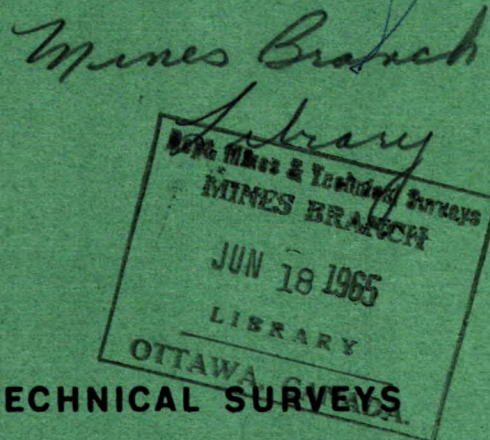


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EXAMINATION OF FAILED EXHAUST MANIFOLD FROM A HELICOPTER

by

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PHYSICAL METALLURGY DIVISION

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EXAMINATION OF FAILED EXHAUST MANIFOLD FROM A
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by

W. P. Campbell* and R. D. McDonald**

SUMMARY OF RESULTS

The loss of power during the final stages of a landing approach is attributed to an in-flight separation or almost complete separation of the valve portion of the exhaust assembly.

The collector portion of the assembly was severely weakened by progressive oxidation and cracking along grain boundaries containing chromium carbides. Cracking was accentuated due to the stress concentration effect at the junction of welds with the collector wall.

Failure of the valve portion occurred by relatively slow progressive intergranular oxidation and cracking in combination with a final separation involving transgranular cracking typical of high stress low cycle fatigue.

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INTRODUCTION

In a letter dated November 13, 1964 (Reference File No. 5002-2124 (AIGT) Mr. R. L. Bolduc, Chief, Accident Investigation, Civil Aircraft Branch, Department of Transport (D.O. T.), requested that two pieces from a failed exhaust manifold be examined to determine (1) the mode of failure and (2) if possible, whether or not failure occurred prior to ground impact.

According to information supplied by D.O. T., the pieces of exhaust manifold were from a Bell 47G3 helicopter, registration CF-MZE. On October 13, 1963, as the helicopter was transporting a sling load of gravel to a mountain ridge about 8000 ft above sea level, a loss of power occurred during the final stage of approach to the ridge. The craft lost height rapidly and struck the ground among boulders and construction materials. It was stated that failure of the exhaust manifold in flight would cause a sudden loss of power. It was also stated by D.O. T. that the manifold had about 1000 hr service.

DESCRIPTION OF SAMPLES

Figure 1 and 2 show the submitted samples. The lines marked adjacent to the welds indicate the extent of cracking that was apparent by visual examination at or close to the junction of the welds with the collector.

