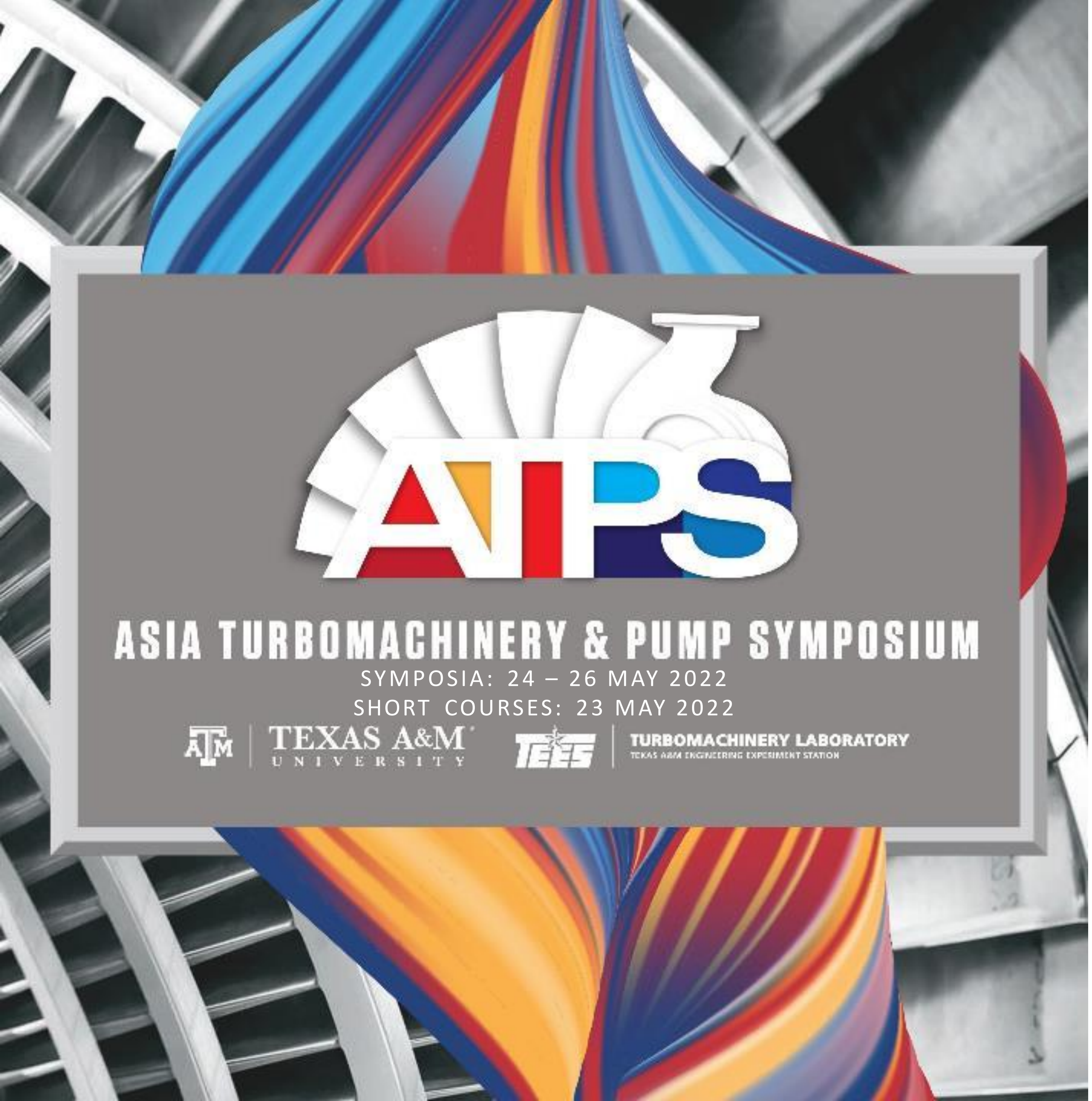

ASIA TURBOMACHINERY & PUMP SYMPOSIUM

SYMPOSIA: 24 – 26 MAY 2022
SHORT COURSES: 23 MAY 2022

TEXAS A&M UNIVERSITY
TURBOMACHINERY LABORATORY
TEXAS A&M ENGINEERING EXPERIMENT STATION

Centrifugal Compressor High Sub-Synchronous Vibration (SSV) During Higher Load and Speed

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Executive Summary

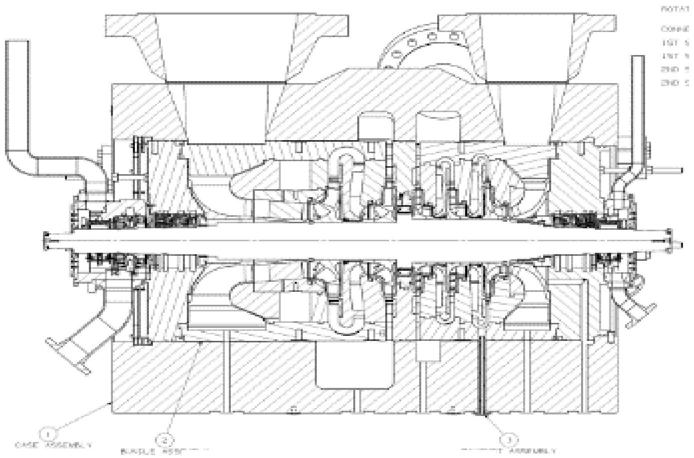
Process fluid changes such as presence of contaminants, water and corrosive gas composition i.e., H2S can give significant impact on the degradation mechanisms of materials which require for design modification or revision in inspection, monitoring & maintenance.

Besides that, it is crucial to have information on spare rotor assembly critical speed whenever any major maintenance done for the compressor. This is essential to ensure operating regime meet sufficient separation margin on system resonances.

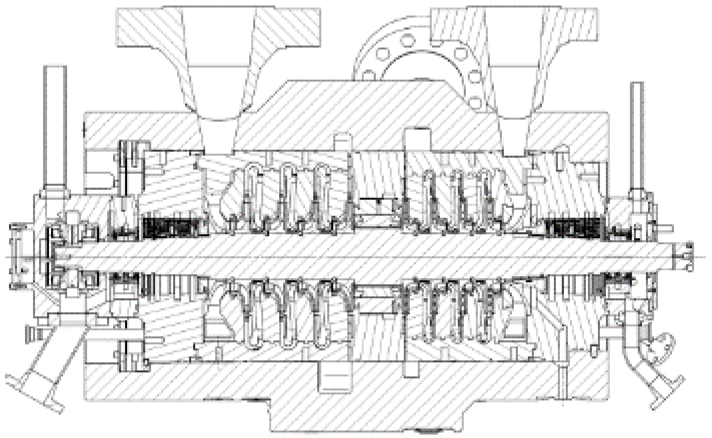
In this case study, presence of moisture, contaminant & H2S in process gas has been discussed that led to compressor component deterioration and damage. In addition, having situation of idling the compressor close to its critical speed also accelerated further impact & resulted in SSV issue

Equipment Overview (Centrifugal Compressor)

