METS III

MIDDLE EAST TURBOMACHINERY SYMPOSIUM

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Pitting Corrosion on Fr6B Gas Turbine Axial Compressor Blades: Investigation and Preventive Measures

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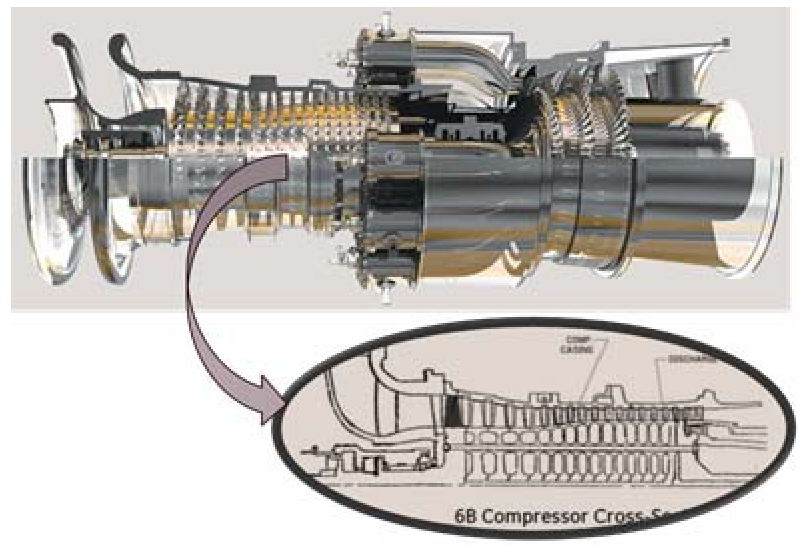
CASE STUDY OUTLINE

- Overview of QG1 Electric power Generation Facility
- Problem Description
- Failure Analysis
- Root Cause Failure Factors
- Review of Inlet Filtration System
- Remedial Actions
- Conclusion
- Q & A

OVERVIEW OF QG1 ELECTRIC POWER GENERATION FACILITY

- Qatargas is one of the world's largest LNG producing companies
  - QG1 : 3 trains (3.3 MTPA)
  - QG2 : 2 trains (7.8 MTPA)
  - QG3/4 : 2 trains (7.8 MTPA)
- QG1 facilities operates six Fr6B Gas Turbines to drive power generators for meeting the electric power demand.
- HGPI and MI of Fr6B turbines is done every 32K & 64K hours respectively.

- Features of QG1 Fr6B gas turbines:
  - ISO rating 38340 KW
  - Simple cycle mode
  - Single shaft, 3-Stage turbine with 1st & 2nd stage buckets and nozzles air cooled
  - 17-Stage axial Compressor
  - 10 Can annular reverse flow combustors
  - Honey comb seals for 2nd & 3rd turbine stages to improve efficiency
  - Accessory base contains starting system, lube oil console, shaft driven accessory gearbox driving lube and hydraulic oil pumps
  - Electric motor starting facility
  - Load gear for speed reduction
  - Hot end drive generator



PROBLEM DESCRIPTION

During rotor inspection in MI of Fr6B turbines, mild to severe pitting corrosion observed on axial compressor rotating and stationary blades. The extent of damage was severe on first 4 rows of both stationary and rotating blades .

FACTS:

- Severity of damage was above acceptance criteria.
- Liberation of affected blade during operation can result in catastrophic failure of downstream compressor stages.
- Premature refurbishment of rotors was therefore carried out to ensure reliability of gas turbines.

FAILURE ANALYSIS

- A comprehensive inspection campaign carried out to investigate severity of issue and to identify failure modes with respect to:
  - Corrosion pitting
  - FOD
  - Missing material
  - Rubbing
  - Crack
  - Erosion
- Three units were identified for the following inspection scope:

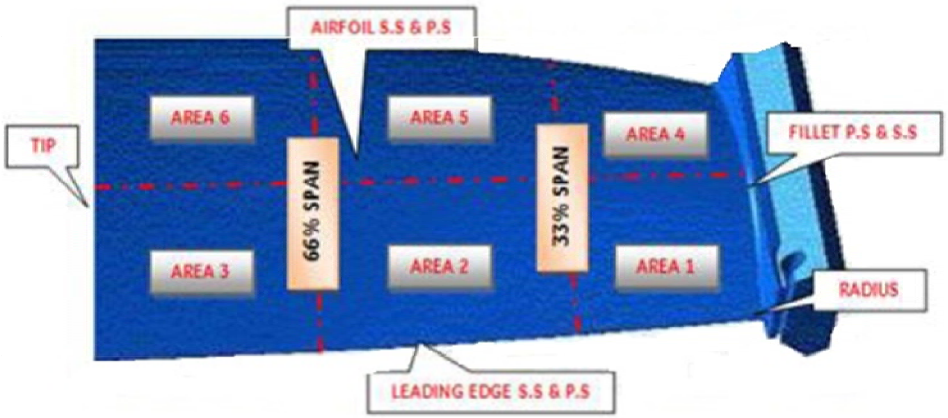
UNIT TAG	SECTION	INSPECTION WORKSCOPE	NOTES
GTG2	AxCo	R1-S1-R2-S2-R3-S3-R4-S4	Inspection performed with rotor exposed and casing removed
GTG4	AxCo	R1	Inspection performed from inlet plenum, without casing removal
GTG5	AxCo	R1	Inspection performed from inlet plenum, without casing removal

FAILURE ANALYSIS – INSPECTION METHODOLOGY

- To investigate severity of issue both rotating and stationary blades inspected using:
  - Visual testing (VT): To measure external dimensions of the indication that opens up to surface
  - Eddy Current testing (ET): To estimate volume of the indication referring to sample defects in the form of flat bottom holes (FBH)
- VT and ET complement each other for data collection purpose
- Visual inspection of Filter House for both dirty and clean sections

INSPECTION PLAN

- Compressor blade divided into different areas and locations
- Customized ET probes used for each location



FAILURE ANALYSIS – INSPECTION FINDINGS

Pitting corrosion observed on 1st four rows of Rotating and Stationary blades

Leading Edge:

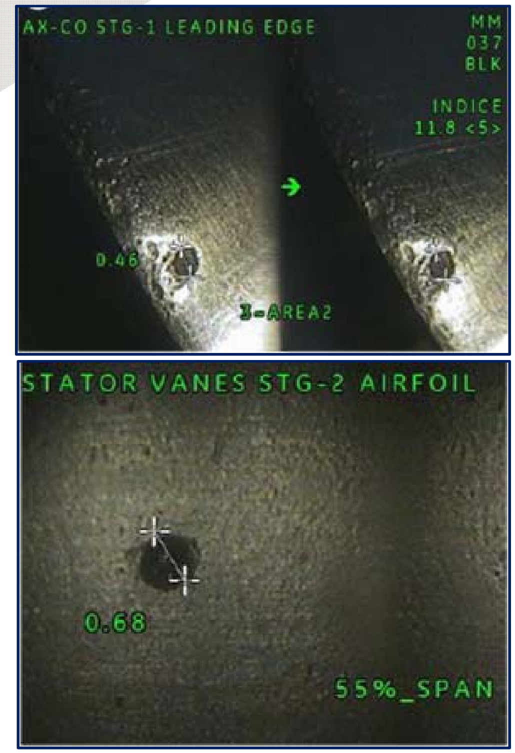
- From root to tip in multiple and cluster formations
- Volumetric dimensions of the pits estimated between 0.25x0.25mm and 0.5x0.5mm (FBH reference)
- External dimensions of the pits up to 1.5mm
- Liquid erosion was detected as well

Airfoil:

- Corrosion pitting was affecting area 2 and 5 in multiple and cluster types with estimated volume between 0.25x0.25mm and 0.5x0.5mm

Fillet:

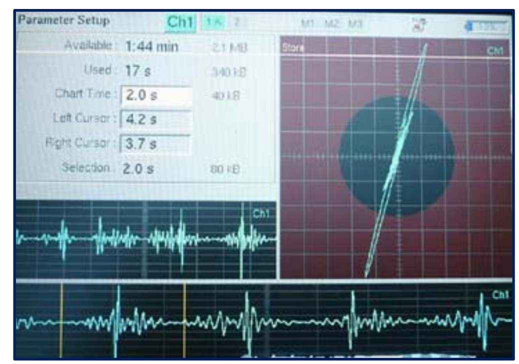
- Randomly distributed smaller pits with estimated volume of 0.25x0.25mm



Sample VT Snapshots

Filter House

- At dirty section, heavy deposit of sand and moisture was covering almost 100% of filter surfaces
- High likelihood that dirty air was regularly ingested by the turbine
- Signs of oxidation and general bad condition of fixtures observed at clean section too
- Self cleaning pulse jet system was not functioning properly



Sample ET Snapshot

FAILURE ANALYSIS - OUTCOME

SUMMARY OF FINDINGS:

- The failure analysis showed severe pitting corrosion damage along leading edge (LE) across the whole airfoil for the 1st four rows of stationary vanes and rotating blades of axial compressor.
- Amount, size and location of pitting led to the conclusion that risk of crack initiation and consequent blade liberation is high.
- Rotor blade liberation or stator vanes detaching during operation would result in severe damage of the whole axial compressor and extended shutdown of the machine.
- Filter house inspection revealed severe impairment of filter cartridges. They were not able to do their duty anymore due to excessive deposits.
- Filter house clean section was found with evident signs of corrosion and general bad condition of fixtures indicating by-passes and imperfect sealing.

