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I-10987 Doc. 1721-3

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Report Covering Examination of Parts From Downhole Steam Generators

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Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of Energy
under Contract DE-AC04-76DP00789

Printed August 1983

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Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
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REPORT COVERING EXAMINATION OF PARTS FROM DOWNHOLE STEAM GENERATORS

for

Sandia National Laboratories
Albuquerque, NM 87185

Contract 37-1057

by

F. S. Pettit
and
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Pittsburgh, PA 15261

ABSTRACT

Combustor head and sleeve parts were examined by using optical and scanning electron metallography after use in oxygen/diesel and air/diesel downhole steam generators. The degradation of the different alloy components is described in terms of reactions with oxygen, sulfur and carbon in the presence of cyclic stresses, all generated by the combustion process. Recommendations are presented for component materials (alloys and coatings) to extend component lives in the downhole steam generators.

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INTRODUCTION

The following combustor head and sleeve parts were obtained after use in the oxygen/diesel (O/D) and air/diesel (A/D) downhole steam generators tested at Long Beach, CA.^{1,2}

TABLE I. Parts Examined From Steam Generators

<u>PART NAME</u>	<u>PART NUMBER</u>	<u>MATERIAL</u>	<u>TIME IN GENERATOR</u> <u>(HRS)</u>
<u>Oxygen/Diesel</u>			
Combustor Inner Sleeves:			
Ribbed, thick design	1	IN 625	122.5
Smooth, thin design	7	IN 625	281
Ribbed, thick design	5	310 SS	167.8
Smooth, thin design	9	310 SS	366.5
Ribbed, thick design	6	Hastelloy X with CoCrAlY coating	186
Injector	11	316 SS	281
Injector	12	316 SS	366.5
<u>Air/Diesel</u>			
Combustor Head	14	310 SS	1934
Combustor Inner Sleeve	13	310 SS	1934

All of these parts were examined and studied to determine the mechanisms by which these materials degraded and to make recommendations for extending the lives of hardware in the combustor sections of downhole steam generators. The techniques used in these studies consisted of:

Visual examination of the hardware using optical metallography.

Cutting of sections from the hardware, metallographically polishing and examining the prepared sections using optical metallography and scanning electron microscopy.

X-ray diffraction analyses of corrosion products removed from the surface of the hardware.

In the following sections of this report, results obtained from these analyses are presented and discussed. Mechanisms describing the degradation of the various materials are developed. Finally, recommendations are made for extending the lives of hardware in the combustion section of downhole steam generators.

RESULTS AND DISCUSSION

The results will be presented following the sequence by which the parts were identified in the Introduction to this report.

IN 625 O/D Sleeves No's. 1 & 7

Visual examination of the surfaces exposed to the combustion environment of both sleeves showed an "orange peel" texture, Figure 1. These features were not uniform indicating some asymmetry in the burning of fuel in, or the cooling of, the combustor. Five metallographic sections were taken from one sleeve and three from the other. It was observed that the thicknesses of the sleeves were generally less than the as-machined values. This thickness reduction was most apparent in sections taken at the lower end of the sleeve and became less significant as sections were taken proceeding towards the combustor head. Thickness values for sleeve #1 are presented in Table II.

TABLE II. Sleeve #1 Wall Thicknesses*

	<u>Section</u>	<u>cm</u>
Combustor Head	A	0.30
	B	0.38
	C	0.35
	D	0.40
	E	0.41

* Initial wall thickness as per drawing: 0.38 cm. The measured sleeve wall thicknesses greater than the initial thickness are believed to result from errors in measuring the wall thicknesses and the presence of deposits on the inner sleeves.

Optical and scanning electron metallography of mounted sections from the IN 625 sleeves showed a variety of microstructural features. Some portions exhibited very little evidence of the corrosion process even though it was obvious that the sleeve thickness had been reduced, whereas others had zones containing many corrosion products. Both sleeves contained cracks but the cracks were much more prevalent in the thin sleeve (#7).