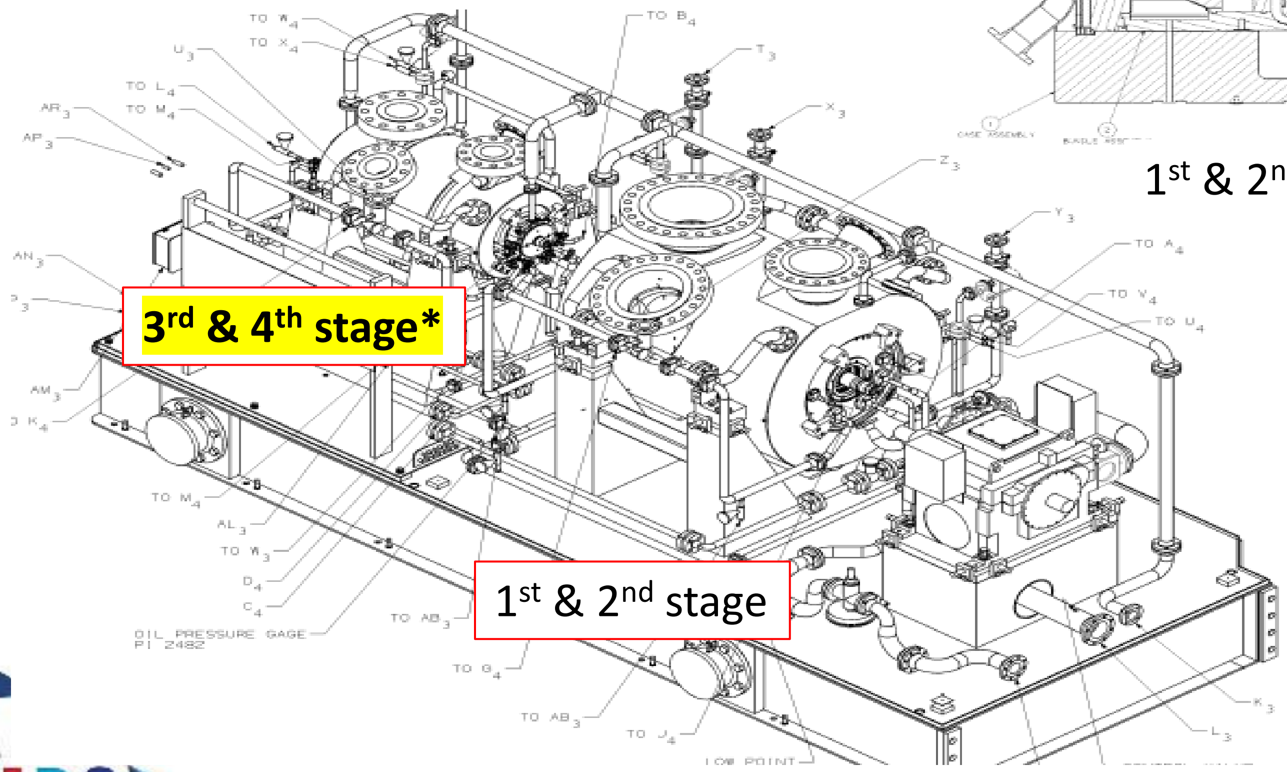
Item	Description
Driver	Gas Turbine
Driven	Centrifugal Compressor (split bundle) 4 stages in 2 body



1st & 2nd stage



3rd & 4th stage*



General Arrangement layout

Item	Description
Interconnection	Gear box & coupling
Process Equipment	Cooler, Scrubber, After Cooler, Glycol Contactor
Speed	Max continuous 11682 rpm
Lateral critical speed	*Concerned: 3rd & 4th Stage First critical 4800 rpm Second critical 17940 rpm
Bearings	Journal – tilting pads
Seals	Interstage – labyrinth Center – honeycomb

Chronology of Events

1st event: 4th Nov 18 – 6th Dec 18

2nd event: 12th Mar 19 – 4th Apr 19

Year 2013 – New compressor package commissioning
- Bundle material: SS410
- 1st CS: 4800 rpm (datasheet)
- Gas composition: no H2S & mercury

4th Nov 18 – Compressor change out
- High vibration, 1X dominant
- Finding: Eroded impeller & diffuser. presence of H2S & mercury from flowing new well/reservoir
- Using spare bundle (Material: SS410)
- Normal speed (>8000 rpm)

6th Dec 18 – Unit back online & running
- 1st CS: 5700 - 5800 rpm. Actual as per observed in vibration plot during startup
- Idle speed: 5840 rpm (50% driver speed)
- Unit at idle speed for few minutes for every startup sequence

12th Mar 19 – Unit tripped & failed
- Indication of rub during coast down

Restart but unit trip during load at higher speed (>7000rpm)
- Vibration spectrum indicate sub-synchronous (SSV) dominant whenever unit started to load at higher speed (>70% of driver speed ~ 7000 rpm)
- Indication of rub
- Troubleshooting to eliminate source that contribute to sub-sync issue

4th Apr 19 – Compressor removal for inspection
- Received confirmation on CS for spare rotor from OEM
- presence of H2S & mercury from flowing new well
- Finding: Eroded impeller & diffuser
- Center seal severe rubbing

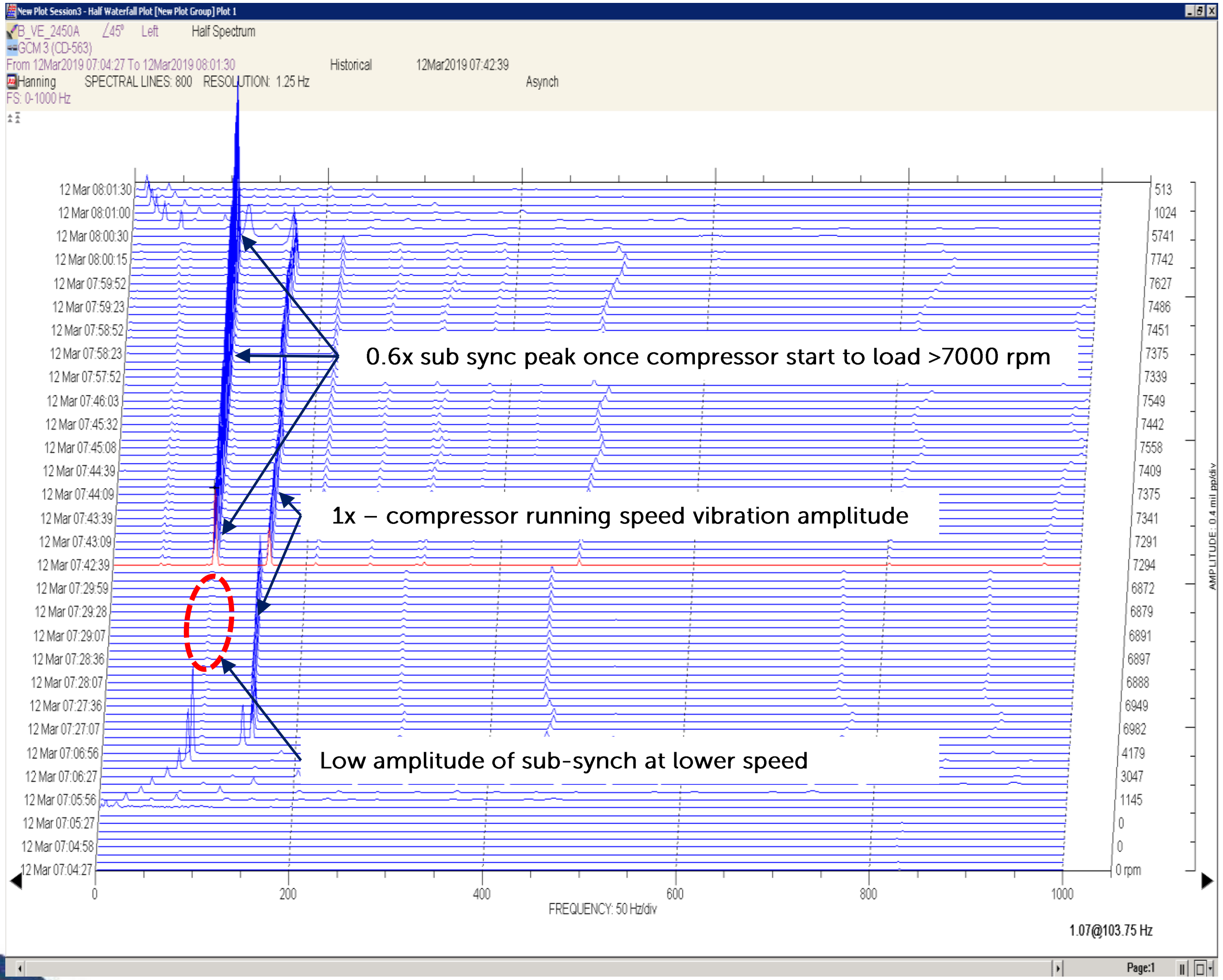
13th May 19 – Compressor replacement. Unit back online
- **Rectification & solution implementation**

MTBF between 1st & 2nd event – 3 months !!

