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GE Power Generation

Gas Turbine Compressor Operating Environment and Material Evaluation

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ABSTRACT

The reliability and performance of a gas turbine compressor is strongly dependent upon the environment in which it operates, the materials that are used, and the filtration system. Erosion and, to a certain extent, fouling can be controlled by the filtration system, but corrosion is largely controlled through site and material selection. The factors which determine the corrosivity of a site are humidity, the concentration of acid-forming gases, and the composition of particulates. The interrelationships of these factors are discussed with an aim of reducing their impact on compressor operation. A necessary condition for corrosion is the presence of moisture. The acidity of the moisture results from its interaction with the gases and particulates of the environment. The details of these interactions which are important to turbine operators are discussed. A considerable amount of corrosion testing of base materials and coatings has been performed, and this is reviewed. A table is presented for selection of compressor materials based on the nature of the site environment and the type of compressor filtration.

INTRODUCTION

The environment is a most important factor in determining the reliability and performance of a gas turbine compressor. The nature of the air entering the compressor in terms of its humidity, trace gaseous species, and particulate determine the fouling, corrosion, and erosion which occur on the blading. The erosion and, to a certain extent, the fouling can be controlled by filtration, but the corrosion may be almost independent of filtration and only limited by the site environment and compressor materials.

Compressor corrosion is an aqueous phenomenon and, therefore, requires moisture. The amount of moisture, its chemistry, and the compressor materials involved will determine the corrosion rate and ultimately how often reblading and/or recoating is necessary.

Pitting corrosion is the usual type of corrosion found on stainless-steel compressor blading. In cases where severe pitting occurs at places of high stress, corrosion fatigue will result and blade failure becomes a possibility.

It follows that great care should be taken in choosing the site for a gas turbine, in assessing the nature of the environment, and in selecting the proper materials for the compressor. This seems more important today when it appears environmentally produced corrosion problems have increased in recent years.

MOISTURE FORMATION

Compressor corrosion is the result of moisture-containing salts and acids collecting on the blading. During operation, moisture can be present due to the ingestion of water from rain. When the turbine is not in operation, the compressor can still become wet as a result of condensation from warm moist air circulating through the compressor (caused by chimney effects). This circulation is substantial when a turbine first comes down and large temperature differences exist between inside and outside. Condensation is also possible within a unit that is not operating when warm humid air contacts cold metal surfaces. This can happen to units in storage.

An often overlooked source of moisture, but perhaps the most damaging in terms of causing compressor corrosion, is that produced when humid air is accelerated at the compressor inlet during turbine operation. When air is accelerated, there is a drop in its static temperature. If this temperature drop is sufficient to cause the air to become saturated with moisture, then condensation will occur if sufficient submicron particles, called condensation nuclei, are present. Most sites will have sufficient nuclei. Table 1 shows the temperature depression for various inlet Mach numbers and the inlet humidity which would result in saturation. GE compressors have inlet Mach numbers of about 0.5, which from Table 1 gives a temperature depression of 24 °F. If 80 °F air having a relative humidity of 46% is cooled 24 °F, its relative humidity will reach 100% and condensation will occur on condensation nuclei. Experience shows that an ambient humidity of about 50% will result in condensation, and humidities of 75% or greater result in extensive droplet formation. A model for droplet formation in gas turbine compressors has been developed by Zerkle (1982, pp. 101-111).

Table 1

TEMPERATURE DEPRESSION DUE TO ACCELERATION AT INLET
(T_{amb} = 80 °F)

$T_{DEPRESSION}$ (°F)	Mach No.	Inlet Humidity Resulting in Saturation
1.0	0.1	98
4.3	0.2	88
9.5	0.3	73
16.7	0.4	55
24.2	0.5	46
37.6	0.6	27

As air goes through a compressor, its temperature will rise due to compression. Calculations show droplets will grow to about a micron in size before they begin to evaporate. Of course, the droplets formed from condensation will impinge on the blading and collect. Eventually, larger drops will form on the blading, be removed by aerodynamic forces, and travel further into the compressor. It is difficult to calculate the details of this process, but field observations make it clear that little moisture survives the eighth compressor stage as liquid (Kolkman and Mom 1984), as corrosion is generally not observed beyond this stage in baseload machines. The reason for this becomes clear when one plots the boiling temperature of water and stage temperature versus stage number. As shown in Figure 1, the curves cross at about the eighth stage.

