CORROSION PROBLEMS IN TURBINES

by
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INTRODUCTION

Gas turbines have been experiencing hot corrosion problems for over 25 years. These problems comprise two main types: vanadium attack and sulfidation. This paper deals with the problem of sulfidation corrosion, a name which is not accurately descriptive, as will be seen.

In line with the philosophy of the 2nd Turbomachinery Symposium. the scope of this paper will be aimed at presenting one particular experience of the author: the problems undergone by a Westinghouse W-191-G gas turbine installed in the Tachira Plant of C.A. de Administracion y Fomento Electrico (CADAFE) located in La Fria. Tachira State, Venezuela, near the Colombian border.

No attempt will be made to delve into the purely theoretical or mathematical aspects of the problem, but concurrently with the analysis of the different aspects of the problem. the necessary theoretical background will be mentioned to support our reasoning and observations.

The W-191-G Westinghouse single shaft unit under consideration is a package plant with the following operating conditions: 14.5 MW rated capacity and 15.64 MW peaking capaciy using natural gas, and 14.25 MW rated capacity and 15.37 MW maximum capacity with liquid fuel No. 2 measured at 305 ft. (93 .m.) altitude with a barometric pressure range of 1008 to 1016 milibars and an ambient temperature range of 61° F to 82° F (16 to 28° C) in the La Fria location. The rated speed of the unit is 4912 RPM gear reduced to 3600 RMP. The 15-stage axial compressor has a 6.9 pressure ratio and 231 lb/sec airflow. The 5-stage turbine is of the reaction type.

The turbine inlet temperature is 1450°F (788°C) as base load and 1500°F (816°C) peak and the turbine exhaust temperature is 728°F (417°C) base and 812°F (433°C) peak.

After 22,312 hours of operation with 52.7% average load factor and using fuel oil No. 2 most of the time, this unit suffered the catastrophic effects of hot corrosion in its diaphragms and blades which required the reconditioning of the first three stages and cleaning of the fourth one at an appreciable cost. Concurrently, this unit also experienced considerable fouling of its axial compressor.

TECHNICAL CONSIDERATIONS OF HOT CORROSION

The fouling and corrosion of turbines almost always go hand in hand, but they do not necessarily have to be present at the same time. Cases have been known in which the blades have heavy deposits without corrosion taking place and conversely, cases where the deposits are light but the corrosion is quite severe.

The fouling of the turbine blades results in an output and efficiency drop although to a lesser extent than when resulting from compressor fouling. Compressor fouling causes a temperature rise at the compressor outlet, while turbine fouling produces an exhaust temperature rise resulting in a change in the fuel quantity. Depending upon the installation, the thermal efficiency deterioration is approximately parallel to the output drop or nearly half (1).*

The increased roughness and profile thickening caused by the corrosion of blades are responsible for the efficiency reduction. It has been shown (2) that efficiency deterioration due to surface roughness is not greatly influenced by the speed of the machine or by the type of blading used (impulse or reaction).

In particular, efficiency is greatly dependent upon the surface roughness. The influence of the profile change due to deposits on efficiency reduction is less marked, as it amounts to only 20 to 30% of the total measured effects of the rough layer.

It has been observed (1) that even with the same fuel, not all gas turbines suffer equally from fouling and corrosion.

The frequent starts and stops of the units tend to reduce the average increase of fouling due to the fact that every time the unit stops, a certain amount of the deposits over the blades is loosened due to thermal shock. In some instances (3) this has been translated into an output recovery.

The hot corrosion mechanism is not yet fully understood and there is considerable controversy on the subject. Some theories have been postulated (4) but they but the lowest amounts according to Sims (11), while it is reported to have a beneficial effect on hot corrosion according to others (5) (7).

(4) *Titanium,* which for some is innocuous up to about 8% (11) and is beneficial according to others (7).

(e) Since high creep resistance is not strictly compatible with high corrosion resistance, it is sometimes customary to use protective layers of non-corrosive material. The W-191-G units have no protective layers of this type and recent studies (5) seem to indicate that their use has not been successful, or that they are unlikely to provide a permanent safeguard (6).

do not seem to explain fully all the problems being experienced.