Top event

Findings

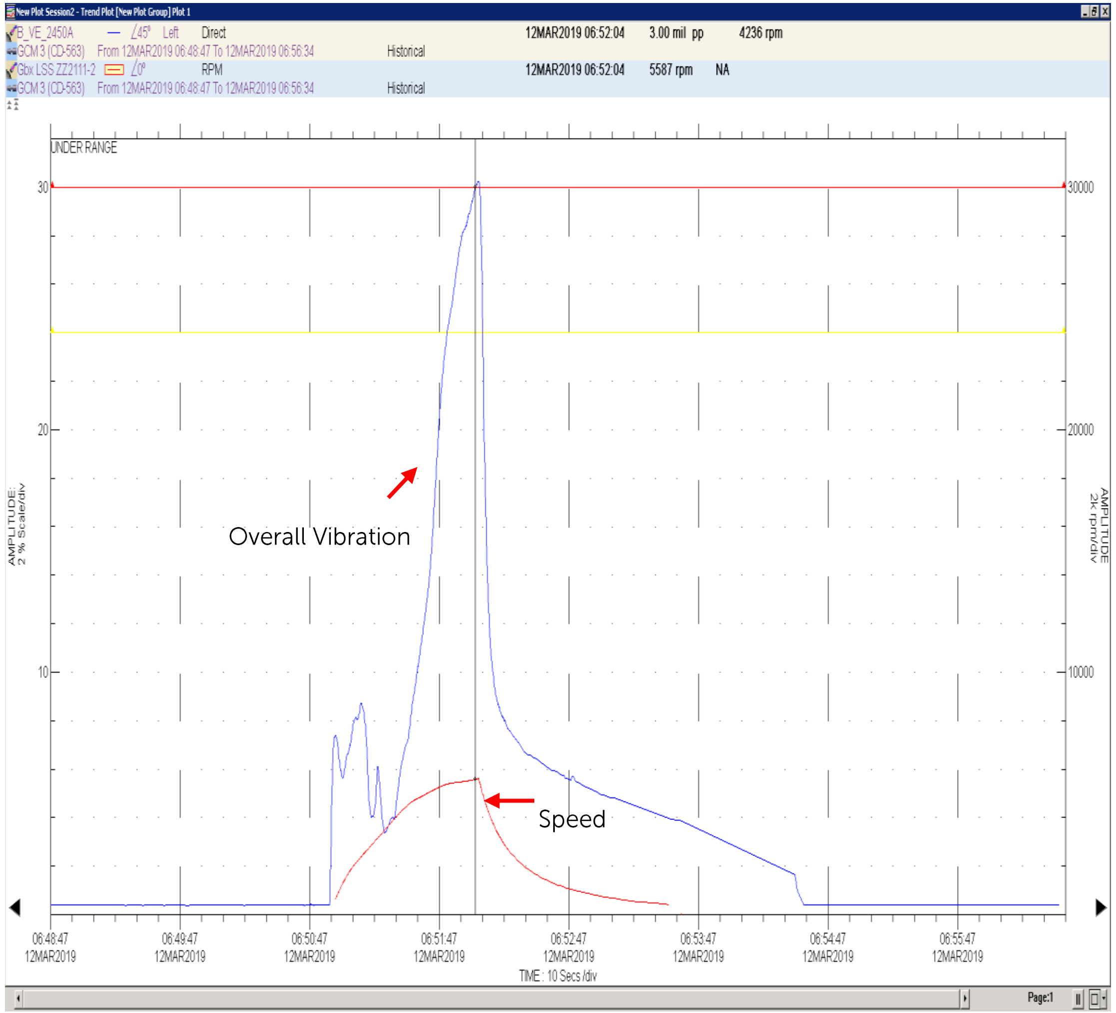
Vibration Data – Sub Synchronous



0.6x sub sync peak once compressor start to load >7000 rpm

1x – compressor running speed vibration amplitude

Low amplitude of sub-synch at lower speed



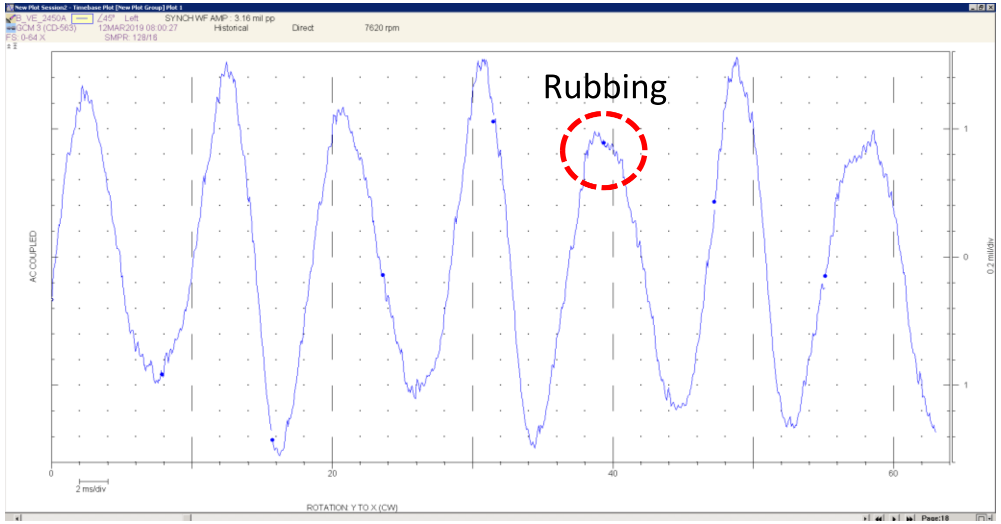
Overall Vibration

Speed

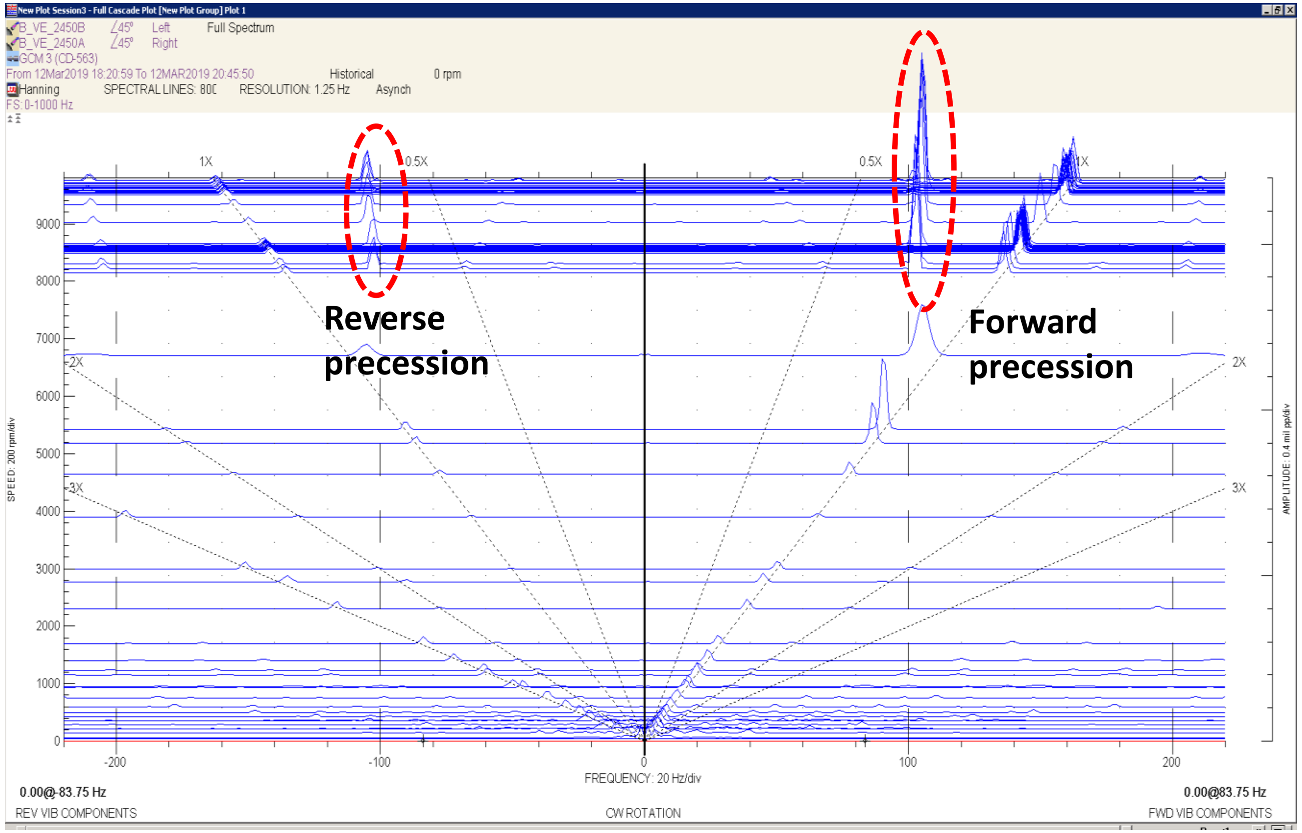
SSV only dominant once compressor load at higher speed

Overall vibration rapidly increase when speed is higher than 7000 rpm

Vibration Data – Evidence of Rub

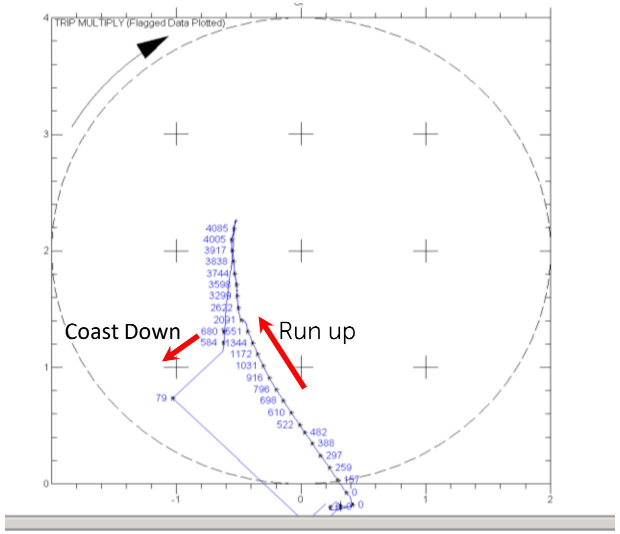


Indication of rub



Waterfall plot: Reverse precession indicate sign of rub

Different rotor path between running & coast down