CORROSION, MOISTURE, AND DEPOSITS

The fine drops occurring because of condensation of humid air in the inlet, together with the wet blading, make for a very high surface area and an excellent scavenger (indeed scrubber) for various gases entering the compressor. In scrubbing the air, the moist surfaces and the droplets almost certainly become acidic, for the gases being scrubbed from the air are usually CO_2, SO_x, NO_x, HCl, and Cl_2. A possible exception to this might be NH_3, but experience has shown that there is sufficient chloride and sulfate in most environments to result in deposits which are ammonium sulfates, nitrates, and chlorides. Solutions of these salts are acidic.

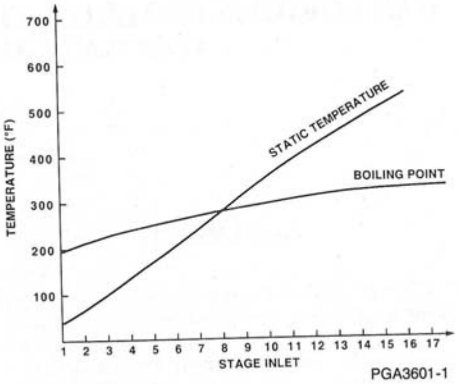

Figure 1. Approximate temperature and boiling point versus compressor stage.

The acidity of the moisture on the blading, and certainly part of its corrosive character, is determined by the partial pressures of the gases being scavenged. Table 2 gives some idea of the magnitudes involved. Here the acidity of the moisture in equilibrium with certain levels of a gaseous specie has been calculated. The two cases are for a gas forming a strong acid (hydrochloric) and a weak acid (sulfurous). In the case of SO_2, ambient levels of 100 ppb are not uncommon, which according to the table lead to a pH of 4.5. For the strong acid-former (HCl), even one ppb can lead to extremely acidic conditions.

The important point to be made from these thermodynamic considerations is that low levels of certain gases may result in very acidic conditions; thus, the importance not only of where a turbine is sited, but in what direction it faces. It should be appreciated that the low levels of gaseous contaminants which produce acidic moisture can be generated locally. Thus, careful consideration should be given to what is in the local environment of the turbine. What chemicals are near the turbine? Will these chemicals produce an acidic dew or moisture? As noted in Table 2, even minute amounts of some chemicals can result in a very acidic dew or

Table 2

ACIDITY OF AMBIENT GASES

Sulfurous Acid

Ambient Sulfur Dioxide (ppb)*	Dissolved SO_2 (ppm)*	pH
1	0.20	5.5
10	0.64	5.0
100	2.0	4.5
1000	6.4	4.0
10000	19.8	3.5

Hydrochloric Acid

Ambient HCl (ppb)*	Dissolved HCl (ppm)*	pH
1	1600	1.44
10	5500	0.94
100	17600	0.44

*Parts by Weight

moisture. Although there may not be much choice where a turbine is to be sited, a choice should exist as to what direction it will face and what chemicals will be placed nearby.

The chemistry of the moisture entering a compressor is determined not only by the gases in the environment, but also by the particulate present. Industrial gas turbines ingest hundreds of pounds of air each second and with it about 0.03 to 0.3 ppm of dust (Tatge 1983). Much of this dust is relatively insoluble and can be filtered out. That part of the dust which is water soluble will traverse the filters when they are wet and ultimately enter the compressor. This is shown by the observation of puddles saturated in water-soluble salts on filter compartment floors behind the high-efficiency filters, certainly a result of the water moving through the filters, and dissolving material up to the saturation limit.