ACTIONS TAKEN:

- Premature replacement of affected rotors was therefore carried out with refurbished ones. Also impaired stationary vanes (S1-S4) were replaced with new ones.
- Thorough checks and cleaning of filter house carried out and filter cartridges replaced.
- Sample rotor blades (R1-R4) and stationary vanes (S1-S4) removed from affected turbines as well as dirty filter cartridges were thoroughly investigated at OEM laboratory to find out root cause of pitting corrosion failure.

ROOT CAUSE FAILURE ANALYSIS

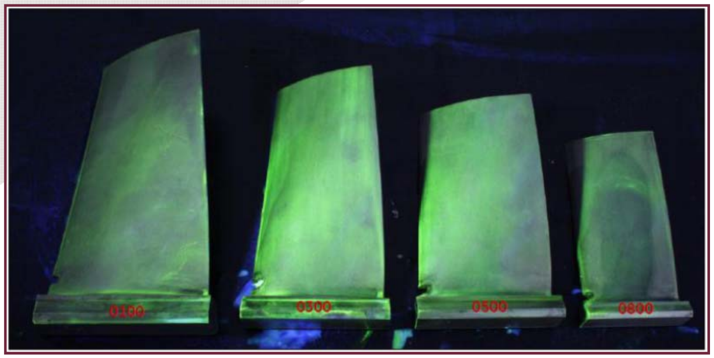
- Four sets of stationary vanes (S1-S2-S3-S4) and rotating blades (R1-R2-R3-R4) were sent to the OEM for root cause failure analysis.
- Below tests performed on Sample blades/vanes:
  - Visual Inspection
  - Magnetic Particle Testing (MPT)
  - Base Material and coating condition evaluation
  - Corrosion Products Analysis
  - Air Filter Powder Analysis

VISUAL INSPECTION:

- The stationary vanes and rotating blades were visually inspected.
- The most significant damage observed is related to severe pitting corrosion and erosion – mostly along leading edge (LE) and on pressure side (PS).

Vane	Findings	Blade	Findings
S1	Corrosion pits along LE, TE, TIP, PS, SS; shank fretting; erosion (discoloration) at LE; discoloration close to TIP; dents within 20-60% span TE	R1	Corrosion pits along LE, SS; Erosion (discoloration) of airfoil PS; shank fretting; disassembly dents
S2	Corrosion pits SS, PS, TIP, whole LE; shank fretting; discoloration at TIP; erosion at LE; dents at 30% span TE	R2	Corrosion pits LE, PS (low span); Erosion (discoloration) at LE, SS (low span); shank fretting; disassembly dent
S3	Corrosion pits along LE, PS, SS (low span); erosion at LE; shank fretting	R3	Corrosion pits LE, PS; discoloration at LE SS, airfoil PS; shank fretting; disassembly dents
S4	Corrosion pits along LE, PS (upper span), SS; erosion (discoloration) at LE; shank fretting	R4	Corrosion pits LE (upper span); discoloration at LE, airfoil PS, SS; disassembly dents

ROOT CAUSE FAILURE ANALYSIS

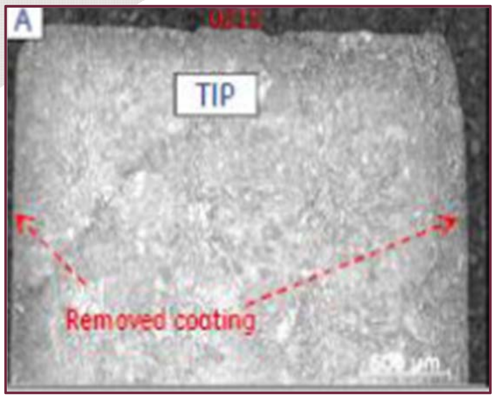


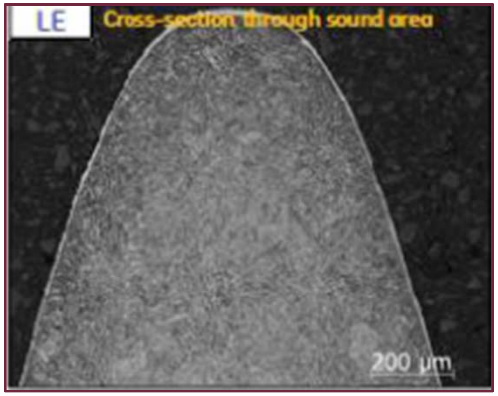
MAGNETIC PARTICLE TESTING:

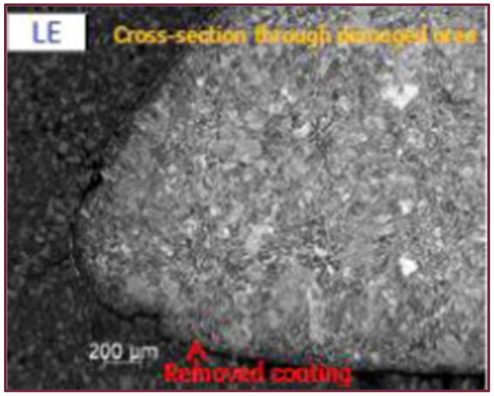
- Magnetic Particle Testing of sample vanes and blades carried out by using wet fluorescent method.
- The test revealed no indication other than corrosion pits on the airfoil surface.

COATING CONDITION EVALUATION

- Ni-Cd diffusion coating is applied on vanes.
- In sound areas, coating thickness was in range of 5-8 µm.
- Coating was found partially or totally removed at LE and close to Tip on all vanes.



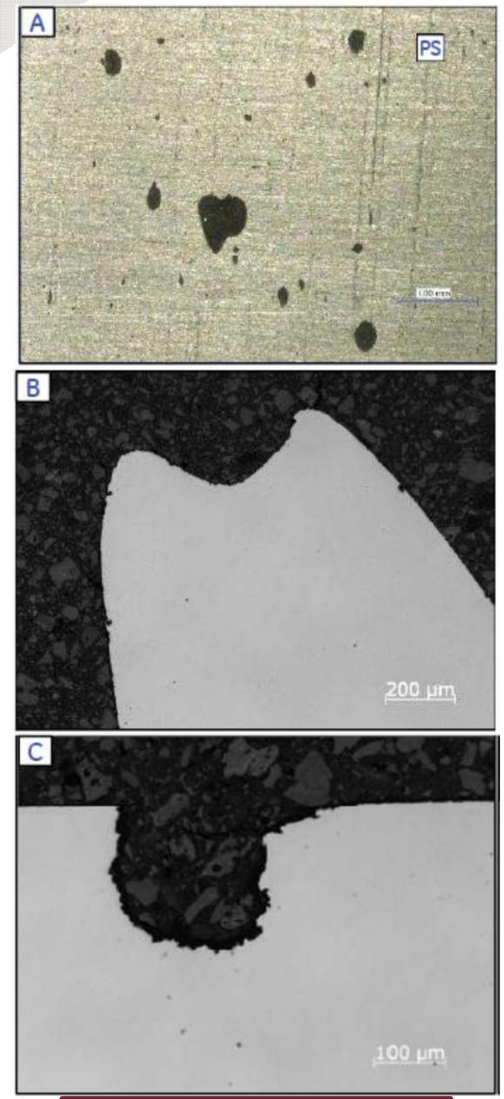




ROOT CAUSE FAILURE ANALYSIS – PITTING EVALUATION

- Pitting Corrosion was assessed on representative stationary vanes (S1-S4) and Rotating blades (R1-R2)
- Pits were analyzed according to ASTM-G46 for density, size, depth and shape

Sample Vane #	Pitting evaluation				
	Density (pits/mm²)	Max size (mm²)	Average size (mm²)	Max depth (µm)	Shape
S1	2.8	0.29	0.012	300	Elliptical, undercut, subsurface
S2	3.4	0.15	0.004	90	Elliptical, undercut, subsurface
S3	1.6	0.11	0.008	460	Elliptical, undercut, subsurface
S4	2.4	0.04	0.008	260	Elliptical, undercut, subsurface
R1	0.42	0.097	0.014	207	Standard elliptical
R2	0.35	0.23	0.031	524	Standard elliptical
R3	0.26	0.16	0.022	384	Narrow deep elliptical
R4	-	-	-	428	Narrow elliptical