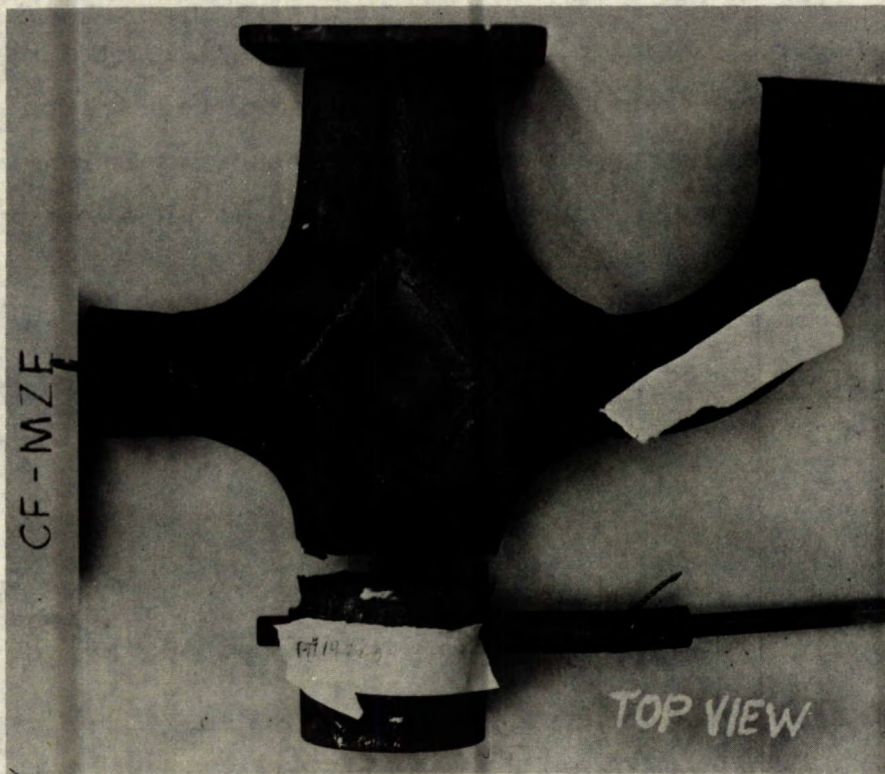


Figure 1 - Top view of part when installed.

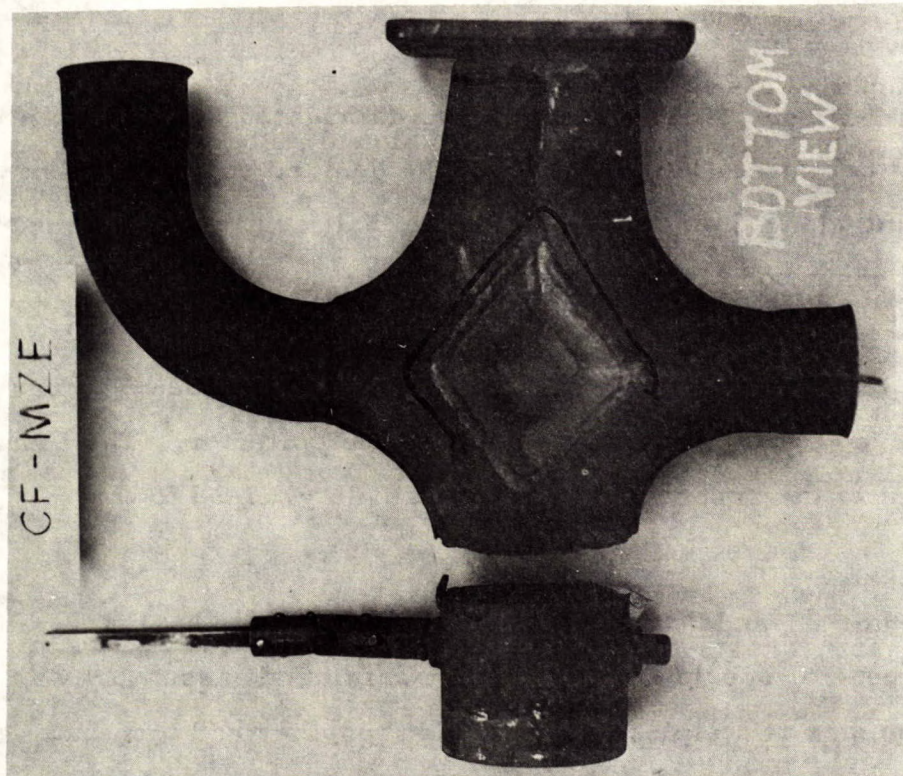


Figure 2 - Bottom view of part when installed.

Referring to either Figure 1 or 2 the right hand and left hand tubes each deliver exhaust gases from three cylinders. The lower portion that has broken off from the part carries a butterfly or waste gate valve. When this valve is closed, the exhaust gases are forced to escape through the turbo-supercharger which is bolted to the flange seen at the top of Figure 1. When the valve is opened, the exhaust escapes through the lower tube and by-passes the turbo-supercharger.

The main body of the assembly was fabricated by pressing each of two stainless steel sheets into one-half of the desired configuration followed by welding along the juncture of the two half sections. Subsequently in this report the main body of the assembly will be described as the collector. The pipe section which contained the valve will be described as the valve portion or section. The right and left hand pipes (See Figures 1 and 2) and the valve portion were butt-welded to the collector. The flange for the attachment of the supercharger unit was fillet-welded to the collector.