GE experience is that most fouling deposits on compressor blading consist of soot, lube oil, water-soluble constituents, insoluble dirt, and rust. These fouling deposits are probably held together by moisture and lube oil. If corrosion has occurred, it will help in holding the deposit together by increasing the adhesion with the substrate. Certainly the bulk of the particulate which would enter a compressor and form deposits can be controlled by filtration* but fine material ($<1\ \mu m$) is not removed by filtration and, of course, there is no control over the moisture produced by condensation when humid air enters the compressor as described earlier.

Deposits affect the corrosion process by contributing water-soluble material such as chlorides, sulfates, and nitrates to the moisture. In fact, the moisture is usually saturated in these salts. Also, deposits set up crevices and barriers which promote electrochemical activity.

MATERIALS AND COATINGS

For handling a wide variety of environments, GE has used the following materials for the wet stages of compressor blading: nickel-cadmium (NiCd) or Sermetel coatings on AISI 403 stainless blades and uncoated GTD-450†, a precipitation-hardened martensitic stainless steel.

NiCd/AISI 403

The nickel-cadmium (NiCd) electroplated coating has been used for about 20 years by GE. It combines a tough barrier coating, nickel, with a sacrificial cadmium layer. The coating is applied by first electroplating about 0.2 mil of nickel followed by 0.1 mil of cadmium. The plate is then chromate-dipped and heat-treated at 650 °F for an hour to even out the cadmium over the nickel and to promote a diffusion bond. This heat treatment also drives off any absorbed hydrogen. Although the chromate coating is responsible for the color of the coating, it serves no role other than protection of the cadmium layer prior to heat treatment. (Its usefulness is destroyed by the heat treatment.) This coating has outstanding corrosion resistance in neutral ($pH = 7$) and near-neutral environments. It is excellent against sea salt environments. It is also more erosion resistant than most coatings.

Sermetel 5380/AISI 403

The Sermetel 5380 coating is an aluminum spray coating which contains chromate and phosphate corrosion inhibitors. The coating is sprayed on and cured at 650 °F for 30 min and then burnished to promote electrical conductivity. A chromate-type topcoat is applied and also cured at 650 °F for 30 min. This coating has better corrosion resistance than NiCd in acidic environments. This is a result of the better corrosion resistance of aluminum relative

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*High-efficiency filters should remove most particles greater than several microns. Particles 10 μm and larger will produce erosion.

†Currently available from Carpenter Technology as Custom 450.

to cadmium in acid environments. An approximate representation of the dependence of the corrosion rate on pH for these metals is shown in Figure 2.

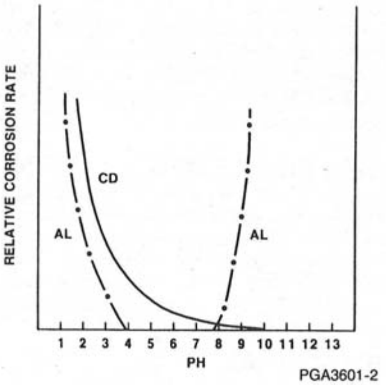

Figure 2. Relative corrosion rate of cadmium and aluminum versus pH (adapted from Uhlig 1948, 842; Uhlig 1963, 299).

GTD-450

GTD-450 is an age-hardenable, martensitic stainless steel, recently introduced by GE for the compressor in the MS7001F. It has the strength characteristics of a martensitic stainless steel combined with a corrosion resistance comparable to an 18 Cr, 8 Ni stainless.

Its excellent corrosion resistance derives from a composition which includes 15% Cr, 6% Ni and 0.8% Mo. Its strength and corrosion-resistance properties relative to other stainless steels are shown in Figure 3. GTD-450 offers improved stress-corrosion cracking resistance at higher strength levels than does a conventional martensitic steel such as AISI 410. This is shown in Figure 4.

GTD-450 has an advantage over coated AISI 403 because the coatings wear away on the pressure side of the first stator and rotor blading. This side of the blading on the early stages is subject to both erosion and corrosion. This is true even for turbines having high-efficiency filtration. In addition, the use of nutshelling to clean a compressor is acceptable with GTD-450 but is not good practice where coatings are present.