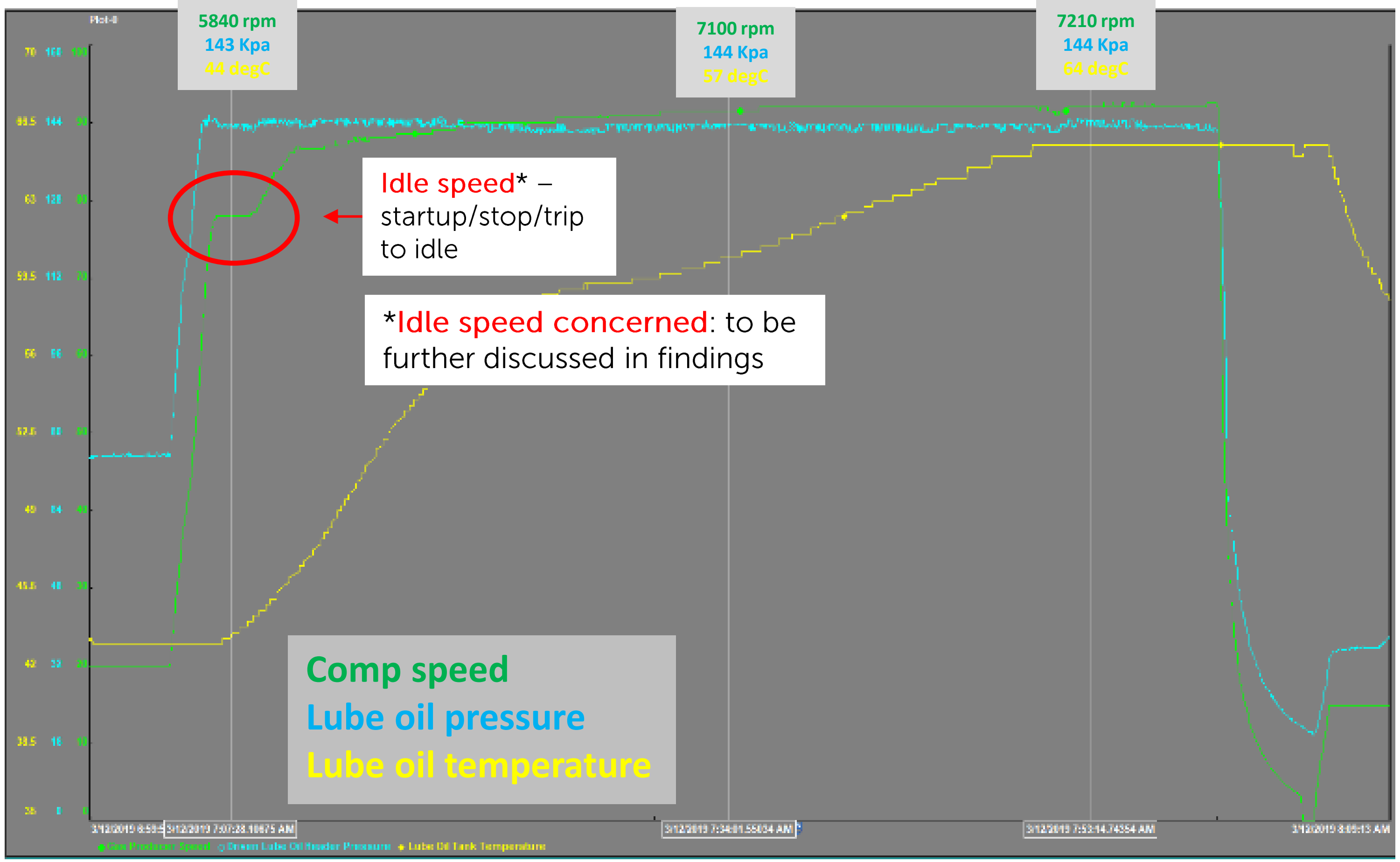
Possible Causes On Sub-Synchronous Vibration (SSV)

Multiple start-up unit were tripped on 3rd & 4th stage compressor high vibration whenever unit need to load at higher speed (>7000 rpm). From vibration plot, it was revealed that the unit was exhibiting SSV issue, whereby 1x and other vibration frequency generally exhibit low amplitude

SSV problem experienced for this compressor maybe generated from following mechanism:

a) Hydrodynamic fluid film related issues i.e., oil whirl / whip
b) Aerodynamic induced instability i.e., rotating stall, incipient surge
c) Rotodynamic instability i.e., self excited
d) Excessive clearance for internal component i.e., journal bearing

