EDGE SHOWING WELD PENETRATION INTO WICK AREA.

LOCATION C. FOLDED EDGE SHOWING CONTINUOUS CONTACT OF WICK WITH FIN SURFACE.

FIGURE 2. - APPEARANCE OF THE TYPE 316 STAINLESS STEEL WICK WITHIN THE INCONEL 600 FIN AND CORROSION EFFECTS AT THE LEADING EDGE. (LOCATIONS A, B, AND C WITH VIEWING DIRECTIONS ARE SHOWN IN FIG. 1.)

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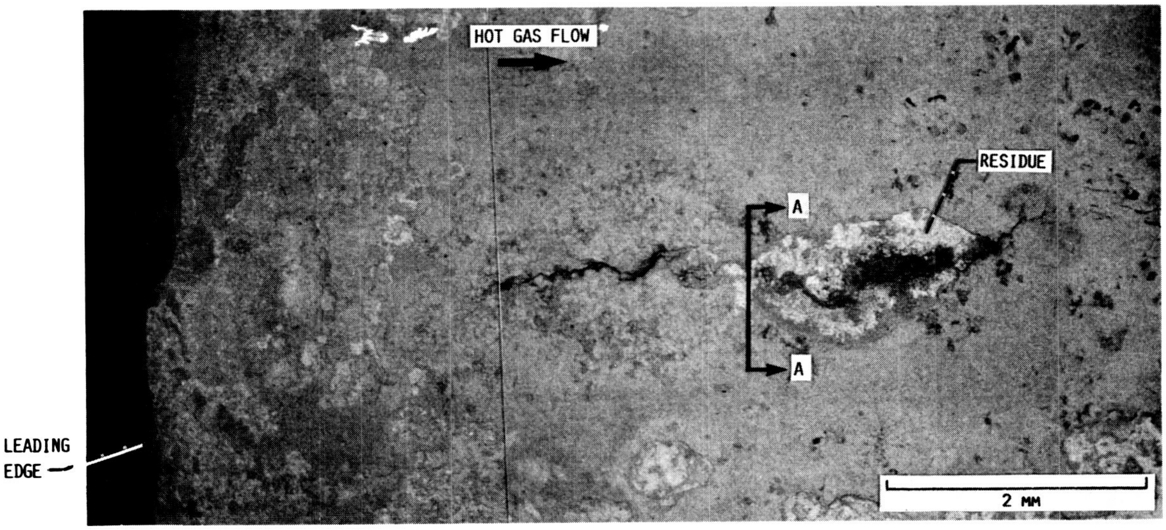
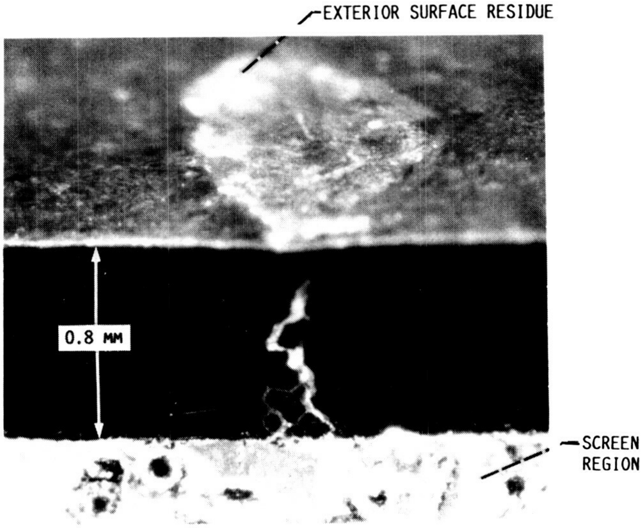