Some of the important microstructural features observed in sleeve #1 are presented in Figures 2-5. A portion of the surface of this sleeve is shown in Figure 2a. It can be seen that a rather large amount of corrosion product is evident in some areas but not others. More detailed examination of the zones with corrosion products revealed oxide and sulfide phases (Figures 2b and 3). The inner part of these zones usually contained chromium sulfide particles whereas the outer zone, adjacent to the combustion environment, contained chromium oxide along with what appeared to be molybdenum and nickel sulfides. In the portions of the surface where large amounts of corrosion product were not readily apparent (Figure 2a), close examination showed that a number of zones had developed immediately adjacent to the alloy surface (Figure 4). The zone deepest in the alloy appeared to be a carbide zone that had formed along grain boundaries of the alloy. It is possible that this phase could be a metallic phase (e.g., sigma phase) that forms as a result of precipitation of the sulfides in the intermediate zone. As the surface of the alloy was approached it appeared that sulfides and eventually oxides were present. Such a microstructure indicates that sulfur and oxygen, and probably carbon, were present in the combustion environment. Since carbides generally are less stable than sulfides or oxides, the carbide zone can only exist deep in the alloy where the oxygen and sulfur activities are low. The sulfide zone occupies a position between the carbide and oxide zones because the stability of sulfides usually is less than oxides but greater than carbides. The cracking which was observed in sleeve #1 almost always was found associated with the corrosion product as shown in Figure 5.

Some of the important microstructural features observed in sleeve #7 are presented in Figures 6 and 7. Sulfide phases were not readily apparent in sections taken from this sleeve. On the other hand, a network of carbides was evident at grain boundaries of the alloy extending into the alloy from the surface exposed to the combustion environment (Figure 6a). It appeared that this carbide phase, or the alloy immediately adjacent to it, was preferentially oxidized which resulted in intergranular oxidation of the sleeve (Figure 6b). In addition to the corrosion products, numerous cracks were evident in the specimens taken from this sleeve (Figure 7). It was difficult to discern whether the alloy cracked because of the corrosion products or if cracking took place first. All cracks were filled with oxides and numerous corrosion products were evident with no cracking. It therefore appears that corrosion took place first and the cracking occurred subsequently at those locations where corrosion products were formed.

The microstructural features which have been observed in the IN 625 sleeve indicate that the combustion environment establishes sulfur, carbon and oxygen activities over the alloy. Moreover the composition of this environment appears to vary with time and the oxygen pressure always is relatively low. The composition* of IN 625 is Ni-22Cr-9Mo-4Cb-0.2Al-0.2Ti-3Fe-1.5Mn-0.3Si-0.05C. This alloy develops resistance to oxidation by forming a continuous layer of Cr_2O_3 upon its surface. In the environment of the oxygen/diesel combustor the low and fluctuating oxygen pressure can result in sulfide and/or carbide formation in the alloy. Subsequent oxidation of these sulfide and carbide phases results in reaction product barriers which are not as protective as when oxide scales are formed directly. Hence, the alloy is degraded at a much more rapid rate than would have occurred had there been no sulfide or carbide phases formed in the alloy. Finally there is evidence that the inner surface of these sleeves has been subjected to stresses which result in cracking of the alloy at those areas where corrosion products (i.e., oxides, sulfides,

* All compositions are given in weight percent.

carbides) existed in the alloy.

The proposed development of stresses in the combustion sleeves is not surprising. Combustion processes are not uniform and the sleeve will be at different temperatures at different points over its surface. Furthermore, this temperature distribution will change with time. Consequently the sleeve surface will be subjected to cyclic, thermally induced stresses. Such stresses are not uncommon in burner liners used in the combustors of gas turbines³ and cracking is often an important mode of material degradation in these liners.

310 SS O/D Sleeves No's. 5 & 9

Visual examination of the 310 SS sleeves also showed an orange peel texture rather similar to that observed on the IN 625 sleeves (Figure 1). In addition, the thicknesses of the sleeves were significantly reduced below the as-machined values as shown in Table III.

TABLE III. Sleeve #5 Wall Thicknesses*

	<u>Section</u>	<u>cm</u>
Combustor Head	A	0.31
	B	0.29
	C	0.29
	D	0.30
	E	0.35

The microstructural features of both sleeves were very similar. Both contained numerous cracks and in some cases the cracks extended completely through the sleeve wall thickness, as is evident in Figure 8a. These cracks were almost always filled with corrosion products as can be seen in Figure 8b. The corrosion products appeared to be oxides of chromium and iron but sulfur was also detected in the corrosion products immediately adjacent to the unaffected alloy, as indicated in Figure 9. Cracking in the 310 SS was intergranular (Figure 10a). In many of the sleeve specimens examined, a zone of what appeared to be chromium carbides was observed adjacent to the surface that had

* Initial wall thickness as per drawing: 0.38 cm.

been exposed to the combustion environment (Figure 10b). It appeared that oxidation of this carbide network resulted in grains of the alloy becoming completely enveloped by oxide (Figure 11). Such a condition caused these grains to be removed from the alloy and reduced the wall thicknesses of the sleeves. It is possible that the cracking of the 310 SS sleeves, which was more severe than in the IN 625, may have been caused by the network of oxides that formed due to oxidation of the alloy in those areas where carbide phases had been initially present.