In Figures 1 and 2, a central smaller assembly having a diamond-shaped central opening can be seen. This small assembly was made up of four pieces of stainless steel welded together and then butt-welded into the collector. The small assembly was fabricated from stainless steel approximately 0.07 in. thick and the wall thickness of the collector was approximately 0.04 in. It was reported by D. O. T. that this small central assembly was inserted into the collector during repairs after about 570 hr of service. At this time, cracking and loss of metal were found at the original welds which joined the two half sections of the collector. As shown in Figures 1 and 2, subsequent cracking has occurred at or close to the welds that joined the inserted assembly into the collector. On the bottom side (Figure 2), cracking has extended around more than one-half of the periphery of the joint. On the top (Figure 1), similar although less cracking was evident. The contour of the external surfaces of the welds joining the inserted assembly to the collector was satisfactory.

However, the penetration beads on the inside of the assembly were quite irregular and had a sharp transition with the adjacent metal.

Extensive cracking was also observed in the collector metal adjacent to the welds that joined the mounting plate to the collector. Cracks had extended completely through and at some locations there was a gap of about $1/32$ in. It was evident also that welding repairs had been made here at some time during the service life and that cracking had recurred.

A crack, at least one inch in length, was found in the collector adjacent to the junction of the butt weld attaching the bell-mouth pipe seen at the left side of Figure 1.

EXAMINATION OF SURFACES OF MAIN FRACTURE

The surfaces of the fracture that caused complete separation of the valve portion were examined at magnifications up to X30 using a binocular microscope. Small "lips" at the inner and outer surfaces of the sheet were found intermittently around most of the circumference of the fracture path and were more apparent at the inner surface. These "lips" had a fine-grained texture and were gray to black in colour. There was usually a change in direction of the fracture path near the intersection with these "lips". Most of the surfaces of the fracture had a rough texture.

In the portion of the circumference of the fracture indicated in Figure 3, oxidation colours ranging from pink to deep purple were observed, usually in the central part of the collector wall. These colours were not found on the remaining portion of the circumference. Instead, black oxides that had formed at higher temperatures were detected at some locations on the fracture face. The texture of the fracture was less distinct at these locations.