(A) Image used for Analysis
(B, C) Cross-sections through pits

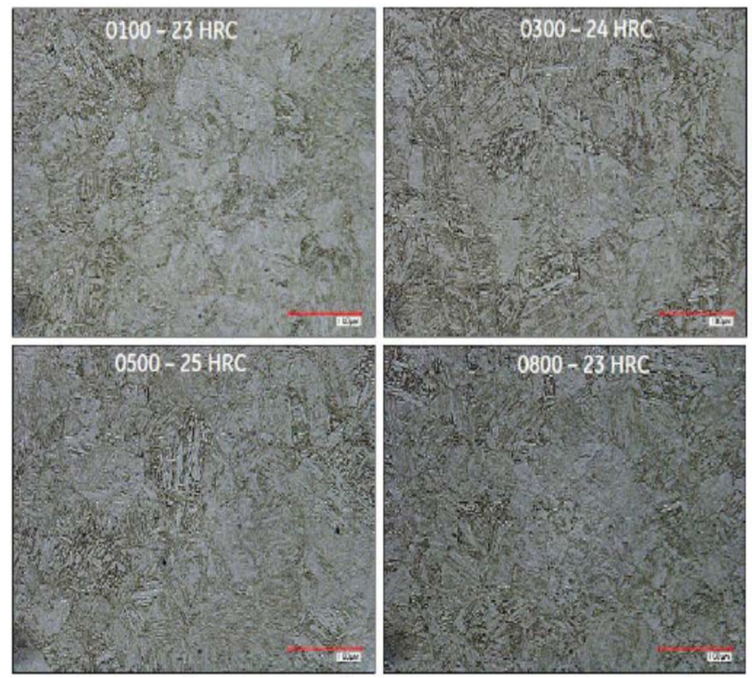
ROOT CAUSE FAILURE ANALYSIS

BASE MATERIAL EVALUATION:

- Base material verification performed on representative vanes and blades (original material: Martensitic SS type 403Cb)
- Microstructure was uniform throughout cross section of blades and in line with martensitic stainless steel of specified type (SS403Cb)
- Vanes/blades base material hardness measured and found in accordance with material specification.
- Chemical composition of base material verified and found in adherence to requirement
- No abnormalities observed

Element	Spec (B50A790C)	Rotating Blades				Stationary Vanes			
		R1	R2	R3	R4	S1	S2	S3	S4
C	0.13-0.18	0.16	0.15	0.15	0.16	0.14	0.14	0.15	0.14
Mn	0.40-0.60	0.53	0.51	0.56	0.50	0.54	0.52	0.52	0.50
Si	Max. 0.50	0.22	0.46	0.25	0.50	0.14	<0.01	<0.01	0.24
P	Max.0.025	0.013	0.024	0.019	0.01	0.02	0.019	0.018	0.022
S	Max.0.010	0.006	0.002	0.001	0.001	0.004	0.003	0.004	0.003
Cr	11.5-13.0	12.1	11.8	11.8	11.9	12.32	12.29	12.24	12.01
Ni	Max.0.60	0.31	0.47	0.54	0.44	0.43	0.43	0.43	0.47
Mo	Max.0.20	0.11	0.01	0.02	0.02	0.19	0.19	0.19	0.09
Nb	0.15-0.25	0.22	0.22	0.21	0.23	0.20	0.18	0.19	0.21
V	Max.0.10	0.05	0.02	0.03	0.06	0.07	0.07	0.07	0.05
Fe	Balance								

Chemical composition (wt.%) of rotating (R1-R4) & stationary vanes (S1-S4)