It is well documented that stainless steels are susceptible to intergranular corrosion due to the formation of chromium carbides at the grain boundaries.⁴ The precipitation of these carbides depletes the alloy of chromium adjacent to the grain boundaries and hence more rapid oxidation occurs at the grain boundaries relative to the bulk grains since continuous layers of Cr_2O_3 cannot be formed. The composition of 310 SS is Fe-25Cr-20Ni-2Mn-1.5Si-0.25C and a Cr_2O_3 scale provides protection against oxidation. It is also well documented that stainless steels are susceptible to stress corrosion cracking⁵ where small amounts of certain elements such as chlorine can sensitize the alloys and cause them to be vulnerable to stress corrosion cracking. Results from examining the 310 SS sleeves clearly show that such alloys should not be used as combustor sleeves due to the formation of cracks. These data are not sufficient, however, to identify unequivocally the cause of these cracks. It seems likely that they were caused by the cyclic stresses generated during the combustion process. The stresses could have caused cracking due to the network of carbides and oxides formed at the grain boundaries or the alloy could have been sensitized to cracking due to the presence of sulfur or some other element (e.g., chlorine, hydrogen) in the combustion atmosphere.

CoCrAlY Coated Hastelloy X O/D Sleeve No. 6

Visual examination of the CoCrAlY coated Hastelloy X sleeve showed very substantial attack with the sleeve totally consumed in one area. Examination

of sections through this sleeve showed that a relatively thick deposit had been formed on this sleeve (Figure 12a) and that the CoCrAlY coating had spalled from the Hastelloy X sleeve in many areas (Figure 12a). The CoCrAlY coating that remained contained much oxide intermixed with it (Figure 12b). The microstructural features of the coating were typical of a plasma sprayed coating that was deposited using a technique which resulted in a substantial amount of oxidation. Such a condition is not unusual for fabrication of this coating while not taking precautions to avoid oxidation during processing. It therefore appears that the CoCrAlY was not necessarily degraded due to the environment, but spalled from the Hastelloy X and therefore did not provide any protection. Significantly better protection could be expected from a higher quality coating.

The deposit which accumulated on the surface of this sleeve is shown in more detail in Figure 13. It was found to contain Si, Mg and Al. It is believed that this deposit is due to impurities in the water that was used to emulsify the fuel in the oxygen/diesel steam generator.

Microstructural features observed from examination of the Hastelloy X that had been exposed by spalling of the CoCrAlY coating are presented in Figures 14-16. Substantial amounts of attack were evident, as shown in Figure 14a, and detailed examination of this corrosion product showed that it was composed of a mixture of oxide and sulfides (Figure 14b). Somewhat different microstructures were observed in other areas of the Hastelloy X sleeve. In particular, some areas contained fewer sulfides with an oxide scale that was rich in molybdenum adjacent to the alloy (Figure 15a). In other regions, nickel sulfide also appeared to have been formed (Figure 15b).

Hastelloy X has the composition Ni-22Cr-9Mo-1.5Co. During oxidation it normally develops resistance to attack by the formation of a continuous scale of Cr_2O_3 . The results obtained in the present analyses show that it is being degraded similarly to IN 625; namely, sulfides, and perhaps carbides, are being formed which do not permit a continuous layer of Cr_2O_3 to be

developed. Since this alloy contains a substantial amount of molybdenum, it is also susceptible to degradation due to MoO_3 formation. Normally this type of attack is observed when the molybdenum in the alloy begins to be oxidized and is commonly observed during hot corrosion attack.⁶ It appears that the combined sulfidation-oxidation of this alloy has caused the molybdenum to be oxidized and this has resulted in even more rapid degradation and hence complete consumption of the sleeve in some areas. It is to be noted that the degradation of Hastelloy X resulting from the combined sulfidation-oxidation has been severe enough to make this alloy unacceptable for use as a combustor sleeve even without the adverse effects produced by the molybdenum.