It is generally accepted that the phenomenon of deposit formation and/or catastrophic corrosion takes place in the presence of a reactive residue, generally of a low melting point. This residue may have its origin only in the fuel components or in the combination of the fuel components and ambient conditions. For instance, in the centrifuge side of Las Morochas plant, which is located on the South shore of Lake Maracaibo, where a twin W-191-G is used, burning No. 2 fuel, 0.85% by weight of SiO_2 and 9.32% of FeO_3, which are erosive matters, were found.

Sulfidation corrosion is a form of hot corrosion which frequently occurs in gas turbines burning residual fuels where the ambient effect may or may not be a contributing factor. But the most significant aspect of sulfidation corrosion is that it may also be a problem when commercial fuels of better purity are used, as in the Tachira Plant, where No. 2 fuel is burned. In this case, the ambient contribution, i.e., the alkali material, is extremely important in order for corrosion to take place.

It is generally accepted that the sulfur of the fuel combines with the alkali material ingested from the environment to produce a reactive residue which contains alkaline sulfates. This combustion residue is deposited in a molten state and subsequently accumulates over the turbine blades, where it reacts with the protective oxide layer which normally covers this surface and destroys it. Much has yet to be learned about this last process (5). However, it appears that under the scale thus formed the sulfur is now capable of effectively diffusing in the basic metal, thus initiating an accelerated reaction of oxidation-corrosion. This reaction seems to be controlled by the chromium depletion of the basic metal by means of the formation of chromium sulfides (Cr_2S_3). The elimination of chromium makes the basic metal less resistant to oxidation.

Confirmation has been given (6) that sulfur is responsible for the high temperature attack by reacting with the alloying element chromium, forming sulfide, and three deleterious effects have been ascribed to this chromium sulfide formation:

1. The remaining matrix scaling resistance is reduced by the severe chromium depletion.

2. An autocatalytic continuation of sulfide formation occurs due to the preferential oxidation (striations) of the chromium sulfide, which again liberates sulfur (7).

3. When extreme chromium depletion takes place, the remaining nickel reacts with sulfur to form sulfides of a lower melting point, causing pronounced acceleration of corrosion.

Sulfur content as low as 0.05% by weight in a distillate fuel is more than adequate to initiate the sulfidation corrosion. Salt water spray or the crystals transported by the wind from marine environments are the most common sources of alkali matter.

Similarly, it is also known that the contamination of high-quality fuels by sea water has resulted in sulfidation corrosion. This alkali matter source can effectively be reduced by means of appropriate maintenance of storage tanks and by filtration and purification of the fuel. However, it must be pointed out that the Tachira Plant under scrutiny is an inland installation. The filtration of alkali particles from the air ingested by the turbine is, however, a major engineering consideration although it may not be feasible for many applications for reasons of cost and size requirements.

According to some investigations (8), nickel-base alloys with a chromium content of 15% or less are particularly sensitive to sulfidation corrosion. According to others, nickel-base alloys have a corrosion resistance to sulfur-bearing environments superior to other materials, and it has been emphasized that chromium has a greater affinity than nickel for oxygen as well as for sulfur, for which reason in the chromium-nickel alloys, the initial corrosion products are the chromium oxides and sulfides (7). For this reason there exists the opinion that high-chromium content alloys are desirable from the point of view of sulfidation corrosion attack when they are provided with adequate mechanical properties.

It has also been stated (9) that the ingestion of any sodium compound, either from the atmosphere or contained in the fuel, can result in the rapid corrosion of nickel or cobalt based alloys at temperatures above

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*Numbers in parentheses designate References at the end of the paper.

TABLE 1.

Stage	Alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Fe	Ti	Al
1	Udimet 520	.05	—	—	19.0	Bal.	12.0	6.0	1.0	—	—	3.0	2.0
2,3,4	Inconel 700	.12	.10	.30	15.0	Bal.	28.5	3.7	—	—	.70	2.2	3.0

1470°F (800°C). During combustion the sodium salts (NaCl) are converted to sodium sulfate (Na_2SO_4) which deposits on the metal as a liquid flux, consequently stripping off the protective oxide layer and exposing the basic material to rapid oxidation. For example, a typical sulfur content of 0.07% by weight is capable of converting approximately 250 ppm of sodium to sodium sulfate. It is argued that since 1 ppm of sodium in the fuel is sufficient to initiate sulfidation attack, then logically there seems to be little point in limiting the fuel sulfur content and every point in preventing the ingestion of sodium. This, of course, implies that a judicious choice of materials has previously been made in the hot-gas-path section.