Corrosion tests have been run on the above three materials and a variety of others. These tests consisted of the ASTM B117 salt fog test (5% NaCl, T = 95 °F) and a GE-devised acid salt immersion test. The latter test involved the immersion of specimens in 5% NaCl with sulfurous acid to give pH = 4 at 170 °F. A 2:1 mixture of oxygen to nitrogen was bubbled into the solution. This test was considered a worst-case compressor environment.

Most coatings provided excellent resistance in the ASTM B117 salt fog test. Figure 5 shows the protection provided by NiCd over AISI 403 in this test. The results of the acid salt laboratory tests are shown in Figure 6. Coatings were applied to both AISI 403 and GTD-450 in these tests. It was found that uncoated GTD-450 was comparable or better than any coating applied to AISI 403, and was superior to coated GTD-450 for aluminum spray-and-bake-type coatings and NiCd.

Results of the acid salt exposure for NiCd and Sermetel 5380 over AISI 403 are shown in Figure 7. These results show the limitations of NiCd in an acid environment. They also show that the Sermetel coating is attacked in this environment. The blisters shown on the Sermetel coating are sites where attack of the underlying AISI 403 has occurred. The rust formation in the AISI 403 produces a blister on the surface of the Sermetel coating. Figure 8 shows that pitting of GTD-450 does occur in the acid salt test but the attack is minor, the pit size being about 1 mil in 3000 hr.

In severe acidic environments in the field the NiCd coating is undermined and attack of the base metal occurs as shown in Figure 9. Our investigations show the NiCd coating can endure loss of cadmium and nickel over small areas (approximately 0.25 in.) as the surrounding cadmium will sacrifice itself for the exposed steel. Cadmium loss over large areas is more likely to occur in acidic environments. If the nickel is breached in such environments, serious pitting corrosion can occur, driven by the presence of a large cathode (nickel) and a small anode (steel).

Although Sermetel 5380 is more resistant than NiCd in acidic environments, it exhibits a similar attack, as shown in Figure 10. Here the coating has become breached or is permeable to the environment, allowing attack of the base metal. Futhermore, the coating must have become passive, as it is no longer sacrificing itself for the AISI 403.

Although it is early in our field testing of GTD-450, it is clear that GTD-450 provides corrosion resistance at least equal to or better than the coatings over AISI 403 stainless steel. Results from a rotor one rainbow test in a severe environment for a domestic gas turbine are given in Table 3. The

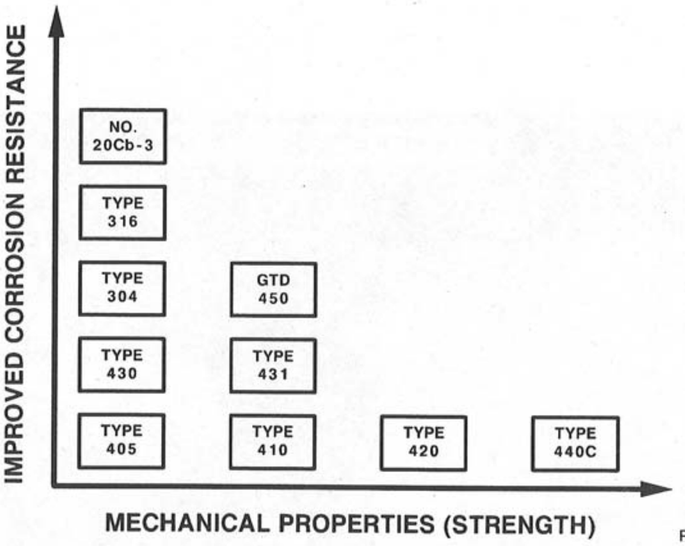

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Figure 3. Comparison of corrosion resistance versus strength for GTD-450 and other stainless steels (Henthorne, Debold, and Yinger NACE).