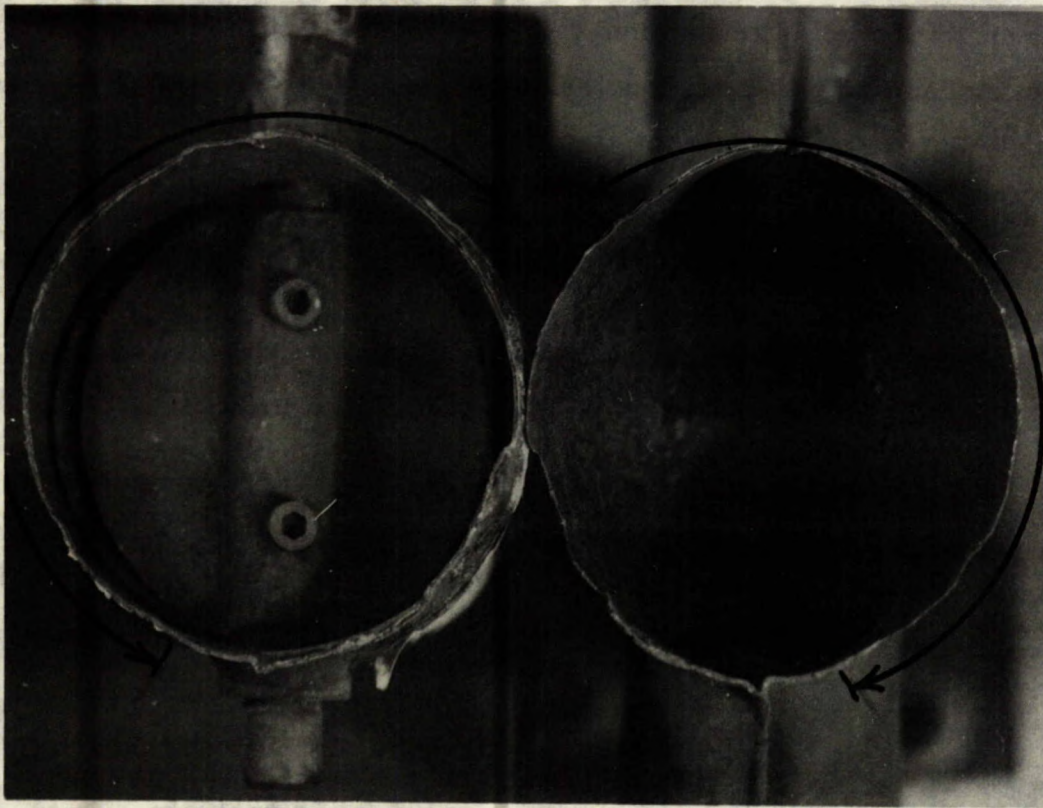


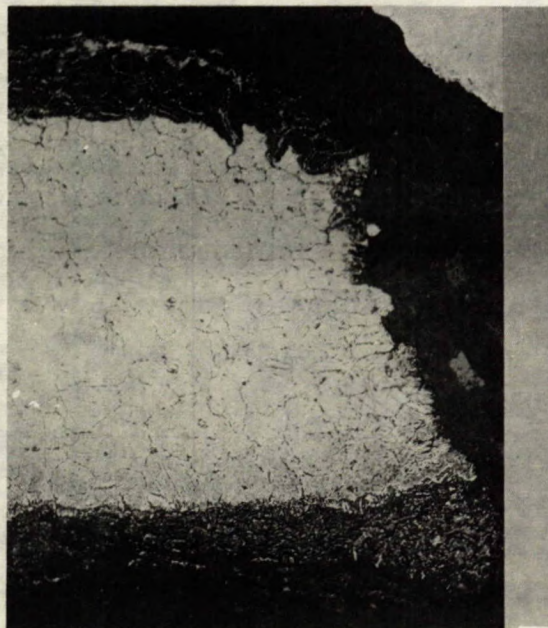
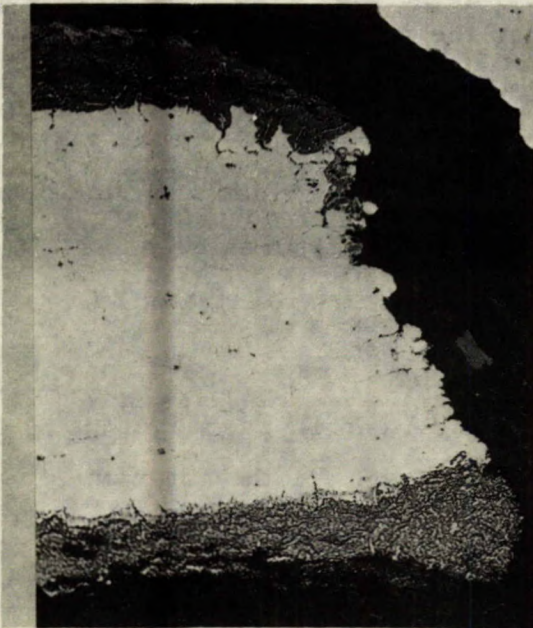
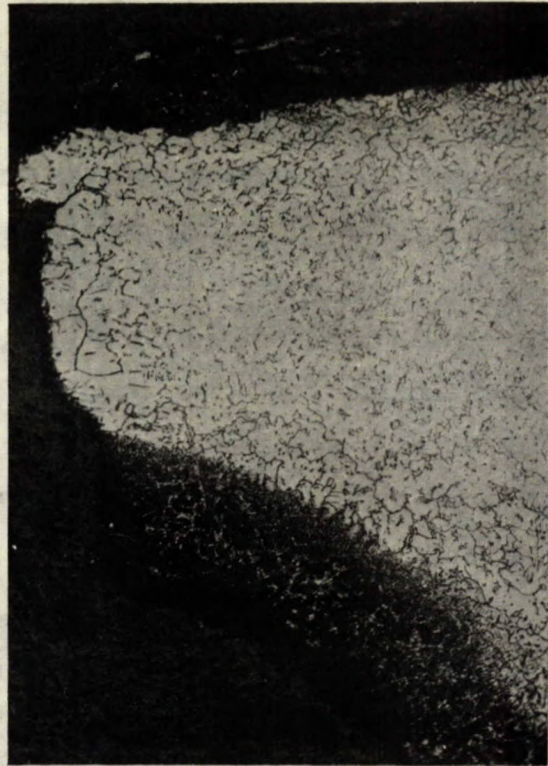
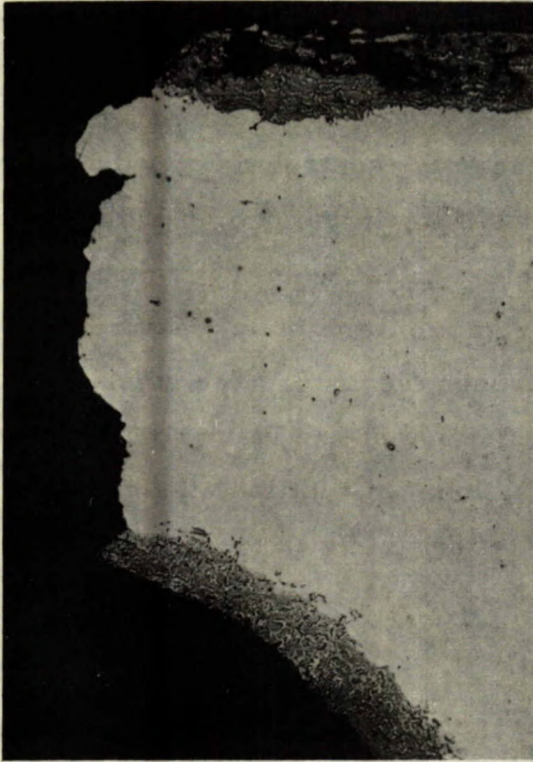
Figure 3 - Showing end view of main fracture. The valve portion is at left and the collector at the right. The arrow indicates the part of the fracture surface which showed low temperature oxidation colours.