Tests made by Bergman (7) confirm that the hot corrosion problem could not be resolved by a reduction of sulfur in the fuel to a very low level (0.0002%). Even if the sulfur in the fuel were completely eliminated, the sulfur in the sea salt would probably be sufficient to promote sulfidation corrosion.

As shown in Table 2, the sodium content in the gas-oil used in the W-191-G units varies from 0.3 to 1.2 ppm, while the sulfur concentration varies from 0.51 to 0.6% by weight as shown in Table 3.

Methods used to minimize corrosion in gas turbines burning liquid fuels

The efforts being made to minimize corrosion in gas turbines burning liquid fuels are the following:

(a.) Limiting the operating temperature to 1550°F (843°C), which of course limits the machine efficiency and fuel economy. The W-191-G unit under analysis here operates within this limit.

TABLE 2. SUMMARY OF 13 SAMPLES OF GAS-OIL USED BY SIX W-191-G UNITS

Determinations	Standards	Results Range	Units
1) Low heating value		19,000-19,700(a)	BTU/lb
2) High heating value		19,380-19,690(a)	BTU/lb
3) Specific gravity		0.8344-0.8619	
3a) Gravity, deg. A.P.I.	ASTM-D287	32.4-37.3	
4) Distillation	ASTM-D86		
Initial point		351-429	°F
10%		394-488	°F
20%		416-520	°F
50%		440-582	°F
90%		577-676	°F
Decomposition point (96.5%)		653-712	°F
5) Kinematic viscosity at 100°F	ASTM-D-445	2.52-5.74(b)	centistokes
5a) Saybolt viscosity at 100°F	ASTM-D-445	34.46-44.73(b)	Saybolt sec
6) Water content	KF	30(c)	p.p.m.
7) Sediment	ASTM-D473	0(d)	% by weight
8) Sulfur	ASTM-1266	0.41-0.52(e)	% by weight
9) Copper strip corrosion	ASTM-D130	2	
10) Carbon residue (Conradson)		0	% by weight
11) Total acid N°		0.45-0.50(f)	mg KOH/gm
12) Strong acid N°		0.20-0.30	mg KOH/gm
13) Strong base N°		———	
14) Ash content	CS	0	% by weight
15) Calcium (Ca)		0-0.9	p.p.m.
16) Lead (Pb)		<1-5	p.p.m.
17) Sodium (Na)		0.3-1.2	p.p.m.
18) Sodium + Potassium (Na + K)		0.3-1.2	p.p.m.
19) Vanadium (V)		0	p.p.m.
20) Magnesium (Mg)		0.1<1	p.p.m.
21) Organic matter		0	p.p.m.
22) Iron (Fe)		<1-3	p.p.m.
23) Copper (Cu)		<1	p.p.m.
24) Aluminum (Al)		<1	p.p.m.
25) Chromium (Cr)		<1-<5	p.p.m.
26) Nickel (Ni)		<1-<5	p.p.m.
27) Silver (Ag)		<0.1<1	p.p.m.
28) Potassium (K)		0-0.3	p.p.m.
29) Color		1.5-3	

NOTES

a) The 3 samples taken at Yaritagua and La Cabrera plants showed the lowest heating values.
b) The same samples as in (a) showed the greatest viscosity.
c) The same samples as in (a) showed a 50% larger water content.
d) The sample corresponding to the storage tank of Las Morochas plant showed an abnormal quantity of sludge.
e) The same samples as in (a) showed a 10% larger sulfur content.
f) The only sample which showed a total acid N° of 0.5 mgKOH/gm corresponded to the return tank from the Laval centrifuges of Las Morochas plant.