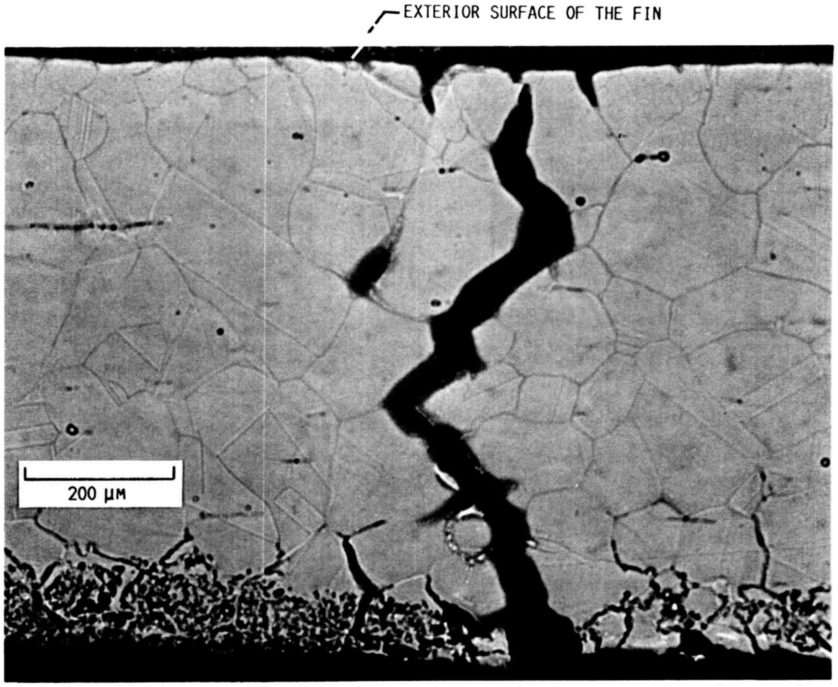
(a) EXTERNAL SURFACE OF THE FIN WITH CRACK NORMAL TO THE WELDED LEADING EDGE.



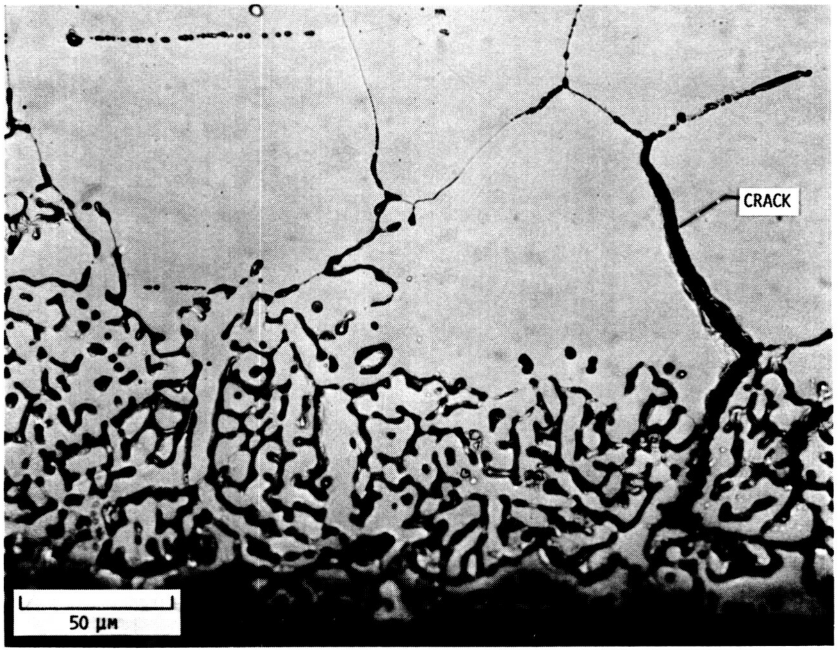
SECTION A-A

(b) AT THIS LOCATION, THE CRACK, WHICH STARTED AT THE INNER SURFACE EXTENDS ALMOST TO THE OUTER SURFACE OF THE FIN.

FIGURE 3. - THROUGH-THE-WALL CRACK IN THE INCONEL 600 FIN WALL SHOWING PROGRESSION FROM THE INNER TO THE OUTER SURFACE.