In Figure 1 and 2, two small projections can be seen. On the valve portion, the projection was located near the control rod. This projection resulted from a departure of about 1/4 in. in the path of the fracture in the collector from its normal location close to the weld junction. On the collector portion, the projection departed from the main fracture path and extended for approximately 1/2 in. through the weld. The steely blue colouration was most noticeable on the projection on the valve portion, indicating a lower temperature oxide formation. In addition, the change in direction of the fracture path would indicate that this was the last segment to fail.

METALLOGRAPHIC EXAMINATION

Several representative sections were removed from the failed joint and also across the welds which joined the diamond-shaped assembly into the collector. Figures 4A-4D inclusive show two sections cut from the failed joint between the collector and the valve portion from the part of the fracture circumference where no low temperature oxides were indicated by low power microscopic examination (Figure 3). Figures 5A and 5B, at higher magnification, show a portion of the fracture illustrated in Figures 4C and 4D.

The section illustrated in Figures 4A and 4B has a fracture path that appears to be mainly transgranular except for the outer one-third which has a tendency to be intergranular. The fracture path is in the coarse-grained heat affected zone close to the weld fusion line. A "lip" of scale, such as was observed during low-power examination of the fracture face, is evident in Figure 4A. In this unetched view, high temperature oxidation products are apparent on both inner and outer surfaces, but no oxidation is evident on the fracture face. The appearance of this section is reasonably representative also of other sections from the part

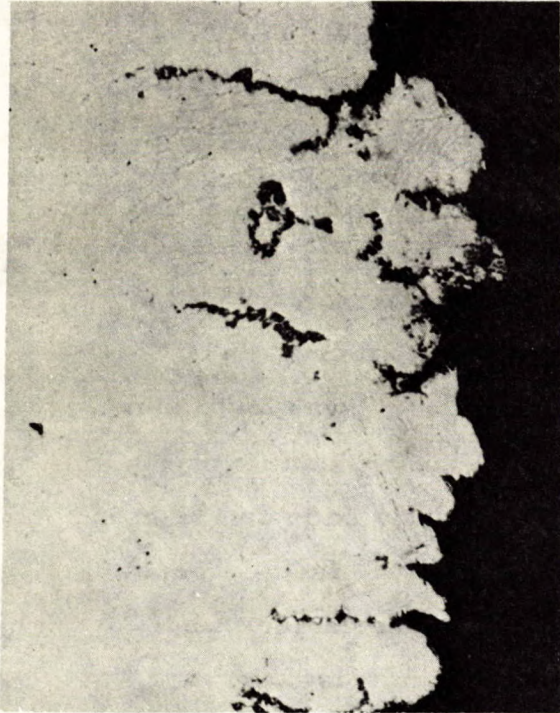


4C

4D

Figures 4A and 4C - as-polished. Figures 4B and 4D - etched electrolytically in 10% Sodium Cyanide. 100X.