Possible Causes #1 – Instability From Hydrodynamic Fluid Film



5840 rpm
143 Kpa
44 degC

7100 rpm
144 Kpa
57 degC

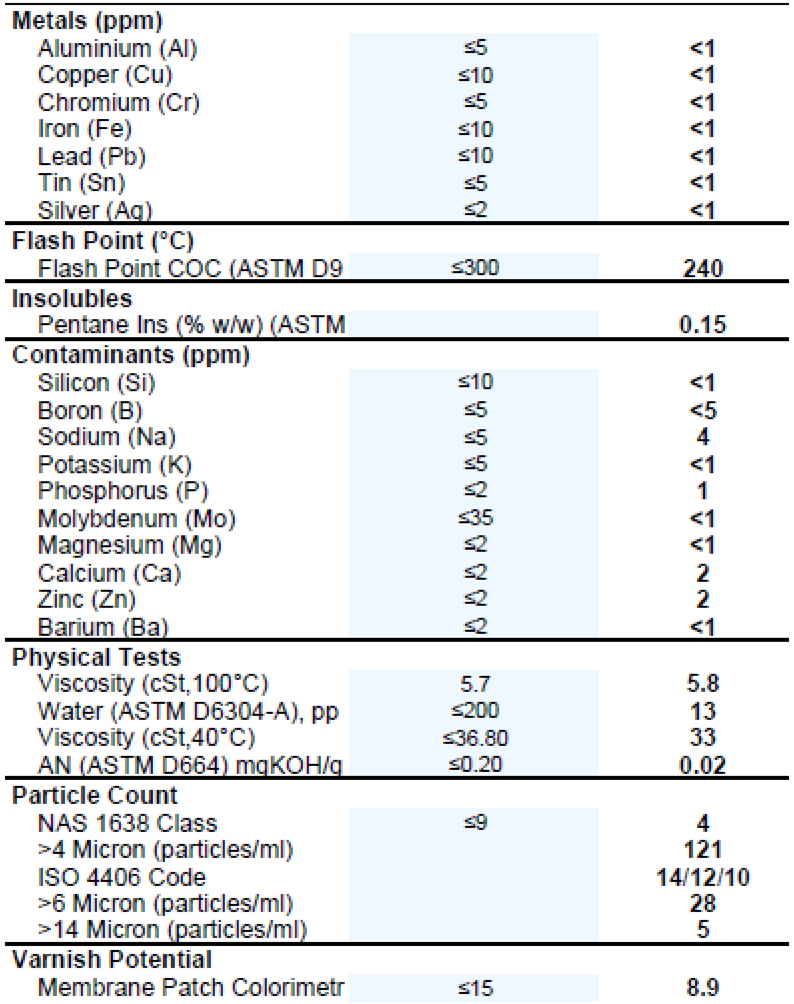
7210 rpm
144 Kpa
64 degC

Idle speed* – startup/stop/trip to idle

*Idle speed concerned: to be further discussed in findings

Comp speed
Lube oil pressure
Lube oil temperature

Lubrication parameters were found satisfactory during unit in operation (within allowable range)



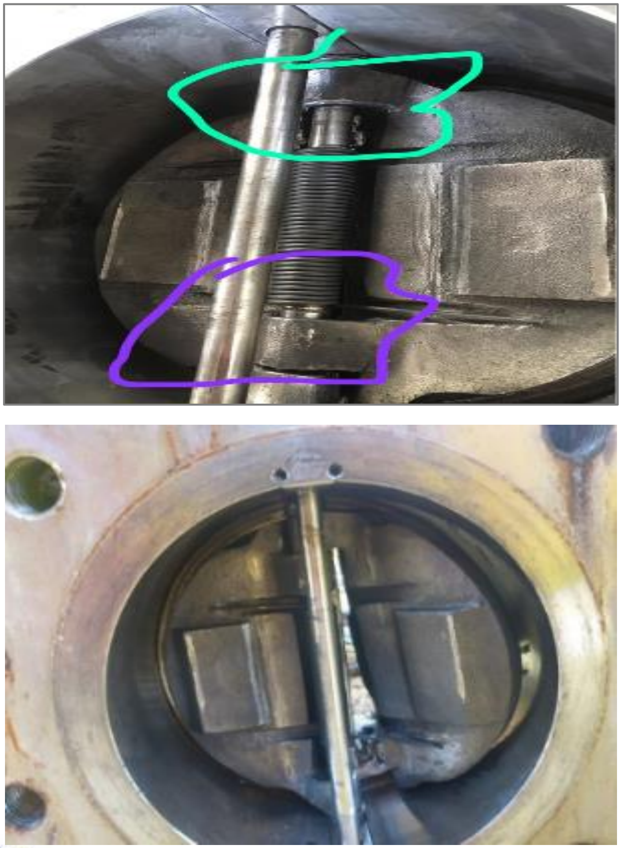
Metals (ppm)		
Aluminium (Al)	≤5	<1
Copper (Cu)	≤10	<1
Chromium (Cr)	≤5	<1
Iron (Fe)	≤10	<1
Lead (Pb)	≤10	<1
Tin (Sn)	≤5	<1
Silver (Ag)	≤2	<1
Flash Point (°C)		
Flash Point COC (ASTM D9	≤300	240
Insolubles		
Pentane Ins (% w/w) (ASTM		0.15
Contaminants (ppm)		
Silicon (Si)	≤10	<1
Boron (B)	≤5	<5
Sodium (Na)	≤5	4
Potassium (K)	≤5	<1
Phosphorus (P)	≤2	1
Molybdenum (Mo)	≤35	<1
Magnesium (Mg)	≤2	<1
Calcium (Ca)	≤2	2
Zinc (Zn)	≤2	2
Barium (Ba)	≤2	<1
Physical Tests		
Viscosity (cSt,100°C)	5.7	5.8
Water (ASTM D6304-A), pp	≤200	13
Viscosity (cSt,40°C)	≤36.80	33
AN (ASTM D664) mgKOH/g	≤0.20	0.02
Particle Count		
NAS 1638 Class	≤9	4
>4 Micron (particles/ml)		121
ISO 4406 Code		14/12/10
>6 Micron (particles/ml)		28
>14 Micron (particles/ml)		5
Varnish Potential		
Membrane Patch Colorimetr	≤15	8.9