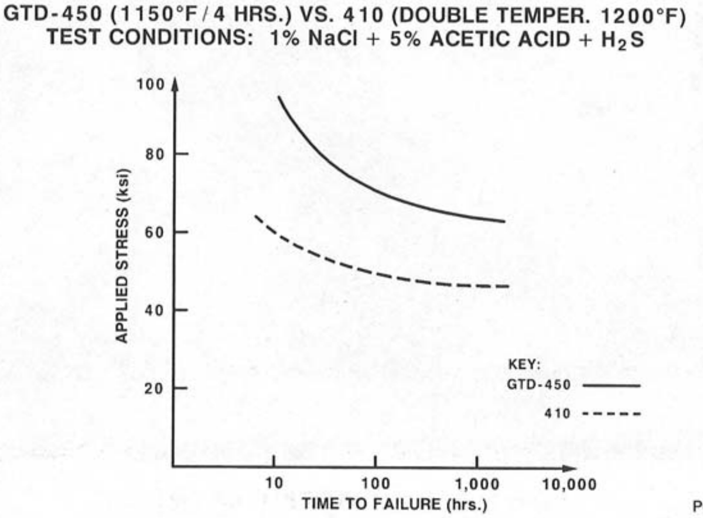

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Figure 4. Comparison of applied stress versus time to failure (stress-corrosion cracking) between GTD-450 and Type 410 (adapted from Schmidt and Henthorne).

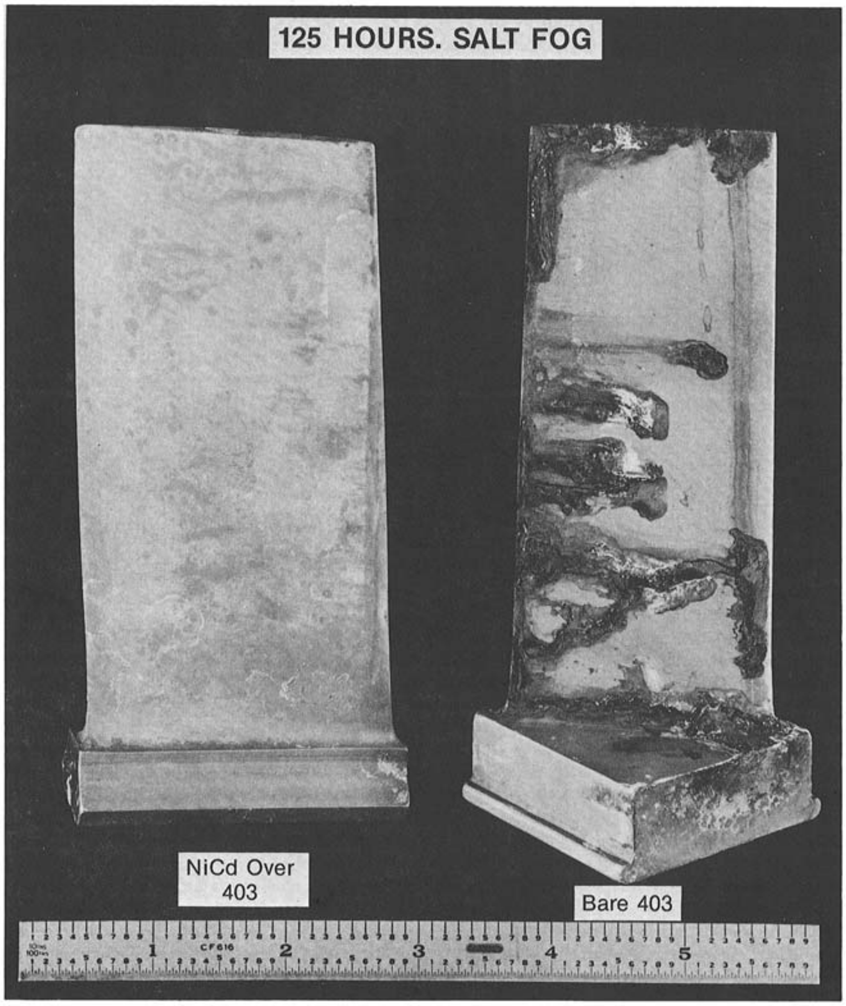

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Figure 5. Results of ASTM B117 salt fog test.