Cracking was generally not evident on the CoCrAlY-coated Hastelloy X sleeve. On those portions of the sleeve where the CoCrAlY coating had not spalled no cracks could be detected (Figure 12b). In those areas where the coating had spalled, however, a few cracks were detected in the Hastelloy X, as shown in Figure 16. These results suggest that the observed cracking may have been caused by the corrosion process. In particular, corrosion products (e.g., oxides, sulfides, carbides) are formed in this alloy which permit cracks to develop under the action of the thermally induced cyclic stresses.

316 SS O/D Injectors No's. 11 & 12

Metallographic examination of the two injectors showed that these components had been attacked only at their tips where the injectors coincided with the plane of the combustor head surface. The attack was confined to those areas near the E-beam welds and also was observed extending a short distance up the external surface of the outer tube of the assembly, as indicated in Figure 17. This attack did not involve a large amount of corrosion but many cracks were evident, as shown in Figure 18. The cracking appeared to be intergranular (Figure 19). It was not conclusively established that carbides or sulfides were present in this alloy in advance of the cracks.

The composition of 316 SS is Fe-17Cr-12Ni-2.5Mo-2Mn-1Si-0.08C. In view of the lower chromium content than 310 SS, it should be a poorer Cr_2O_3 -former

than 310 SS. The mode of degradation of the 316 SS injectors appears to be similar to the 310 SS combustor sleeves, namely, excessive cracking due to the cyclic stresses and the presence of corrosion products (i.e., formation of oxides-sulfides-carbides or sensitization). The degradation of the injectors is less severe than the 310 SS combustor sleeves. This is probably due to the development of less severe operating conditions in the vicinity of the injectors, compared to the combustor sleeves, as opposed to the 316 SS alloy being more resistant to the type of degradation that has been observed.

310 SS A/D Sleeve and Head, No's. 13 & 14

Both the combustor head and sleeve from the air/diesel generator exhibited features very similar to the 310 SS sleeves from the oxygen/diesel unit. Numerous cracks were evident and carbide networks were detected in the alloy surface that had been exposed to the combustion environments (Figures 20 and 22). It is believed that the 310 SS sleeves were degraded by the same mechanisms in both the oxygen/diesel and air/diesel systems. Cracks were evident (Figure 20) and portions of the alloy were totally enveloped with corrosion product (Figures 20 and 21). When specimens were etched, the attack was seen to be intergranular and networks of carbides were observed in the alloy (Figure 22). It was observed that the number of cracks in the sleeve from the air/diesel combustor was significantly less than that in sleeves from the oxygen/diesel. This was the case even though the sleeve from the air/diesel had much more operating time than those from the oxygen/diesel. Such results suggest that the operating conditions of the air/diesel, while similar to those of the oxygen/diesel, are not as severe.

CONCLUSIONS

The results which have been obtained from examination of components from the oxygen and air downhole steam generators permit the following conclusions to be formulated.

1. The gas environment in the combustor is characterized by low oxygen

pressures accompanied by significant activities of sulfur and carbon.

2. The composition of this gas atmosphere fluctuates with time and position over the combustor surface.
3. Deposits on the surfaces of some of the combustor parts are believed to be formed due to impurities in the fuel, air and water. The formation of deposits on the combustor sleeves is not believed to be necessary for degradation of the alloys, but the deposits will aggravate the situation.
4. The temperature of the combustor sleeves adjacent to the combustion gases, as well as some portions of the injectors, is sufficient to result in a significant amount of reaction between the alloys used for these components and the combustion gases.
5. This reaction is typical of that observed in gases containing low oxygen pressures and significant pressures or activities of other reactive elements (e.g., sulfur, carbon).^{7,8} In particular, zones containing carbides, sulfides and oxides are formed in the alloys immediately beneath the surfaces exposed to the combustion gases. These phases are distributed sequentially in the alloys with the carbides deepest in the alloy and the oxides at the surfaces of the alloys. The formation of the carbide and/or sulfide phases results in the development of less protective oxide barriers and hence more rapid corrosion of the alloys. Since the composition of the combustion gases is not constant, all three corrosion products, two products, or only one product can exist in the surface regions of the alloys exposed to the combustion gases at any given exposure time.
6. The combustor sleeves, as well as probably the injector surfaces, are subjected to significant temperature fluctuations which cause cyclic stresses to be established over the surface of these components.
7. The combined cyclic stresses and corrosion products result in cracking of the alloys. This cracking is by and large

intergranular. It consists of both large and small cracks. The large cracks are more or less evenly spaced which gives rise to the orange peel texture that is a common feature observed on the surfaces of the combustor sleeves. The smaller cracks undercut individual grains of alloy and result in very substantial metal recession rates.