TABLE 3. GAS-OIL SPECIFICATIONS ACCORDING TO SHELL

Refineries	San Lorenzo	Punta Cardon
Specific gravity at 60°F	0.8453	0.8389
Color ASTM	0.5	2.0
Diesel Index	54.6	57.3
Cetane No.	41	52
Viscosity Redwood I at 100° F, sec.	32.35	—
Cloud point, °F	—36	0
Sulfur content	0.60	0.51
Copper strip corrosion	N° 1	N° 1
Sediment	0	0
Ash	0	0
Total acid N°, mgKOH/gm	0.49	0.22(*)
Flash point PM, °F	169	—
Distillation:		
Collected at 350° C, % vol.	92	94
Final point, °C	680	649
Kinematic viscosity at 100°F, Cst	—	3.0

(*) This figure seems to correspond more to strong acid N° (Author's note)

(b) Attaining a uniform temperature throughout the cross section of the hot gas path.

(c) Shaping carefully the hot gas paths, particularly the turbine—inlet piece, and providing them with an adequate cross section.

In connection with the foregoing Items (a), (b) and (c), Lee et. al. (10) have shown that the surface temperature of the blade or vane rather than the gas-stream temperature is the critical factor in determining the amount of corrosive attack to be expected at a given contaminant level and that the amount of this attack is an exponential function of this temperature under dynamic flow conditions such as in an operating gas turbine. This finding is of significant importance in cooled blades.

(d) Using materials which are sufficiently resistant to hot corrosion. The key ingredients of contemporary superalloys which affect their hot corrosion performance are:

(1) *Chromium*, which is considered vital to help protect alloys from oxidation and hot corrosion. A minimum requirement is 15-20%; the higher the temperature, the more is required. See Table 1 for comparison with the alloys actually used in the W-191-G units under consideration.

(2) *Molybdenum:* its presence is deleterious, at least in amounts of 1 or 2%, according to References (1) and (11), while its addition to Ni-19% alloy (such as Udimet 520) enhances weight loss above 2190°F (1200° C) according to Reference 5. Others (7) assign no effect to its presence.

(3) *Aluminum:* a key ingredient in generating γ' in nickel alloys, aluminum appears to be deleterious in all

2. On the part of the user:

(a) Removing the harmful ingredients from the fuel. The best methods used today (12) are cleaning and centrifuging the fuel. Sodium, potassium and calcium compounds in liquid fuels are most often present in the form of salt water. Because no additive has yet been found which will counteract the effects of these compounds during combustion, they must be removed from the oil prior to its use, particularly if it is a residual type (13). The centrifuge usually discharges the liquid fuel above its bowl, while the sludge, oil and suspended solids flow outside through a certain number of small nozzles at the bowl rim. Due to the fact that the solids are flushed out through these nozzles by means of sufficient liquid, the bowl is essentially self-cleaning and can work many hours, or indefinitely, without shutting down. A concentrating, self-cleaning type of centrifuge is the De Laval make, as used in Las Morochas plant.

(b) Providing fine fuel filtration ahead of the turbine, generally 5 microns, for mechanical and low-pressure air atomized distillate fuels (12).

DISTILLATE FUEL CONSIDERATIONS

With regard to the sodium salts, these are generally present in the fuel in small quantities and are difficult to eliminate, but in practice it has been found that being water soluble, and the amount that is soluble being negligible, they can easily be removed by filtration and water removal. Thus, due to the fact that the amount of sodium that is acceptable to the machine is very small, say 0.6 ppm, the amount in the fuel need not be severely restricted if proper equipment to remove the salt is included in the fuel installation.

The ASTM specifies that for untreated gas turbine fuels the total alkali content must not exceed 5 ppm. It has been suggested (14) that this figure ought to be kept under 0.5 ppm. The analysis of the fuel used in the W-191-G units shows a sodium + potassium content range of 0.3 - 1.2 ppm, the potassium content alone being 0 - 0.3 ppm, Table 2. Maintenance costs start climbing almost exponentially (14) whenever the total alkali concentration goes above 0.5 ppm.

A conclusion based on field experiences indicates that some corrosion takes place with a sodium level lower than 1 ppm, but not of the catastrophic type which occurs at higher contaminant levels. This has not been the case with the W-191-G unit.

If the quantity of sodium present in the liquid fuel No. 2 is approximately 0.2 ppm, corrosion is not enhanced. In the present case the figures exceed 0.3 ppm.

The action of the sodium chloride (NaCl) can be doubly harmful:

1. by promoting the vanadium attack by means of the formation of sodium vanadates ($NaVO_3$, Na_3VO_4).