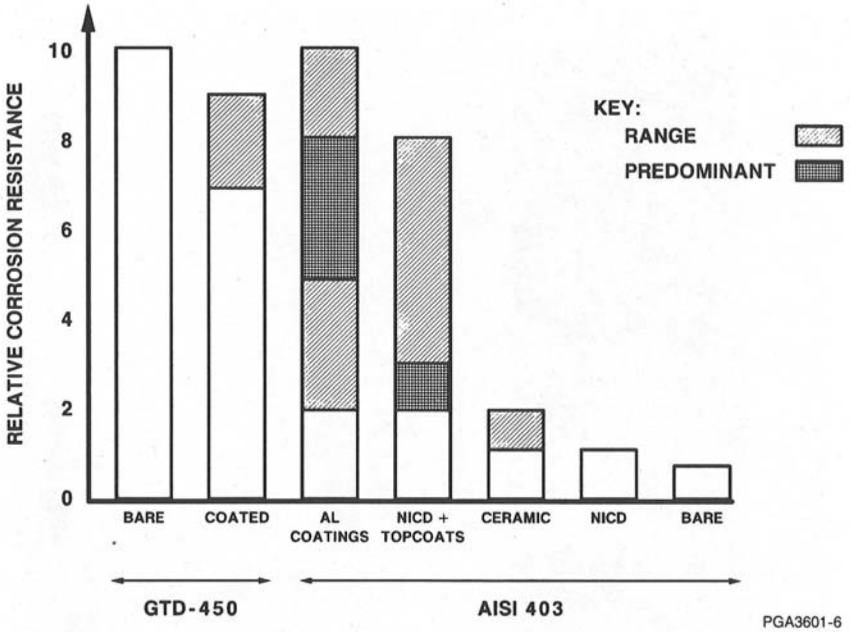


Figure 6. Chart of relative corrosion resistance. Test conditions: pH = 4.5 sulfurous acid, 5% NaCl, 170 °F, immersion.

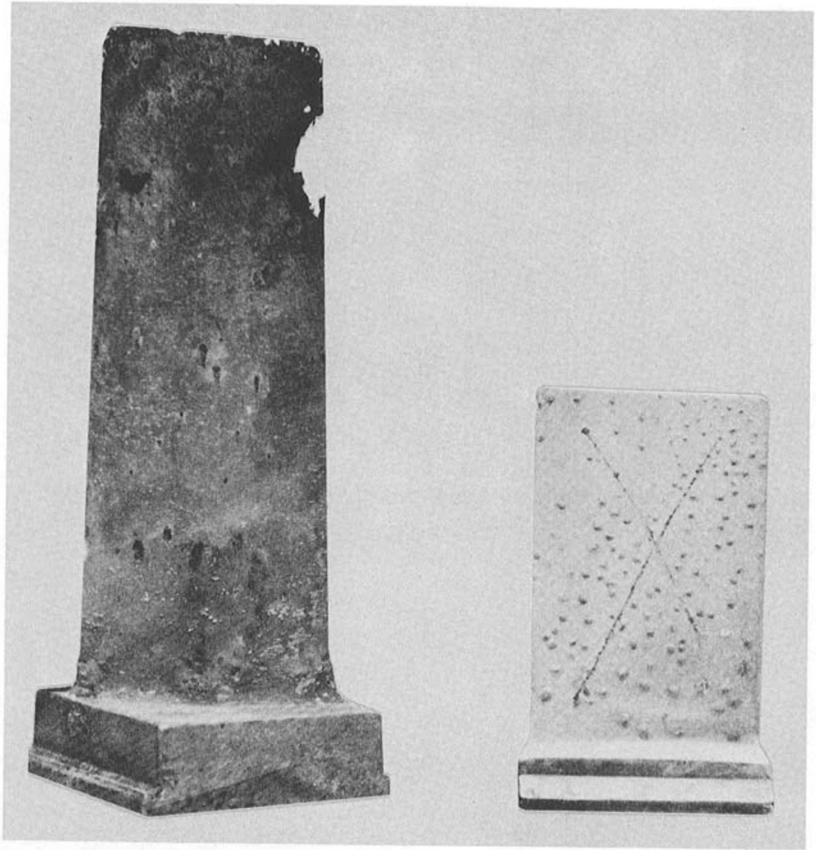
rainbow consisted of aluminum spray and bake coatings (Sermetech's Sermetel 5380 and Alloy Surface's Microfinish) over AISI 403 and uncoated GTD-450. The NiCd value of 50 mil is based on previous experience. A problem with the coatings which does not appear in laboratory corrosion tests is that the coatings are removed from the pressure side of the rotor blading because of erosion. This is an added advantage of GTD-450, as shown in the table.