RECOMMENDATIONS

Based upon the conclusions which have been presented previously, in order to obtain increased lives of components used in downhole steam generators it is necessary to prevent the reactants in the combustion gas, other than oxygen, from reacting with or gaining access to the alloy. Such conditions can be achieved by utilizing alloys upon which continuous oxide scales are formed that prevent, or inhibit, the ingress of other reactants in the combustion gases. Oxide scales such as alumina have been found to be the most effective in producing such a condition. In addition, it is also necessary to use alloys that will form the least deleterious phases when, or if, these other reactants gain access to the alloy. It has been found that nickel can combine with sulfur to form an especially deleterious phase with regard to corrosion resistance. Finally, since the observed combustion environment is severe, it is also necessary to attempt to avoid the use of elements in the alloys such as molybdenum which can form liquid oxide phases. In view of these considerations, the following recommendations are proposed to attempt to obtain components with increased lives in the downhole steam generators:

1. The use of stainless steels should be avoided. The tendency of these alloys to crack under the combined influence of stress and formation of corrosion products (carbides, sulfides, and oxides) makes them unacceptable for long term use even when general surface recession due to corrosion is not significant.
2. Cobalt-base and iron-base alloys should be used in preference to nickel-base alloys because of the tendency of nickel to form sulfides

which are particularly deleterious to corrosion resistance.

3. If Cr_2O_3 -forming alloys are to be used, the Cr content should be as high as is feasible to improve the ability of the alloy to develop and maintain a protective Cr_2O_3 scale.
4. The refractory metal (Mo, W, Nb, etc.) content of the alloy should be minimized to avoid the formation of deleterious phases such as MoO_3 , WO_3 , etc.
5. Consideration should be given to the use of Al_2O_3 -forming alloys since Al_2O_3 scales have been shown to provide good resistance to mixed oxidant corrosion in such applications as coal gasification atmospheres. The most convenient application of Al_2O_3 formers would be in the forms of CoCrAlY or FeCrAlY coatings or claddings. It should be noted that the severe degradation of CoCrAlY-coated Hastelloy X in the present study is believed due to the spalling of a poor quality coating. In regions where the coating remained adherent it provided good protection despite its poor quality. Therefore, the consideration of using high-quality CoCrAlY or FeCrAlY coatings or claddings is highly recommended.
6. The construction of components from a dispersion strengthened FeCrAl- Y_2O_3 alloy, such as MA 956, might be considered as a means to obtain an Al_2O_3 -forming system without coating.
7. The use of a thermal barrier coating such as Y_2O_3 - or MgO-stabilized ZrO_2 to lower the metal surface temperature would prolong the life of any of the above recommended systems. Such coatings have been useful in combustion liners in gas turbines where thermally induced cyclic stresses play an important role in the degradation of alloys.
8. The use of fuel additives to lessen the corrosive nature of the environment should be considered. Additives containing chromium (Turbogard, United Technologies Corp.) can be used to attempt to

inhibit effects of sodium and sulfur in deposits. Additives with magnesium⁹ can be used to attempt to inhibit corrosion caused by vanadium in fuels.

9. Experience with gas turbines has shown that following a certain set of operational procedures can lead to extended lives of components. In the case of downhole steam generators the attack of the sleeves should be significantly affected by the oxygen pressure. The adverse effects produced by sulfur and carbon become more pronounced as the oxygen pressure is decreased. It is possible that unburned fuel may be deposited on sleeves during startup (prior to ignition) or shutdown. As this excess fuel burns the conditions are suitable for sulfur and carbon to enter alloy. Hence procedures to attempt to prevent deposition of unburned fuel could significantly extend the lives of combustion sleeves.