2. by promoting the low temperature acid attack due to the formation of hydrogen chloride (HCl).

It is interesting to point out that knowing this, the author expressly requested the analysis of the sludge from the centrifuges of Las Morochas Plant with the specific purpose of finding out if it contained NaCl, and this was found absent. The only sodium present was found in pure form in the fuel analysis shown in Table 2.

It has been repeatedly confirmed (1) (15) (16) that the corrosion intensity also basically depends on the weight ratio of sodium to vanadium content, which should not be greater than 0.3 according to the ASTM fuel specifications. In the present case this factor is trifling, as can be seen in Table 2.

For an operation with a blade metal temperature of 1500°F (815°C) practical data (17) indicate that if the contaminants level does not exceed 2 ppm sodium with 2 ppm vanadium or 0.5 ppm sodium with 5 ppm vanadium, the fuel treatment is not necessary.

In view of the fact that some distillate fuels contain up to 2 ppm vanadium, the writer requested that special care be exercised in looking for vanadium traces in the 13 fuel samples analyzed, Table 2, but the results were negative. However, it is realized that amounts below 0.5 ppm vanadium are difficult and expensive to detect with accuracy (18).

Notwithstanding the fact that, based on the above criteria, fuel cleaning and centrifuging is not essential, the author finds them recommendable to counteract any irregularity in the fuel quality coming from the refinery and in view of the catastrophic corrosion damage experienced.

Remarks on the gas-oil analyses

The results shown in Table 2 indicate that the liquid fuel used in all the W-191-G units of CADAFE is in accordance with the ASTM standards, except as pointed out in the next paragraph.

The initial distillation point of the samples taken in the Tachira, Las Morochas, Yaritagua and La Cabrera plants, where identical W-191-G units are operating, is somewhat above normal. This can cause combustion troubles during the start-up of the units.

With regard to Note (c) of Table 2, it can be added that water content should be kept at a minimum because it can produce corrosion of the fuel controls during shutdown.

In connection with Note (d) of Table 2, it is interesting to mention that an excess of sediment can obstruct the fuel filters or interfere with the ease of atomization and combustion.

The measured value of copper strip corrosion is double that indicated by the fuel supplier, Shell, in Table 3.

The value of the total acid N° of the sample taken in Las Morochas plant in the return tank from the centrifuges is the closest to the Shell specifications, Table 3.

The color indicated in the analyses is greater than that specified by Shell, but this is not as important in the combustion characteristics or other criteria of the fuel quality.

The liquid fuel analyses show that it amply satisfies the fuel specifications of the manufacturer, Westinghouse, Table 4.

TABLE 4. DISTILLED FUEL SPECIFICATIONS No. 26717 ACCORDING TO WESTINGHOUSE

A. Physical		
Gravity—°API	Minimum	26
Viscosity—SUV	at 100° F	32-45
Distillation (90% point)	°F maximum	675
Ash—% weight	maximum	0.01
B. Chemical		
Sulfur—% weight	less than	2.0
Vanadium—ppm	less than	2.0
Sodium—ppm	less than	2.0
Calcium—ppm	less than	10.0

NOTE: The fuel viscosity required for combustion is 70 sec Saybolt universal, or less, for starting and 100 sec Saybolt universal after starting.

CONSIDERATIONS REGARDING THE GASEOUS FUEL

There seems to be no reason to limit the sulfur content in natural gas provided the inlet air is well filtered to avoid sodium ingestion. The hydrogen sulfide (H_2S) content of the natural gas supplied by the Corporacion Venezolana del Petroleo (CVP) is, according to them, 5 ppm by volume. Past experience indicates (19) that the sulfur content of combustion gas, after dilution with air, should not exceed about 40 grains/100 cu ft at temperatures between 1200-1400°F (649-760°C). As previously mentioned, the Tachira plant W-191-G unit had also experienced catastrophic erosion of the axial compressor blades which necessitated its expensive replacement due to malfunction of the air filters.

The gaseous fuel must be free of solids, including solid hydrates, because these can plug the burner nozzles. Liquids are also a problem because these can cause a bad distribution and burn the discharge nozzles as well as the diaphragm and rotor blades.

The inert products diluted in the natural gas have the same effect on combustion as the use of foul air.