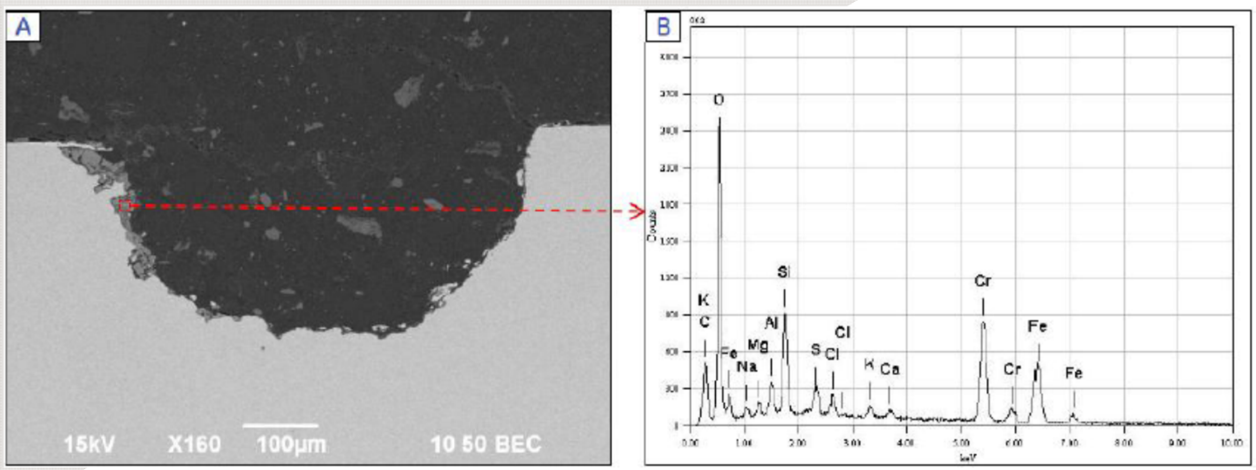


R1-R4 Base material microstructure and hardness

ROOT CAUSE FAILURE ANALYSIS

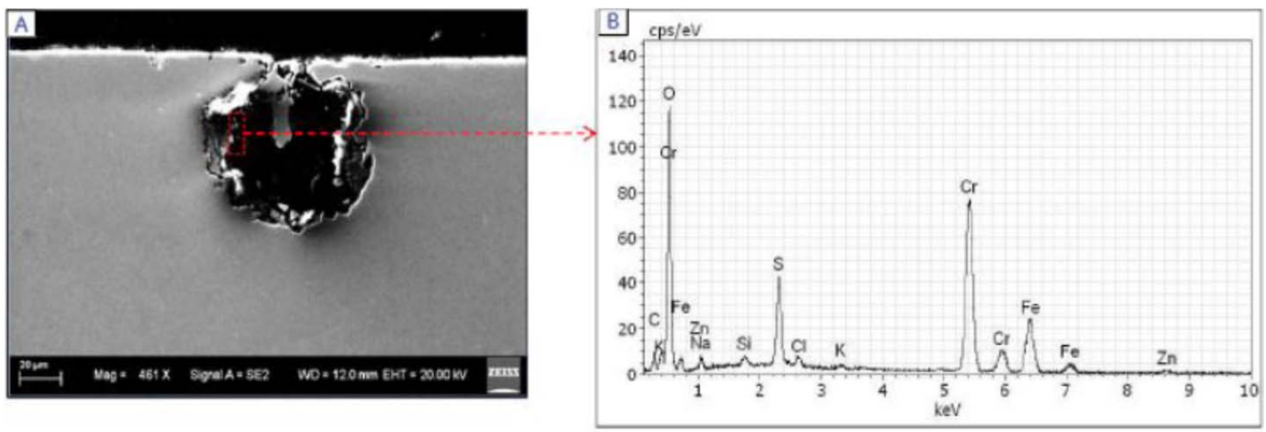
ANALYSIS OF CORROSION PRODUCTS:

- Corrosion products in the pits were analyzed for both rotating and stationary blades
- Apart from base material elements, presence of chlorine (Cl) and sulfur (S) found. Presence of chlorine and sulfur (especially Cl) is cause of pitting corrosion
- Traces of potassium, sodium and calcium were detected