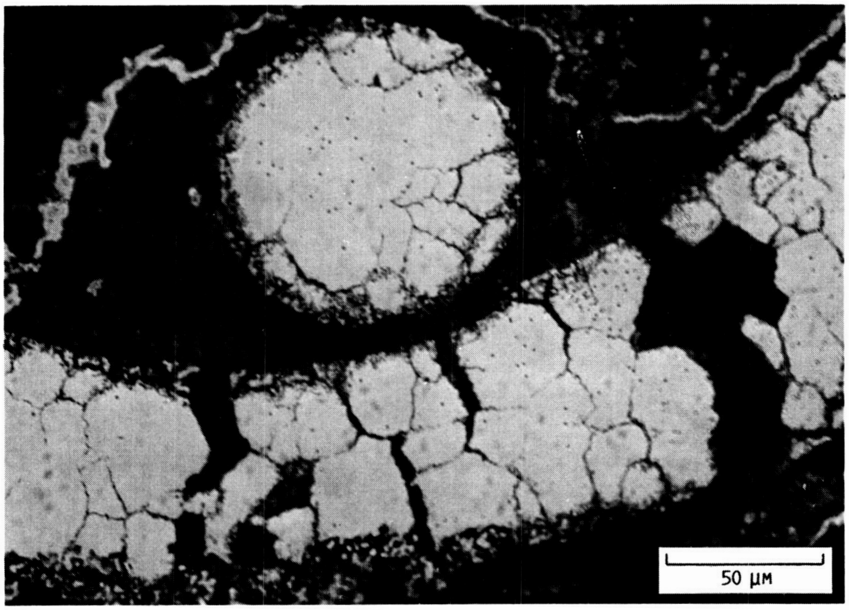


(a) CROSS SECTION OF THROUGH-THE-WALL INTERGRANULAR CRACK IN THE FIN.

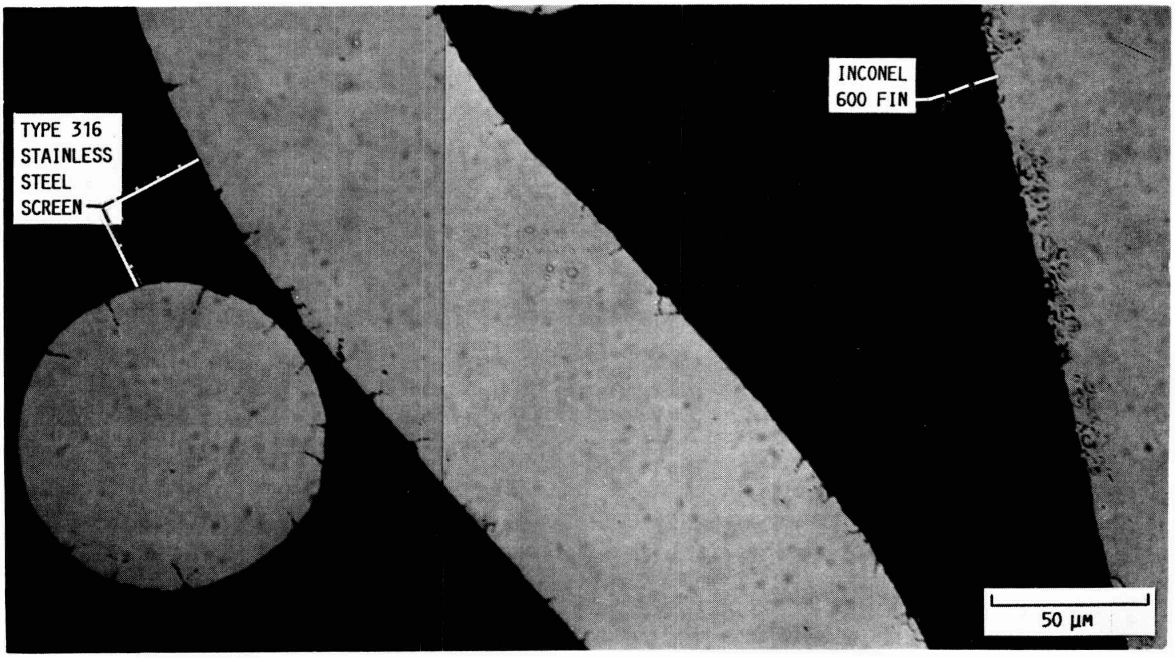


(b) CORRODED AREA AND INTERGRANULAR CRACKING AT INNER SURFACE OF THE FIN.

FIGURE 4. - CORROSION AT INNER SURFACE OF THE INCONEL 600 FIN AND THE INTERGRANULAR NATURE OF THE CRACKS THAT PROCEED FROM THE CORRODED AREAS. (LOCATION D FROM FIG. 1.) ETCH: 33 ml HNO_3, 33 ml ACETIC, 33 ml H_2O, 1 ml HF, ELECTROLYTIC.



LOCATION A. SEVERE INTERGRANULAR CORROSION AND DISINTEGRATION OF THE TYPE 316 STAINLESS STEEL SCREEN NEAR THE LEADING EDGE OF THE FIN.