✓

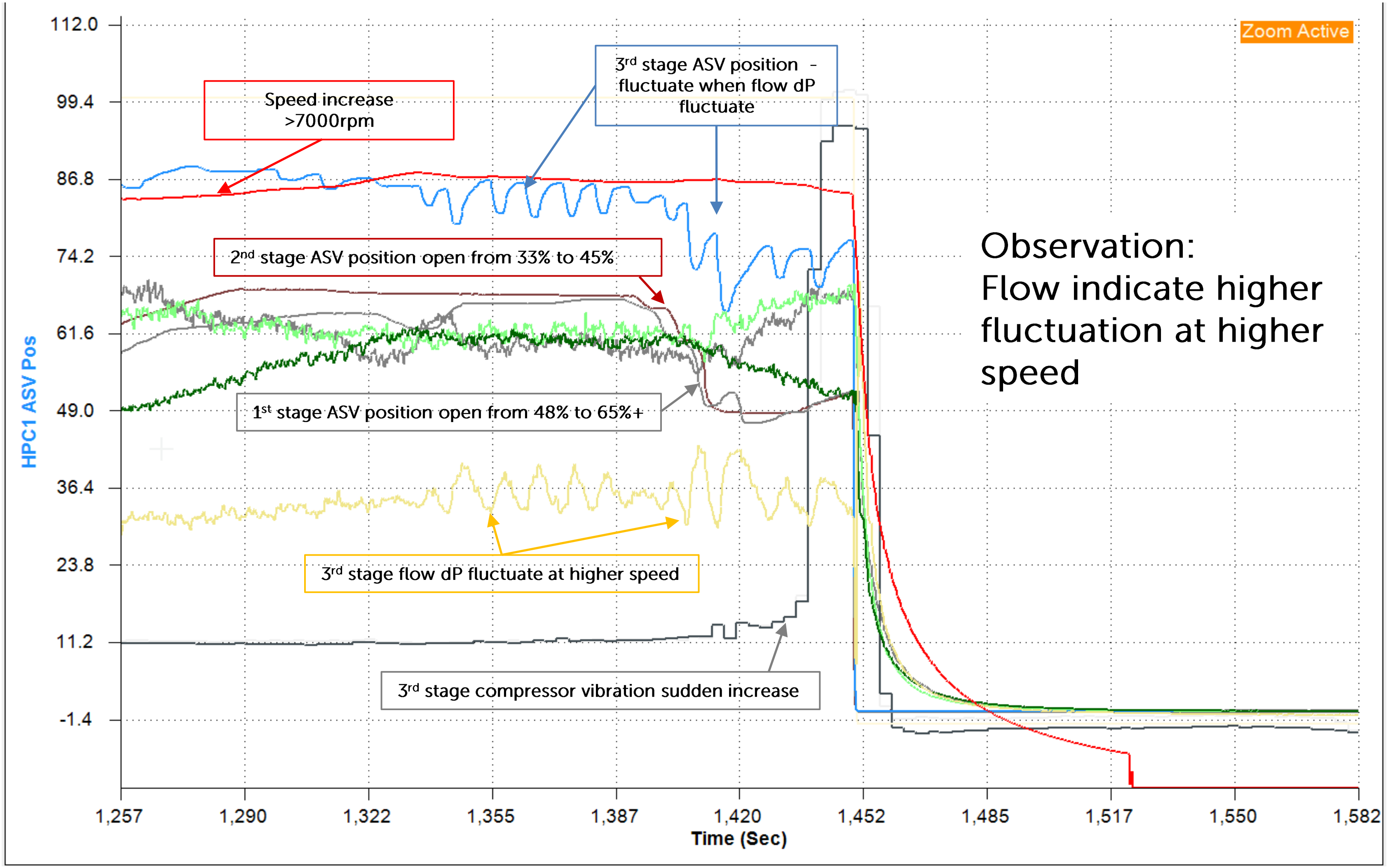
Lube oil analysis is acceptable

Possible Causes #2 – Aerodynamic Induced Instability

a) Flow instability to compressor i.e., flow disturbance due to restriction in the system.



Check valves at 2nd , 3rd & 4th stage found parted and/or passing



Speed increase >7000rpm

3rd stage ASV position - fluctuate when flow dP fluctuate

2nd stage ASV position open from 33% to 45%

1st stage ASV position open from 48% to 65%+

3rd stage flow dP fluctuate at higher speed

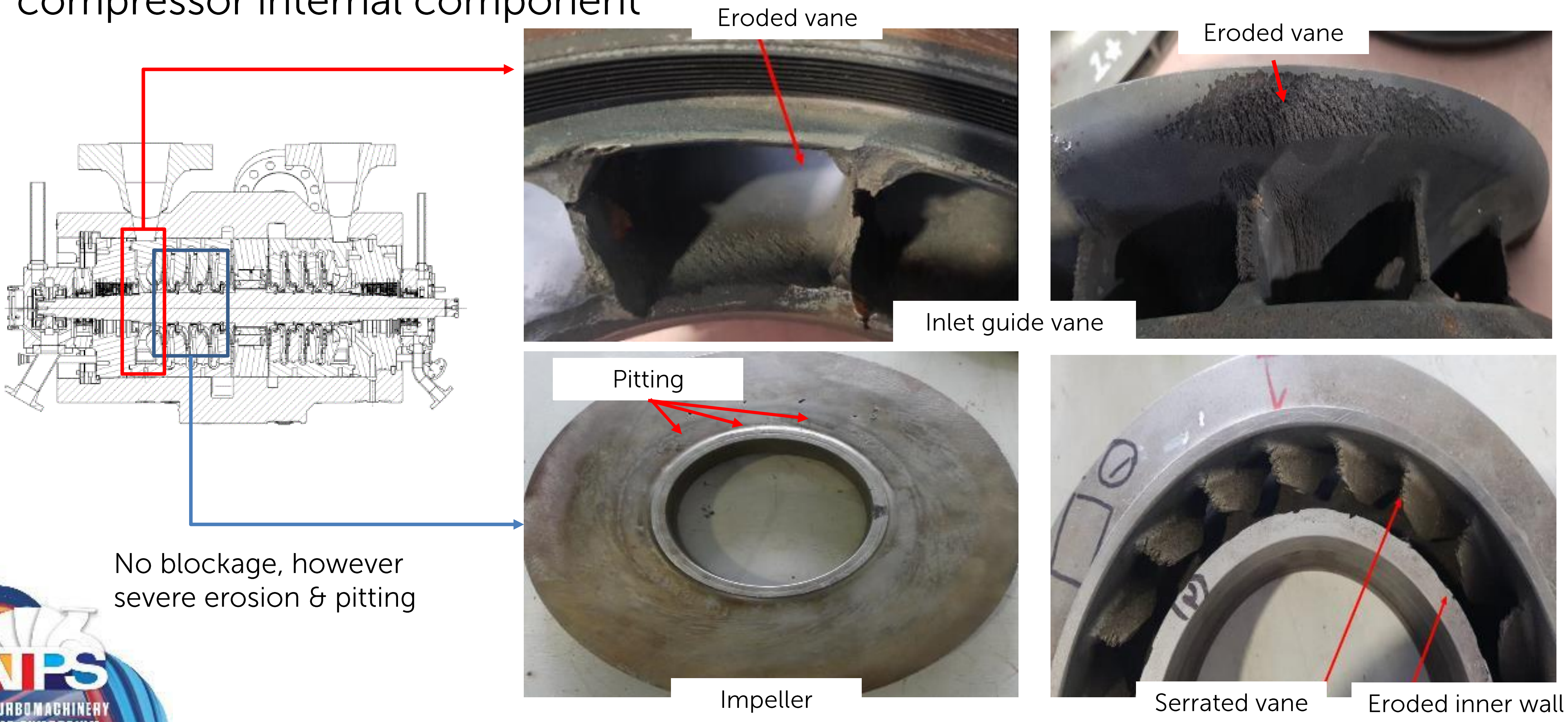
3rd stage compressor vibration sudden increase

100 millisecond high data resolution

Observation:
Flow indicate higher fluctuation at higher speed

Possible Causes #2 (cont.)– Aerodynamic Induced Instability

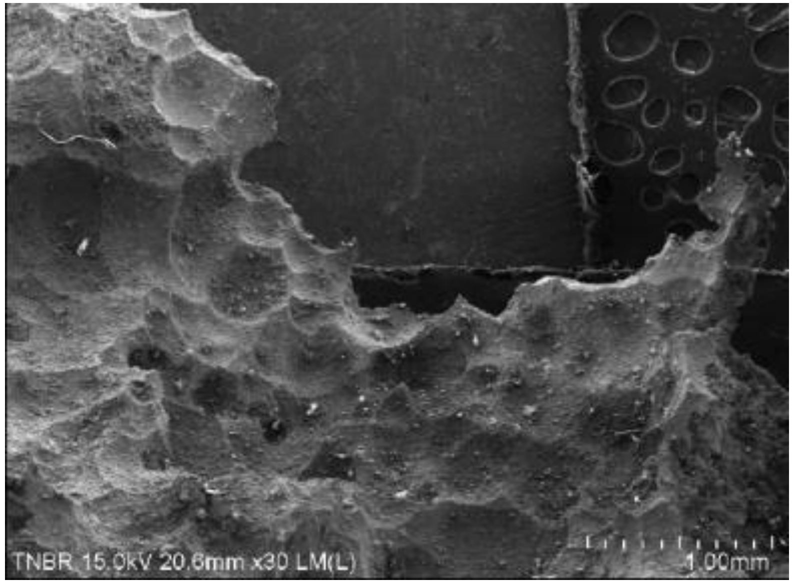
b) Flow instability due to rotating stall i.e., restriction or disturbance at compressor internal component