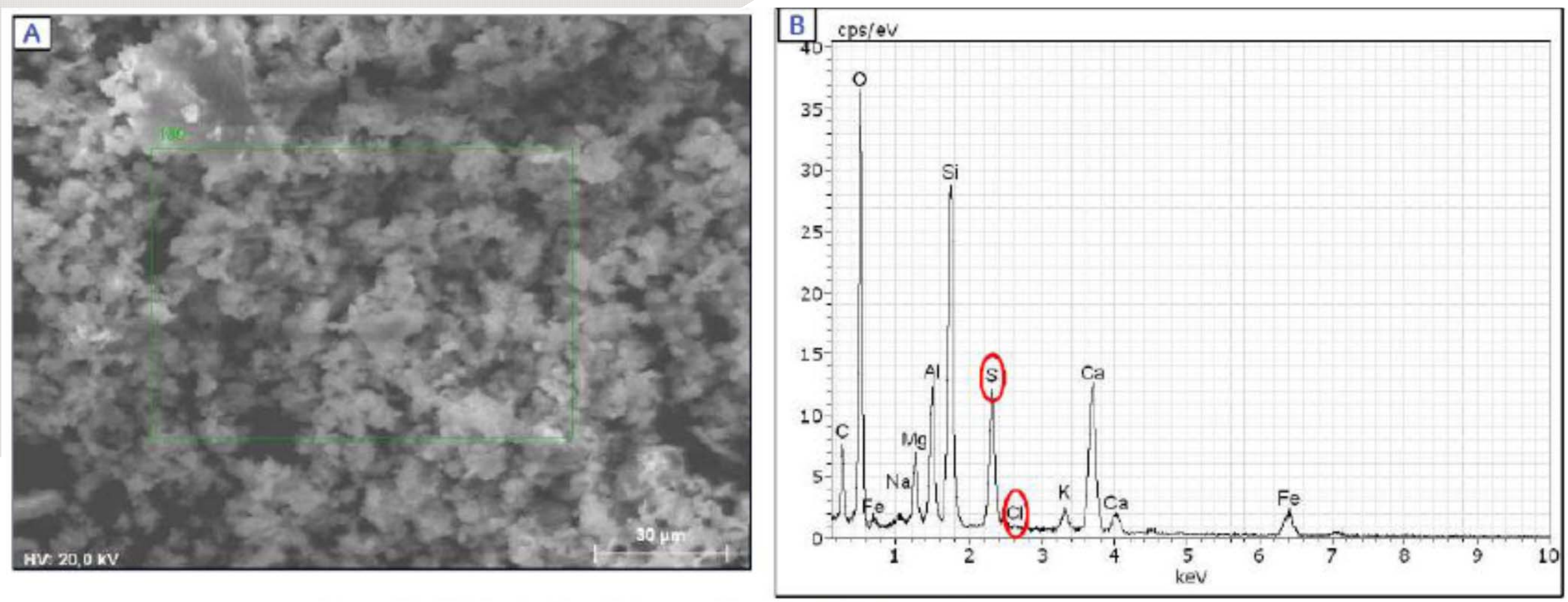
Rotating Blades
(A) Analyzed region within pit
(B) Spectrum of corrosion products

Stationary vanes
(A) Analyzed region within pit
(B) Spectrum of corrosion products



ROOT CAUSE FAILURE ANALYSIS

- **AIR FILTER POWDER ANALYSIS:**
- Powder collected from air filter analyzed
- Main elements detected were: Oxygen, Carbon, Potassium, Magnesium, Calcium, Sulfur, Chlorine and Iron
- Sulfur and chlorine are well known as a primary cause of pitting corrosion



(**A**) Morphology of examined powder; (**B**) ED spectrum

ROOT CAUSE FAILURE ANALYSIS – CONCLUSION

FACTS:

- All examined blades showed eroded coating along LE and severe pitting corrosion damage along LE and across the whole airfoil.
- The severity of damage was more than acceptable tolerances and limits set by vendor for reliable turbine operation.
- Continued operation of gas turbine with defective or damaged blades may result in airfoil liberation and resultant downstream compressor damage.

CONCLUSION:

- Pitting Corrosion observed on rotating/stationary blades was result of presence of corrosive elements (mainly chlorine and sulfur) in aqueous environment.
- The origin of chlorine and sulfur is from the turbine working environment, as confirmed by the analysis of powder from the filter cartridge.
- Low efficiency of filters and incorrect maintenance strategies are the most probable causes of contamination found on axial compressor blades.
- A contributor to sever pitting corrosion of axial compressor blades can be to the lack of optimal water wash strategy.

REVIEW OF INLET FILTERATION SYSTEM

Keeping in view of RCA conclusion a detailed study of FR6B inlet filtration system was carried out to investigate / rectify ingress of corrosive elements into the gas turbines.

REVIEW OF EXISTING FILTERATION SYSTEM:

- Fr6B turbines are installed with single stage, updraft self-cleaning filtration system.
- Existing filter cartridges are made up of cellulose media and rated at filtration grade F7 according to EN classification.

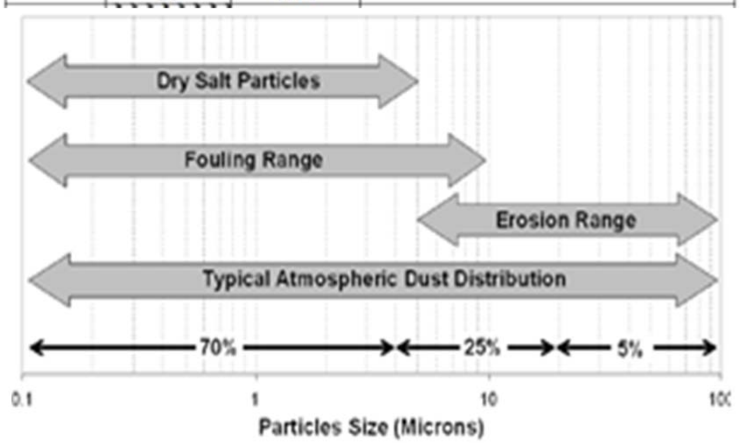
EN Filter Class	ASHRAE 52.2:2007 Average Particle Size Efficiency in micron %			EN779:2002 Average Separation efficiency (%)
F7	0.3 – 1.0μ	1.0-3.0μ	3.0-10.0μ	
	< 75	≥ 90	≥ 90	≥ 80

- The self cleaning pulse jet system on FR6B's was not working adequately.