Experience shows that inlet guide vanes usually have more corrosive activity than other compressor blading. It is believed this is because the residence time of the moisture on these blades is the longest. Recent experience on inlet guide vanes for a nondomestic unit in a severe environment showed that neither NiCd-coated nor Sermetel-5380-coated AISI 403 could give more than one year's service. In the case of NiCd, the blades were scrapped. In the case of Sermetel, the blades were stripped and recoated. Now after a year's service with GTD-450, inspection has shown this material to be in excellent condition with no observable pitting.

A guide to material selection has been constructed and is given in Table 4. The table is based on the material properties and environmental factors already discussed. The material properties are: GTD-450 gives equivalent or better corrosion resistance than Sermetel 5380 over AISI 403, and superior corrosion resistance to NiCd over AISI 403. Being a base material, it is not subject to the erosion restraints of a coated material. The environmental factors are: compressors will run wet when humidities exceed about 50%, and the aggressiveness of the moisture will depend on its acidity, as determined from trace contaminants in the environment and water-soluble species in the deposits.

CONCLUSION

Site considerations are most important in determining what environment a compressor will experience. The considerations are wind direction,



NiCd + 403
1300 HR

SERMETEL 5380
2100 HR

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Figure 7. Results of acid salt immersion test. Test conditions: pH = 4.5 sulfurous acid, 5% NaCl, 170 °F, immersion.

humidity, and what chemicals are present as particulate or gases. Local conditions are important. It has been shown that minute amounts of certain chemicals can result in very acidic conditions and significantly compromise the life of the compressor blading.

A way to determine if a site will have corrosion problems is to consider first the humidity. As we have seen, if humidities are above 50% for substantial periods, then moisture will be formed at the bellmouth and corrosion is possible. Next, one should consider if the environment will be acidic. This can be determined by noting the acidity of the dews and the rains in the areas. A knowledge of what acid-forming gases are present in the air is also useful. Information about their concentration can give some idea of their acidity as shown in Table 2. Local conditions, in terms of emissions or chemical storage, should not be overlooked in determining the suitability of a site. Corrosion experience at the

GTD-450 ACID-SALT
IMMERSION TEST (30X)

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Figure 8. Fine black spots are corrosion pits which developed during 3000 hr of exposure. (Scratches were present prior to testing.)

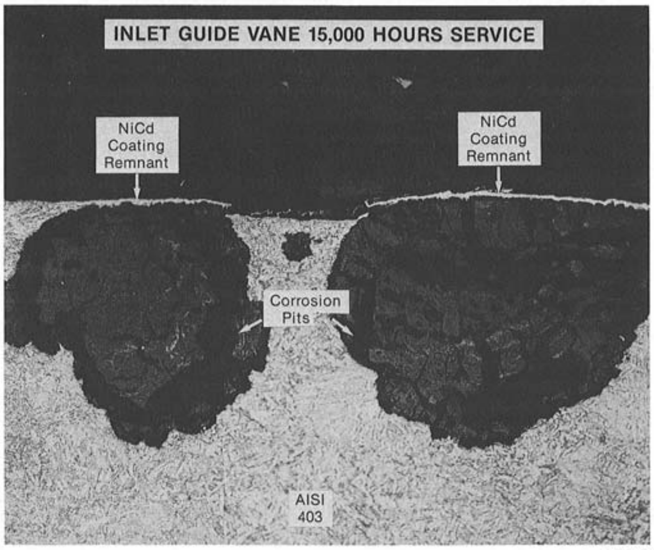

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Figure 9. Corrosion pits under cadmium-depleted NiCd coating (300X).