In the present analysis the existence of liquid components in significant amounts in the gas duct has not been confirmed because there have been no indications of their effects, but if this had been the case, the solution of the problem consists in installing liquid separators with drains and filters.

BLADE CORROSION EVALUATION

Two means are available for rating the degree of hot corrosion: the weight loss method and metallographic analysis.

The *weight loss method* is considered by some (7) misleading, because it does not indicate a significant weight change for intergranular attack, which can be very deep. For instance, a misleading weight gain can be observed when the material has been actually rendered useless because of massive sulfide penetration. Also, since the weight loss is averaged over the weight of the entire specimen, its value is not significant when only localized corrosion occurs. Because of the foregoing, a deep pit may not register as an appreciable attack.

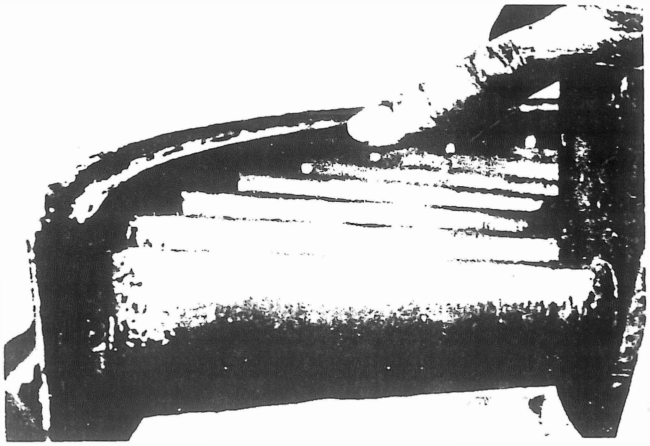

Figure 1. Corrosion of the leading edge of nozzle blades. (CADAFE photo)

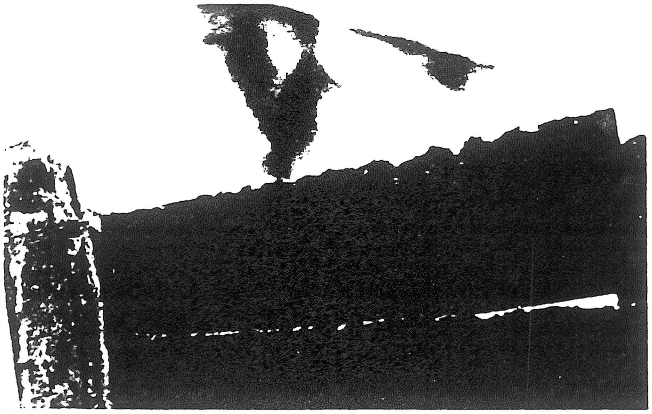

Figure 2. Corrosion of the trailing edge of nozzle blades. (CADAFE photo)

Metallographic analysis, on the other hand, seems to be a more representative and significant means of evaluating the degree of hot corrosion. This method takes into account all types of oxidation and sulfidation.

Metallographic analysis

The extension and severity of the sulfidation corrosion suffered by the W-191-G unit of the Tachira Plant can be seen in Figs. 1 and 2.

The manufacturer sectioned the blades and subjected them to microscopic examination in order to observe the depth of corrosion and the corrosion-affected zone. The results are summarized in Table 5.

TABLE 5. METALLOGRAPHIC ANALYSIS

Stage N°	Material	Estimated Depth of Scale, in.	Depth of Alloy Affected Region, in.	Estimated Total Corrosion Affected Zone, in.
1	Udimet 520	0.004	0.004	0.008
2	Inconel 700	0.004	0.003	0.007
3	Inconel 700	0.002	0.004 (inter-granular attack)	0.006
4	Inconel 700	0.001	0.001	0.002

The microscopic examination of the corrosion affected zone revealed intergranular spiking and grey globular sulfides, which are characteristics of sulfidation. Fig. 3 shows the corrosion attack on the surface grain boundaries of one first stage blade. The sulfides are the grey globular particles seen underneath the oxide layer. No striations indicative of oxides as described in (ii) of the chromium sulfide formation mechanism are evident.

The microstructure of stage 2 blade showed evidence of sensitization of the grain boundaries.