REVIEW OF QG SITE ENVIRONMENTAL CONDITIONS:

- Per ISO-9223 & 9224 standards, QG site environmental conditions are classified as C5-m (i.e. Industrial areas with high salinity/humidity and aggressive environment).

Grade	ASHRAE Filter Class MERV	EN Filter Class	Particles Separated
Coarse > 10 micron	1	G1	Leaves, insects, textile fibers, sand, flying ash, mist, rain
	2	G2	
	3	G2	
	4	G2	
	5	G3	Pollen, fog, spray
	6	G3	
	7	G4	
	8	G4	
	9	G4	
Fine > 1 micron	10	F5	Spore, cement dust, dust sedimentation
	11	F6	Clouds, fog
	12	F6	
	13	F7	Accumulated carbon black
	14	F8	Metal oxide smoke, oil smoke
	15	F9	
EPA and HEPA > 0.01 micron	16	E10	Metal oxide smoke, carbon black, smog, mist, fumes
	16	E11	
	16	E12	Oil smoke in the initial stages, aerosol micro particles, radioactive aerosol
	17	H13	
	18	H13	
	19	H14	Aerosol micro particles
	20	H14	



Expected contaminants and appropriate rated filters (ASHRAE and EN standards)

REVIEW OF INLET FILTERATION SYSTEM

DISCUSSION:

- Review of existing filtration system with respect to site environmental conditions revaluated:
  - Existing F7 filters are of low efficiency and they are not capable to filter out solid contaminants (sand, dust and salt particles of size 0.1 to 2.5 µ).
  - F7 filters are also not suitable for liquid contaminants like moisture, fog / smog.
  - Formation of dust caking on filter cartridges due to presence of liquid contaminants and open to atmosphere design is common.
  - Self-cleaning pulse jet system remains no more effective after formation of dust cakes.
  - Due to poor filtration efficiency, FR6B turbines exposed to various other contaminants / salts (chlorine, sulfur, potassium, calcium, sodium etc.) which are present in atmospheric air depending upon particle size and composition.

CONCLUSION:

- Recommended to replace existing F7 filter cartridges with H12 membrane type (ePTFE) filters.

Feature	F7 Filters (Existing)	H12 Filters (New)
Filtration Efficiency	≥ 80%	≥ 99%
Filters lifetime	1 – 1.5 years	1 – 1.5 years (yet to prove at QG site conditions)
Water & Salt Retention	Not capable	Capable

F7/H12 Filter Cartridges Comparison Table

REMEDIAL ACTIONS

- Recommended to proceed for modified filter cartridges (F7 to H12) to improve filtration efficiency and prevent ingress of corrosive elements and moisture particles into axial compressor section (H12 filter cartridges are on order).
- Refurbishment of self-cleaning pulse jet system carried out according to original design. The scope of refurbishment included:
  - Replacement of defective solenoid valves
  - Adjustment of sequential timing of pulsing cycle
  - Adjustment of pulse air pressure
  - Adjustment of pulse air stroke cycle
- Check/rectify filter houses for possible air leakages. Ensured correct installation of filter cartridges and no damage of flexible transition pieces.
- Review the water wash strategy which is currently under development (Earlier water wash was performed on need basis in case of performance deterioration).
- Improved operating philosophy by minimizing standby duration of each Fr6B turbine to reduce the possibility of corrosion attack on machine internals. Furthermore water wash and accurate dry out of the turbine is ensured before putting it on stand by.

CONCLUSION

- Gas turbine reliability is dependent upon integrity of the axial compressor blades.
- A defective or damaged compressor blade may result in airfoil liberation and downstream compressor damage if left unattended.
- Stringent inspection and acceptability criteria of compressor blades should therefore be followed during scheduled overhauls to ensure trouble free operation of the unit.
- Careful selection, optimal operation and preventive maintenance of gas turbine auxiliary systems are also of utmost importance for reliable unit operation.
- Area classification is an important design consideration especially in the ME region and special attention to the filtration system is a must.

Q & A