Figures 4A-4D - Showing sections through the main fracture which caused separation of the valve portion. In each figure, the weld is to the right of the fracture and the inner surface of the collector is at the bottom of the picture.



5A



5B

Figure 5A - as-polished. X600. Figure 5B - etched electrolytically in 10% Sodium Cyanide. X600.

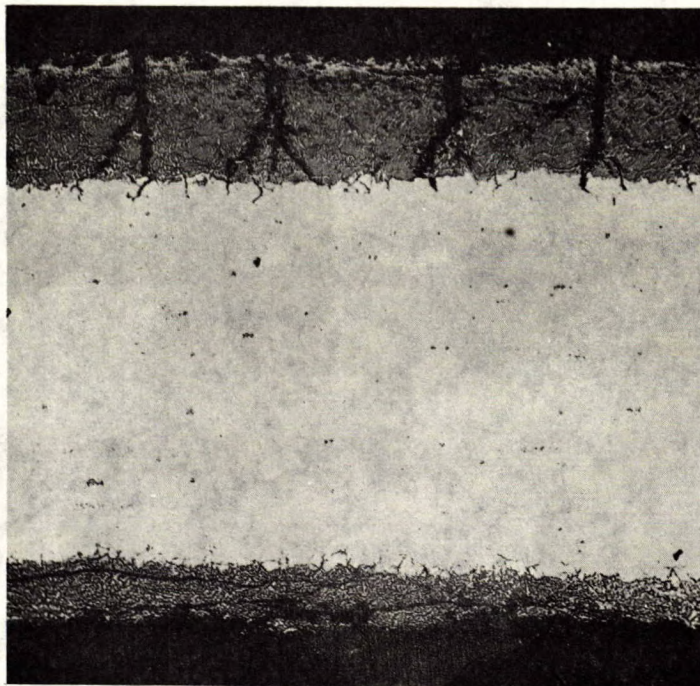
Figures 5A and 5B - Showing a portion of the fracture illustrated in Figures 4C and 4D.

of the circumference of the fracture which showed only low temperature oxidation products (Figure 3).

The fracture path of the section illustrated in Figures 4C, 4D, 5A and 5B is entirely or mainly intergranular. This fracture path was also in the heat-affected zone in the collector but slightly farther from the weld fusion line than in the section shown in Figures 4A and 4B. In addition to the high-temperature oxidation products on the inner and outer surfaces of the collector, a similar product is associated with the fracture face. The low-power microscopic examination indicated more scale on the surface of this fracture than is apparent in the photomicrographs. However, it is believed that some high-temperature scale was lost from the fracture face of the sample shown in Figure 4A during sample preparation. In Figures 5A and 5B, traces of gray to black oxide can be seen extending along grain boundaries inward from the fracture face. These grain boundaries contain precipitated chromium carbides as shown by electrolytic etching in a sodium cyanide solution. Thus it is concluded that the failure at this location was by progressive cracking and oxidation along grain boundaries containing chromium carbide precipitates.

The etched sections shown in Figures 4B and 4D illustrate that there was a significant increase in carbide precipitation towards the inner surfaces of the collector. A similar increase was noted in other sections from the valve portion and from the collector remote from the weld. Figure 5B exhibits more clearly the large amount of carbide particles within the grains and at grain boundaries. The irregular lines, which do not correspond to grain boundary carbide precipitation, are believed to be due to carbide precipitation along slip bands resulting from deformation during manufacture of the collector. Similar irregular lines containing carbides were found in an area including about the inner one-third of the wall in all sections taken from the collector. Except for these slip bands which were not confined to the fracture area, there was little or no evidence of plastic deformation of the fracture surfaces.