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7. IN625 "THIN" SLEEVE: 281 HOURS,
FAILED SWIRLER, WELD REPAIR
ATTEMPTED, NOT FUNCTIONAL

Figure 1. Photograph showing IN 625 combustor sleeve #7 after 281 hours of operation in the oxygen/diesel downhole steam generator. An orange peel texture (arrow) was evident on the surface of this sleeve that has been exposed to the combustion gases.

(a)

(b)

Figure 2. Photographs of a section taken through combustor sleeve #1 showing the surface adjacent to the combustion gases. (a) The corrosion products were not uniformly distributed over the surface of the sleeve. A large amount of attack is evident in some areas but in others (white arrow) no attack is evident at low magnifications. (b) When corrosion products were evident it was not unusual to detect zones in the corrosion products. (The black arrows indicate the interface between the two zones in both photographs.)

Figure 3. Photograph (upper) and x-ray image for sulfur (lower) of the specimen discussed in Figure 2.

(a)

(b)

Figure 4. Two photographs of the IN 625 specimen described in Figure 2 showing features in an area that was not substantially attacked. (a) Lower magnification photograph. (b) Higher magnification showing an outer oxidation zone, an intermediate zone of sulfides and an innermost zone of either carbides or a phase formed as a result of reaction of some elements in the alloy with the sulfur.

Figure 5. Photomicrograph of cracks in corrosion product formed on IN 625 (sleeve #1).

(a)

(b)

Figure 6. Photomicrographs of IN 625 (sleeve #7). (a) A network of carbides at grain boundaries and an intergranular crack is evident. (b) Intergranular oxidation and cracking is apparent at the surface of the sleeve adjacent to the combustion gases.

Figure 7. Large cracks were formed at the surface of IN 625 (sleeve #7) adjacent to the combustion gases and smaller cracks formed at the bottoms of the larger cracks. These two photographs show two large cracks at different areas of sleeve #7 with smaller cracks emanating (arrows) from the larger cracks.

(a)

(b)

Figure 8. (a) Micrograph of section through 310 SS combustor sleeve (#5) which shows cracks completely through the wall of the sleeve. (b) Another photograph of this sleeve shows cracks filled with corrosion products.

Figure 9. Photomicrograph of 310 SS combustor sleeve (#5) showing cracks and EDAX results for the corrosion products in one of these cracks.

Figure 10. Photomicrographs of 310 SS (sleeve #5). (a) Etched specimen showing intergranular nature of cracking. (b) Photograph showing carbon enriched zone at surface adjacent to the combustion gases.

Figure 11. Photomicrograph showing grains of 310 SS (sleeve #5) completely enveloped by oxidation products.

Figure 12. Photomicrographs of CoCrAlY-coated Hastelloy X (#6) after 186 hours in the oxygen/diesel combustor. (a) Photograph showing the alloy, coating and a deposit. (b) Photograph of the CoCrAlY coating.

Figure 13. Photograph of the deposit which developed on the CoCrAlY-coated Hastelloy X during use in the oxygen/diesel combustor.

(a)

(b)

Figure 14. Photomicrographs showing the corrosion products that formed on the Hastelloy X alloy after the coating had spalled. The attack was extensive but nonuniform, (a), and the corrosion product was composed of a mixture of oxides and sulfides, (b).

(a)

(b)

Figure 15. Photomicrographs showing additional features of the corrosion products that were formed on the Hastelloy X alloy described in Figure 14. In some areas molybdenum was detected in the oxide scale, (a), and preferential attack was observed along with the formation of sulfides of nickel and perhaps molybdenum.

Figure 16. Photomicrograph showing cracks in the Hastelloy X at a location where the CoCrAlY coating had spalled and attack similar to that described in Figures 14 and 15 had taken place.

Figure 17. Sketch of injector (#11 and #12) which shows the location of cracking and oxidation of this component.

Figure 18. Photomicrographs showing cracks in oxygen/diesel injector #12.

Figure 19. Photomicrograph of etched section of the injector shown in Figure 18. The cracking appears to be intergranular.

Figure 20. Photomicrographs showing cracks (arrows) and grains of alloy undercut with corrosion product in 310 SS combustor sleeve after 1934 hours in the air/diesel combustor.

Figure 21. Same sections as described in Figure 20 where these photographs show grains of alloy undercut by corrosion product.

Figure 22. Photomicrograph of etched section from 310 SS sleeve described in Figure 20. It can be seen that the attack is intergranular and follows a network of carbides in the alloy.

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