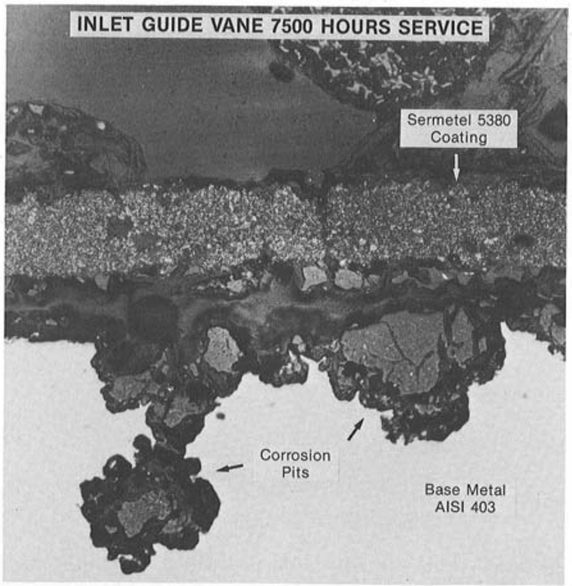

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Figure 10. Corrosion pits under Sermetel 5380 coating (500X).

site, if available, should be considered. If time permits, corrosion specimens should be placed where the turbine will be sited and given a year's exposure.

We have seen that some gases are greatly concentrated in moisture (as shown by the examples in Table 2), causing quite acidic conditions for very low concentrations in the vapor phase. If an environment contains such gases, then the most corrosion-resistant materials should be selected. However, it should be appreciated that if pHs drop below about 4.0 for the condensing moisture, a corrosion problem will exist. As mentioned previously, filtration does not have much effect on reducing corrosion. Water-soluble salts are transported through filters and gases are not stopped by them.

The results of corrosion tests were reviewed. An acid salt corrosion test representing a worst-case compressor environment was shown to cause severe pitting of NiCd/AISI 403 and blistering of Sermetel 5380/AISI 403.

Examples from the field for severe environments were cited in this report and showed similar results. GTD-450 showed minor pitting attack in the acid salt test and has shown superior performance in the field.

To assist those involved in choosing compressor blade materials, a guide is presented in Table 4 which shows what materials could be used under what environmental conditions.

Table 3
COMPRESSOR BLADE RAINBOW RESULTS
24,000-HR TEST IN MS7001
(SEVERE ENVIRONMENT)

Material/Coating	Max. Pit Dia. (Mil)	Erosion	Rank
AISI 403 + NiCd	50	Pressure Side	3
AISI 403 + Al Slurry	30	Pressure Side	2
GTD-450	20	None	1

Table 4

MATERIAL SELECTION GUIDE

Recommended Material[1] (Minimum corrosion/erosion resistance required)	**Is Relative Humidity>50% Most of the Time?**	**Is Moisture Acidity[2] pH>5?**	**Is High-Efficiency Filtration Present?**
NiCd/AISI 403	YES	YES	YES
GTD-450	YES	YES	NO
Sermetel 5380/AISI 403	YES	NO	YES
GTD-450	YES	NO	NO
NiCd/AISI 403	NO	YES	YES
GTD-450	NO	YES	NO
NiCd/AISI 403	NO	NO	YES
GTD-450	NO	NO	NO

NOTES

[1] Corrosion resistance, GTD-450 > Sermetel 5380 > NiCd, where the latter two materials are coatings over AISI 403. Any material in the table could be replaced with any material of superior corrosion resistance, depending on factors such as corrosion resistance desired, erosion loading as determined by filtration system, and whether compressor cleaning would include nutshelling. In the latter case, GTD-450 is the recommended material under all conditions.

[2] Compressor deposit chemistry is important in how it modifies blade moisture chemistry. It may change material requirements. No set method is available for determining compressor moisture acidity. Local pH measurements of rainwater, dew, filter compartment puddles, and blade deposits are used to estimate a value. Deposit pH is taken as the pH of deionized water equilibrated with a deposit for 8 hr at a concentration of 1 gm of deposit per 100 cc of water.

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