Figure 6 shows a section from the collector, taken about 1/2 in. from the severed joint. The heavy coatings on the inner and

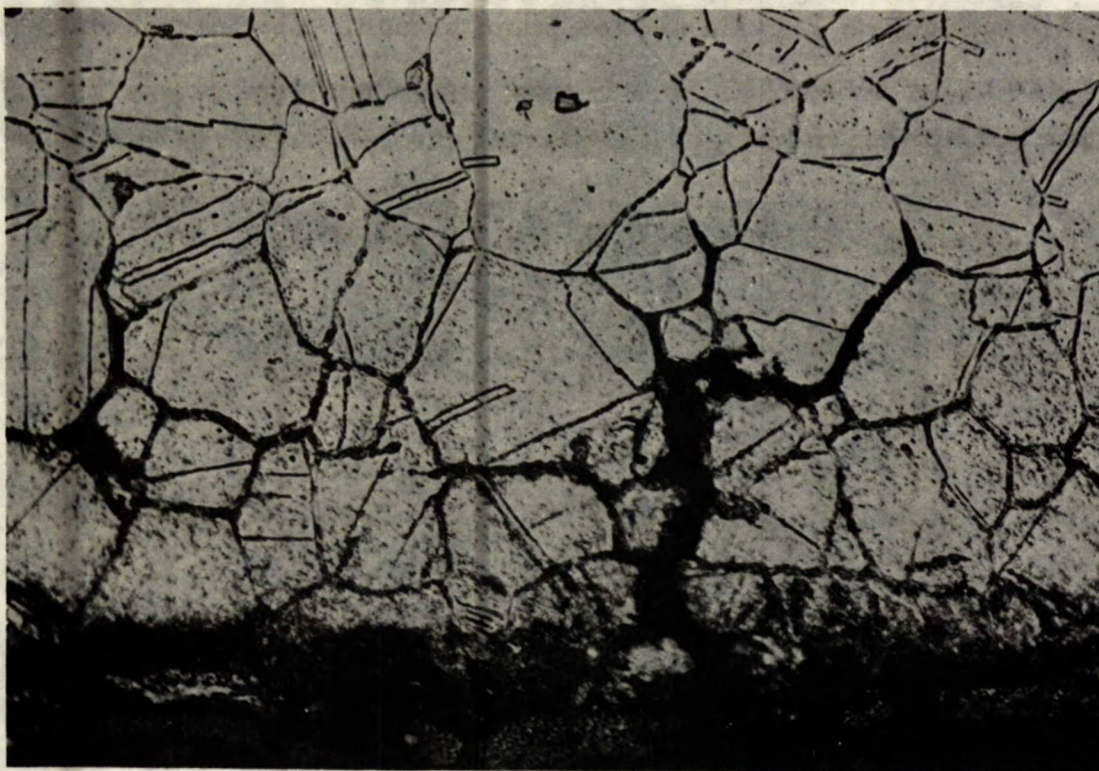


X100

As-polished

Figure 6 - Showing a section through the collector sheet. The inner surface is at the bottom of the picture.

outer surfaces consist chiefly of high-temperature oxide, but contain also smaller amounts of carbides and base metal. In this particular section, several cracks were found which extended through the scale on the outer surface and into the underlying metal. Similar cracking was found at the inner surface in other sections. As shown by Figure 7, the cracks in the underlying metal follow grain boundaries containing precipitated carbides. The cracking is associated with progressive oxidation along these boundaries. Numerous cracks of this nature were found in all sections examined.



X500

Etched electrolytically in 10% sodium cyanide

Figure 7 - Typical appearance at the inner surface of the collector, at the junction of the surface scale with the underlying metal. This sample is remote from the weld.

Special Etching Tests

Etching tests were made on several sections to determine if sigma phase had formed during high temperature oxidation.

The most useful of these etchants for distinguishing sigma phase was the modified Murakamis reagent used boiling for 30 sec. By examining specimens etched in this manner it was observed that a small number of particles of sigma phase were present in the weld and fusion zone of some of the sections but was not evident in others. In addition, the path of the fractures did not appear to follow the sigma phase, where observed, but did follow carbide particles, and in particular those

precipitated at the grain boundaries where oxidation attack was selective.

Chemical Analysis

Sufficient material was obtained from one of the stampings of the collector to permit some chemical analyses to be made. The portion of the collector on which the analyses were made, was first cleaned as thoroughly as possible to remove the scale by means of sand blasting and a rotary wire brushing wheel. Table 1 compares the results of the analyses with the limits specified for the corresponding elements in AISI Type 321 stainless steel, which was said to have been used in the exhaust system.