Chemical analysis

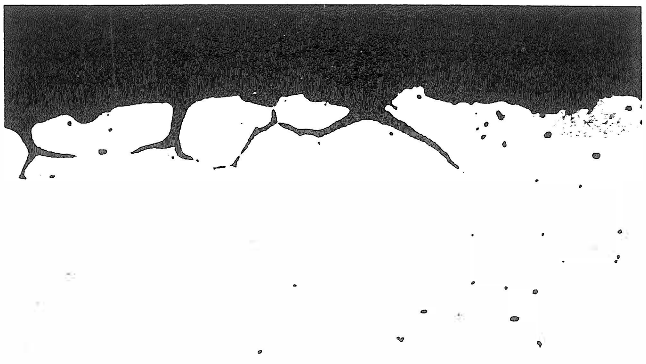

Figure 3. Photomicrograph showing intergranular spiking in the corrosion affected surface layer of Stage 1 blade. (Westinghouse photo)

According to the manufacturer, the analysis of the corrosion products on the blades revealed that the scale contained 0.6% sodium and 3.4% sulfur. Qualitative tests also revealed the presence of chloride and sulfate, although no figures were given. These findings indicated to the manufacturers that the corrosion attack could have resulted from the condensation of sodium sulfate on the blades (hot corrosion mechanism), thus confirming the author's conclusions. The presence of chlorides also suggested to the manufacturer that the sodium was "probably" extracted from sodium chloride salts in the air. However, as mentioned above, the Tachira plant is an isolated, inland one. The manufacturer also stated that "the fuel oil would be the principal source of sulfur contamination."

The chemical analysis made by Westinghouse also revealed a "significant concentration" of vanadium, although no figures were given, and pointed out that this can be extremely detrimental if its is present as pentoxide (V_2O_5), as is well known. However, the manufacturer's finding contradicts the results revealed by the 13 samples of fuel in which, at the writer's request, vanadium traces were specifically sought with negative results. Also, long ago it was stated (20) that uninhibited vanadium retards corrosion which is due to sodium sulfate, and more recently it has been found (21) that even a trace of vanadium pentoxide can actually prevent sulfidation attack in the present range (0.3-1.2 ppm) of sodium, Table 2.

Creep rupture results

The manufacturer removed samples from the airfoil and root of a stage 2 Inconel 700 blade and tested them for creep rupture life. The results are shown in Table 6.

TABLE 6. CREEP RUPTURE TESTS OF STAGE 2 INCONEL 700 BLADE

Sample Orientation	Airfoil	Root	Specifications
Temperature, °F	1450	1450	1450
Stress, psi	50,000	50,000	50,000
Life, hrs.	178	145	100 min.
Elongation, %	11.1	21.5	5 min.
Reduction of area, %	20.3	20.3	5 min.

The above results indicate that the blade still had good creep rupture life and ductility, but the author considers the percentage of reduction of area, which is an indication of the ductility, rather high in comparison with other tests carried out by the same manufacturer (22).

Recommendations

Westinghouse made the following recommendations which will concurrently be commented on by the writer:

1. Recondition all blades from stages 1, 2 and 3 to remove the corrosion affected layer and intergranular spikes. The blades of stage 4 contained only light surface corrosion which can be removed by glass bead cleaning. The writer agrees that reconditioning extends blade life by removing the chromium depleted zone and exposing virgin alloy to the atmosphere.

2. Using a fuel oil with a low sulfur content or, preferably, burning natural gas continually. Also, more stringent controls must be placed on the vanadium content of the fuel. In connection with this recommendation, the author stressed the point to Westinghouse that the sulfur content of the fuel used by SADAFE in their W-191-G units has a range of 0.41 to 0.52% by weight of sulfur, Table 2, which is in accordance with ASTM specifications, with Shell specifications, Table 3, and with Westinghouse specifications themselves, Table 4. It was also reiterated that no vanadium traces were found in the 13 fuel samples analyzed.

3. If possible, the turbine blades should be inspected every 8000 hours for surface corrosion. The writer endorses this recommendation because it is agreed that by monitoring the growth of the corrosion attack and reconditioning the blades when necessary, blade life can be extended and the danger of catastrophic failure due to corrosion can be minimized.

Additional remarks

At the author's request, the manufacturer reported that the blade deposits were hard and dry scale and that the degree of corrosion was the same in the moving and nozzle blades.