LOCATION B. SLIGHT INTERGRANULAR CORROSION IN THE SCREEN AND FIN MATERIAL. THE DEPTH OF INTERGRANULAR ATTACK IS ABOUT 10 μm.

FIGURE 5. - CORROSION OF TYPE 316 STAINLESS STEEL WICK AND THE INCONEL 600 FIN MATERIALS AT VARIOUS LOCATIONS WITHIN THE FIN. (LOCATIONS A, B, AND C ARE SHOWN IN FIG. 1.) UNETCHED.

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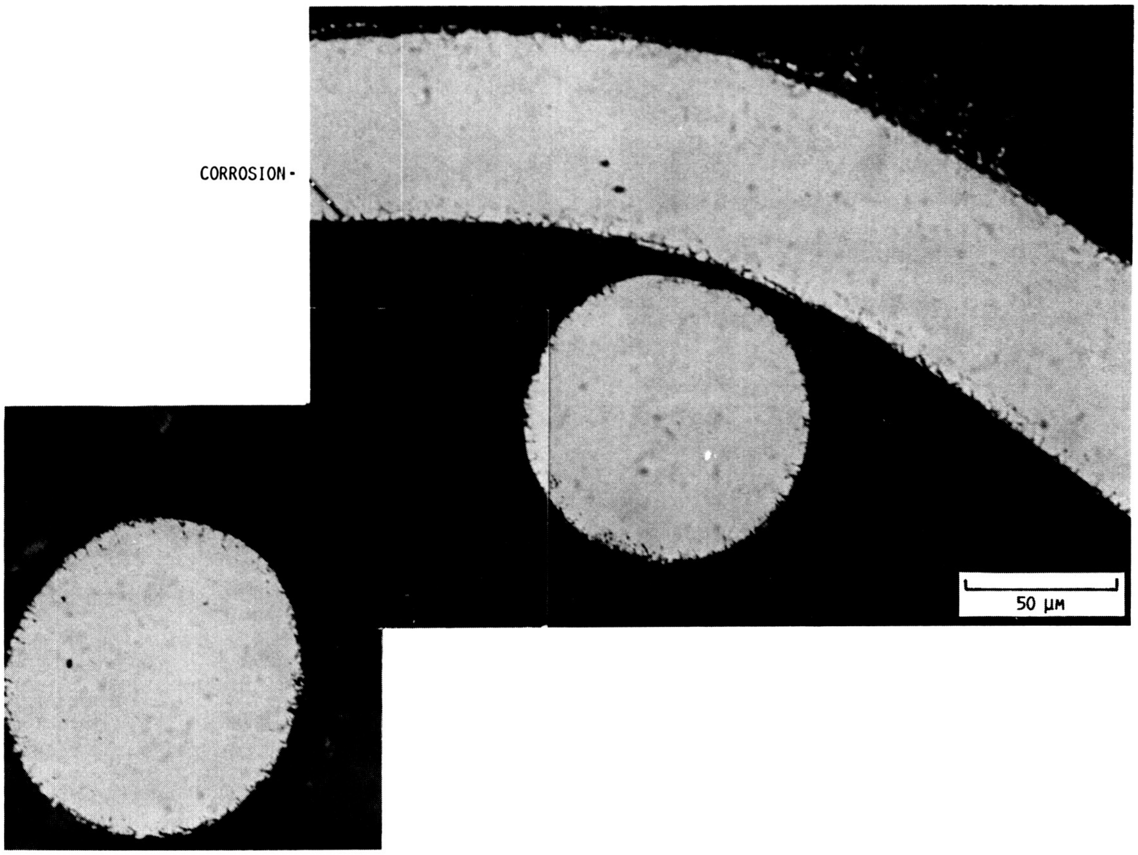

LOCATION C. INTERGRANULAR CORROSION TO A DEPTH OF ONLY 5 μm IN THE TYPE 316 STAINLESS STEEL SCREEN LOCATED AT THE FOLDED SIDE OF THE FIN.

FIGURE 5. - CONCLUDED.

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16. Abstract

Failure analysis was conducted on a heat pipe from a Stirling Engine test rig which was designed to operate at 1073 K. Premature failure had occurred due to localized overheating at the leading edge of the evaporator fin. It was found that a crack had allowed air to enter the fin and react with the sodium coolant. The origin of the crack was found to be located at the inner surface of the Inconel 600 fin where severe intergranular corrosion had taken place.

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