TABLE 1
Chemical Composition

	Collector*	AISI Type 321
Carbon	0.21	0.08 max
Chromium	17.59	17-19
Nickel	9.62	9-12
Titanium	0.47	5x carbon-minimum

* Internal Report MS-AC-65-119

Except for the carbon level, the collector metal conforms in analysis to AISI Type 321, for the elements compared.

Oxidation Tests

Some tests were carried out to determine if low-temperature oxidation colours, similar to those observed on a portion of the main fracture surfaces, could occur within a few seconds after fracture. Tensile specimens of Type 304 stainless steel were heated by an oxy-acetylene torch in the central portion of the 1/16 in. x 1/2 in. reduced section while being subjected to tensile loading. In individual tests, specimens were heated to various temperature ranges as high as 1500°F. The flame was

withdrawn just before fracture occurred. Oxidation colours ranging from a bronze-pink to purple, and thus matching those found on the main fracture, were observed to form very rapidly on the freshly fractured surfaces.

DISCUSSION

The separation of the valve portion was caused by cracking of the collector wall at or very close to the edge of the weld which joins the thicker wall of the valve portion to it. Except for one very short length, the path of fracture was entirely in the wall of the collector or in the fusion zone of the weld. The cracking around the diamond-shaped inserted assembly, and at the welds joining the mounting flange for the supercharger, was entirely in the collector wall or in the fusion zone of the welds.

Severe intergranular carbide precipitation and some associated oxidation and cracking were found in all micro-sections examined. In one micro-section from the main fracture, intergranular oxidation and cracking had penetrated the collector wall (Figures 4C, 4D, 5A and 5B). At other locations, the cracking was predominantly transgranular with little evidence of progressive oxidation (Figures 4A and 4B). Thus the separation of the valve section from the collector has resulted from both relatively slow intergranular cracking and more rapid transgranular cracking.

Intergranular oxidation and cracking in the collector would be particularly harmful when located at the edge of the weld. At this location, these notches and cracks would be exposed to stress concentration due to the contour of the weld reinforcement. Additionally, greater flexing or stressing would be expected to occur in the collector at this location because the wall thickness of the collector is less than that of the valve portion.

The heavy oxidation of the inner and outer surfaces of the exhaust assembly would be detrimental because of the reduction in effective wall thickness. The most significant reduction would be in the thinner wall of the collector.

An abnormally high carbon level for a Type 321 stainless steel was indicated by both the carbon analysis and the observation of a profusion of carbides adjacent to the inner side of the exhaust assembly. This high carbon level has decreased the amount of chromium available to form protective scale and thus would be expected to increase the tendency for grain boundary oxide penetration and cracking. The marked increase in carbide precipitation adjacent to the inner surfaces of the exhaust assembly suggests exposure to carburizing exhaust gases which would be expected to promote the formation of chromium carbides at service temperatures.

This investigation has shown that the fractured sections were in a severely weakened condition due to oxidation attack and fatigue. This condition would be compatible with a contention that final failure of the valve attachment occurred just prior to the severe landing, thereby resulting in the sudden loss of power described. However, although temper colours observed on the surface of the fracture, and obviously of a very recent nature, are consistent with the assumption of failure in the air immediately prior to the landing, it can be shown by laboratory tests that such oxides can occur in a time brief enough to also be consistent with final fracture of the hot assembly at the time of impact. Some very small portions of the fracture surface might have failed after the impact of the landing. However, the absence of evidence of high-temperature impact or tearing on the surfaces of the fracture further supports the occurrence of complete or almost complete failure prior to contact with the ground.

CONCLUSIONS

- (1) Progressive cracking through the collector wall, either in the fusion zone of the weld or immediately adjacent to the weld, was the predominant cause of separation of the gate valve portion.

- (2) Progressive cracking was initiated at the junction of welds with the collector by the development of intergranular oxidation and cracking which followed grain boundaries containing precipitated chromium carbides.
- (3) An abnormally high level of carbon in the collector related to carbon enrichment at the inner surfaces, would be expected to increase the tendency for intergranular carbide precipitation followed by progressive oxidation and cracking.
- (4) Failure through the collector wall was caused by both progressive intergranular oxidation and cracking along grain boundaries and by transgranular cracking typical of fatigue failure.
- (5) The loss of power described by D. O. T. which occurred just prior to the severe landing would be consistent with the timing and evidence of complete or almost complete separation of the valve portion just prior to impact.