It is significant to mention that CADAFE does not take fuel samples from every truck tank arriving at each plant. This may sometimes result in a highly contaminated load of gas-oil being burned in the turbine without ever being detected. Quick and economical fuel analysis methods for field use should be developed. The flame and atomic absorption spectrophotometric techniques are showing some promise (12) in this respect.

In the Tachira Plant, where the gas turbines are located next to a steam plant burning heavy fuel, there exists the possibility that by human error, the gas-oil tank may have been filled with residual fuel of high sulfur content (greater than 2% by weight).

There also exists the possibility that an upset in the oil refinery process itself may occasionally alter the fuel quality.

The means and methods of fuel transportation may be another source of excessive quantities of corrosive elements, particularly if a third-party contract hauler is involved. If the gas-oil were transported in a tank truck previously used to transport residual fuel, the former could be contaminated up to a dangerous level. Only in this way can the presence of vanadium found by the manufacturer be explained because, for example, the contamination of a distilled fuel by 1% of residual fuel containing 200 ppm of vanadium can make the former exceed the 2 ppm specification established by Westinghouse (23), Table 4. For this reason stringent controls are necessary in fuel transport, but this is outside of CADAFE's area of responsibility.

As previously mentioned, another source of the problem lies in the fuel storage system of the power station, its installation according to standards, its cleanliness and maintenance. Several instances have been investigated, alien to CADAFE, in which it has been determined that the concentration at the bottom of the tank can exceed by 50 times the concentration found in the main body of the tank (23). The probability that these concentrations may reach the suction level, and be pumped to the burners, can be reduced by regularly draining the fuel tank bottom.

Another source of blade deposit forming elements, as pointed out before, is the continuous ingestion of small quantities of same in the intake air to the gas turbine. To avoid this, more efficient air filters are required. But in addition, it is recommended that the rate of ingestion be determined by isokinetically sampling the air downstream of the filters as well as determining the full chemical analysis of this material.

The corrosion damage extent can only be evaluated by metallographic examinations; however visual inspection is adequate to determine if attack is taking place. But visual inspection requires that the turbine be shut down for considerable periods of time and much effort be spent to raise the cover, since inspection through the combustor ports is not adequate to detect atttack. This precludes making frequent (1000 hr.) inspections and taking corrective action to limit damage to the turbine.

Some manufacturers have developed alternative means which allow frequent inspection in order to monitor corrosion on the hot turbine parts. This system, commonly called the Corrosion Monitor or Dip Stick, consists of a modified combustor outlet thermocouple which contains samples of material used within the critical sections of the turbine. These materials are exposed to the actual environment of the turbine and may help to show the extent of corrosion deterioration in the turbine. The main advantage of the system is that it takes only about one hour of downtime to remove the exposed samples and replace them with new ones. Also, this can be done during routine downtime. The specimens can then be quickly subjected to metallographic examination to determine the effect of the turbine environment on them.

CONCLUSIONS

1. It has been confirmed that for sulfidation corrosion to occur, the presence, firstly of an alkali and secondly of sulfur, is necessary. The corrosion-inducing proportions of these components is, however, controversial.

2. There is no undisputed agreement on what kind of high temperature alloys are more corrosion-resistant than others and/or what key ingredients of these alloys perform better under corrosion conditions and what the most suitable proportions of these ingredients are.

3. The beneficial effects of protective layers to prevent or retard hot corrosion are still questionable.

4. The provision of fuel centrifuging, previously used only with residual fuels, appears to be recommendable for distillate fuels as well.

5. Correct fuel and air filtration is essential to the corrosion-free operation of gas turbines.

6. Metallographic analysis seems to be a better method of hot corrosion evaluation than the loss of weight method.

7. Quick, accurate and economical fuel sampling methods for field use should be developed to periodically test the fuel loads arriving at the power plants.

8. Fuel oil processing and handling techniques outside the area of control of the users, as well as human error in handling different fuels in power plants, may be responsible for puzzling corrosion problems.

9. Installation standards, cleanliness and maintenance of fuel storage systems must be first-class if corrosion problems are to be avoided.

10. Because no agreement has yet been reached as to the most effective frequency of inspection to determine corrosion buildup, the present development of corrosion monitoring devices should be furthered.

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