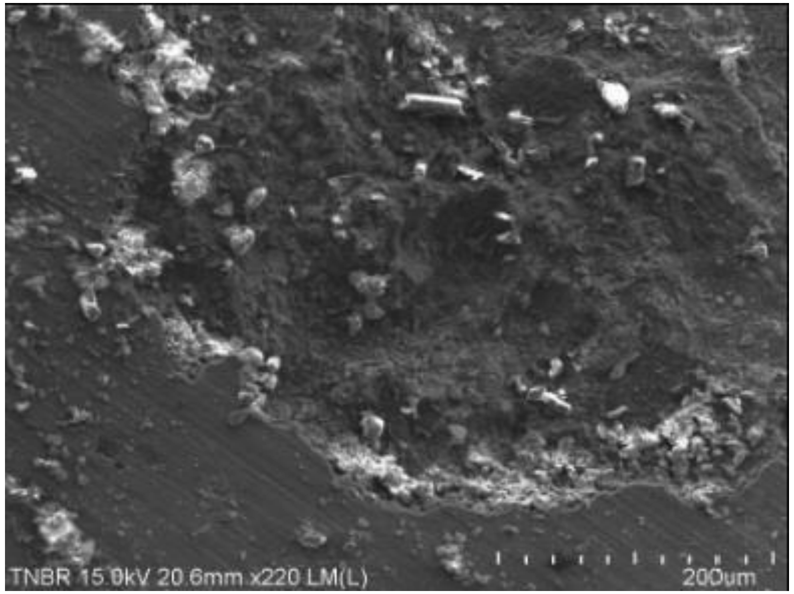


No blockage, however severe erosion & pitting

Summary of Lab Analysis on Damaged Component

The damaged component i.e., shaft, impeller, guide vane were subjected to metallurgical analysis. Summary of finding as below:





Erosion

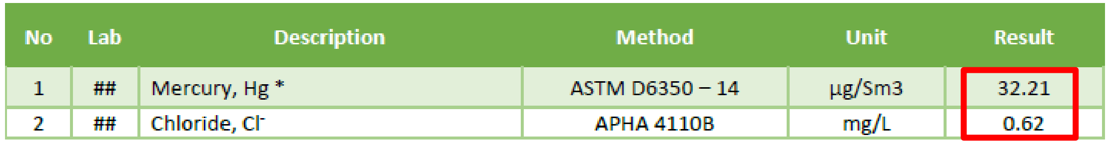
- **Liquid droplet impingement**
- Repeated impacts caused depression and metal flow
- Asperities formed between depressions
- Asperities cracked and removed metal

Corrosion

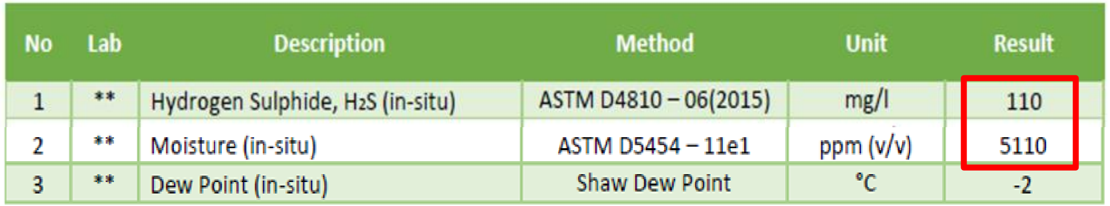
- Areas with dark deposit accumulation
- **presence of corrosion products**
- Corrosion attack form crack / fatigue

Findings on Process Gas Sampling Analysis

Table 1: Physical Analysis



No	Lab	Description	Method	Unit	Result
1	##	Mercury, Hg *	ASTM D6350 – 14	µg/Sm3	32.21
2	##	Chloride, Cl^-	APHA 4110B	mg/L	0.62



No	Lab	Description	Method	Unit	Result
1	**	Hydrogen Sulphide, H_2S (in-situ)	ASTM D4810 – 06(2015)	mg/l	110
2	**	Moisture (in-situ)	ASTM D5454 – 11e1	ppm (v/v)	5110
3	**	Dew Point (in-situ)	Shaw Dew Point	°C	-2

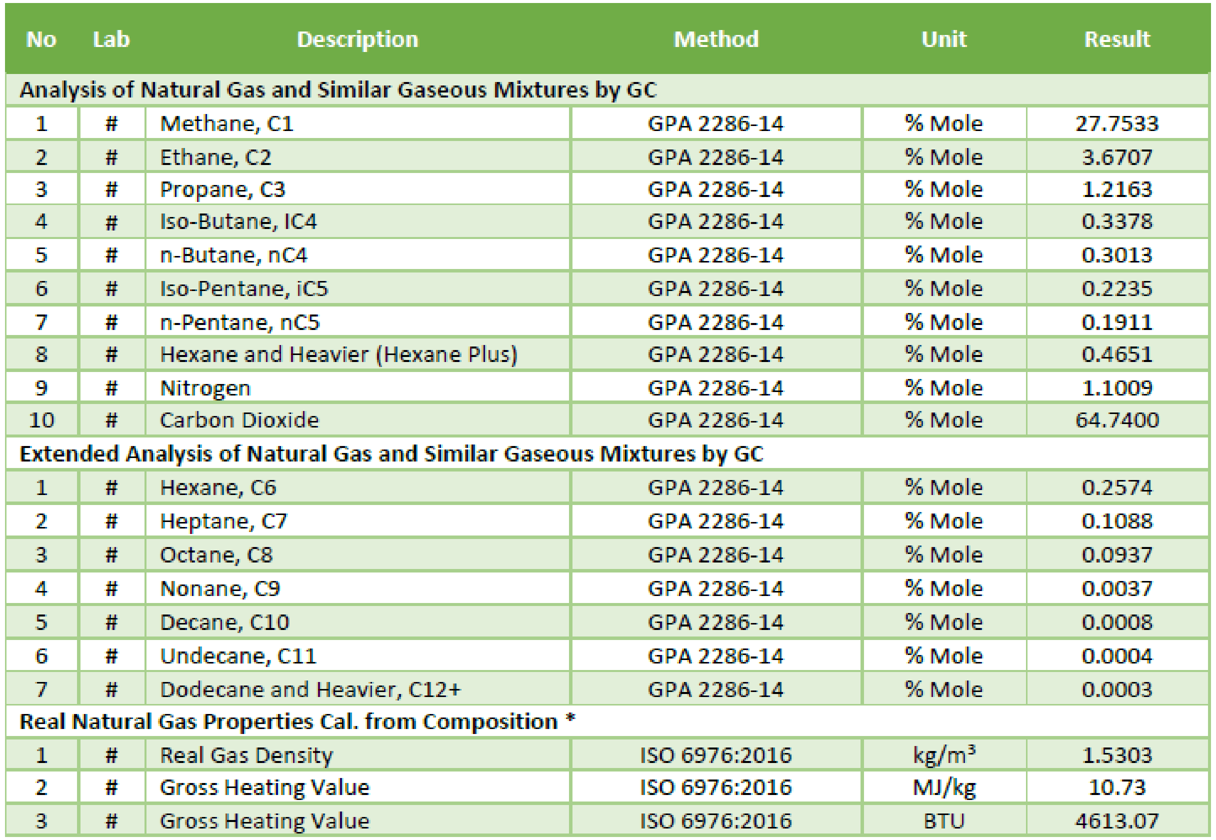
Key observation:

- presence of Mercury
- presence of H2S content
- presence of high moisture

Design basis:

- No mercury, H2S & moisture

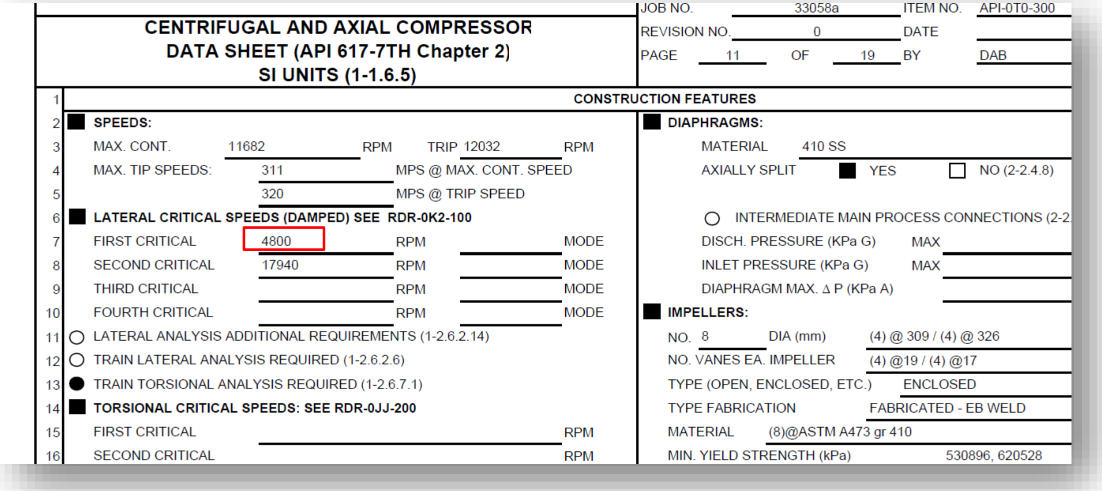
Table 2: Gas GC Compo Analysis



No	Lab	Description	Method	Unit	Result
Analysis of Natural Gas and Similar Gaseous Mixtures by GC					
1	#	Methane, C1	GPA 2286-14	% Mole	27.7533
2	#	Ethane, C2	GPA 2286-14	% Mole	3.6707
3	#	Propane, C3	GPA 2286-14	% Mole	1.2163
4	#	Iso-Butane, IC4	GPA 2286-14	% Mole	0.3378
5	#	n-Butane, nC4	GPA 2286-14	% Mole	0.3013
6	#	Iso-Pentane, iC5	GPA 2286-14	% Mole	0.2235
7	#	n-Pentane, nC5	GPA 2286-14	% Mole	0.1911
8	#	Hexane and Heavier (Hexane Plus)	GPA 2286-14	% Mole	0.4651
9	#	Nitrogen	GPA 2286-14	% Mole	1.1009
10	#	Carbon Dioxide	GPA 2286-14	% Mole	64.7400
Extended Analysis of Natural Gas and Similar Gaseous Mixtures by GC					
1	#	Hexane, C6	GPA 2286-14	% Mole	0.2574
2	#	Heptane, C7	GPA 2286-14	% Mole	0.1088
3	#	Octane, C8	GPA 2286-14	% Mole	0.0937
4	#	Nonane, C9	GPA 2286-14	% Mole	0.0037
5	#	Decane, C10	GPA 2286-14	% Mole	0.0008
6	#	Undecane, C11	GPA 2286-14	% Mole	0.0004
7	#	Dodecane and Heavier, C12+	GPA 2286-14	% Mole	0.0003
Real Natural Gas Properties Cal. from Composition *					
1	#	Real Gas Density	ISO 6976:2016	kg/m^3	1.5303
2	#	Gross Heating Value	ISO 6976:2016	MJ/kg	10.73
3	#	Gross Heating Value	ISO 6976:2016	BTU	4613.07

Compressor major parts i.e., material for impeller, diaphragms, shaft, etc.: SS410 (not susceptible to H2S)

Possible Causes #3 – Rotodynamic Instability (Self-Excited)



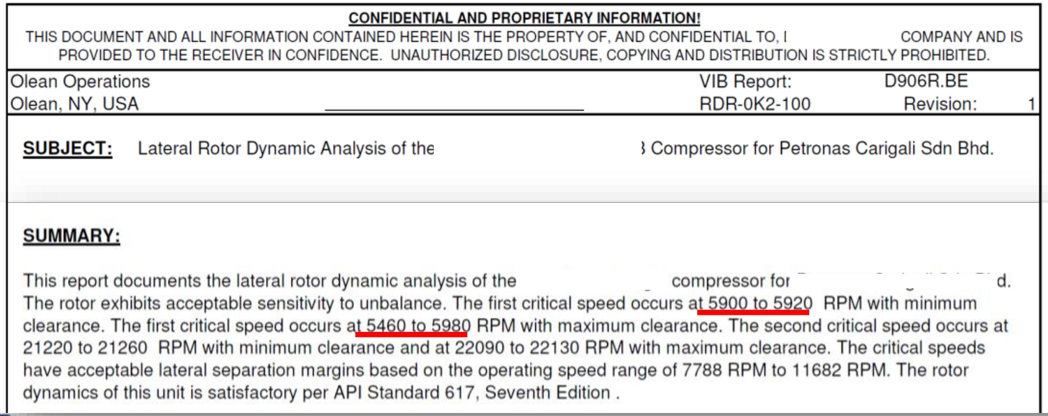
JOB NO. 33058a ITEM NO. API-0T0-300
REVISION NO. 0 DATE
PAGE 11 OF 19 BY DAB

CENTRIFUGAL AND AXIAL COMPRESSOR
DATA SHEET (API 617-7TH Chapter 2)
SI UNITS (1-1.6.5)

CONSTRUCTION FEATURES

2	■ **SPEEDS:**	■ **DIAPHRAGMS:**
3	MAX. CONT. 11682 RPM TRIP 12032 RPM	MATERIAL 410 SS
4	MAX. TIP SPEEDS: 311 MPS @ MAX. CONT. SPEED	AXIALLY SPLIT ■ YES ☐ NO (2-2.4.8)
5	320 MPS @ TRIP SPEED	
6	■ **LATERAL CRITICAL SPEEDS (DAMPED) SEE RDR-0K2-100**	○ INTERMEDIATE MAIN PROCESS CONNECTIONS (2-2
7	FIRST CRITICAL 4800 RPM MODE	DISCH. PRESSURE (KPa G) MAX
8	SECOND CRITICAL 17940 RPM MODE	INLET PRESSURE (KPa G) MAX
9	THIRD CRITICAL RPM MODE	DIAPHRAGM MAX. Δ P (KPa A)
10	FOURTH CRITICAL RPM MODE	■ **IMPELLERS:**
11	○ LATERAL ANALYSIS ADDITIONAL REQUIREMENTS (1-2.6.2.14)	NO. 8 DIA (mm) (4) @ 309 / (4) @ 326
12	○ TRAIN LATERAL ANALYSIS REQUIRED (1-2.6.2.6)	NO. VANES EA. IMPELLER (4) @19 / (4) @17
13	● TRAIN TORSIONAL ANALYSIS REQUIRED (1-2.6.7.1)	TYPE (OPEN, ENCLOSED, ETC.) ENCLOSED
14	■ **TORSIONAL CRITICAL SPEEDS: SEE RDR-0JJ-200**	TYPE FABRICATION FABRICATED - EB WELD
15	FIRST CRITICAL RPM	MATERIAL (8)@ASTM A473 gr 410
16	SECOND CRITICAL RPM	MIN. YIELD STRENGTH (kPa) 530896, 620528

Original Rotor – API datasheet



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Olean Operations VIB Report: D906R.BE
Olean, NY, USA RDR-0K2-100 Revision: 1

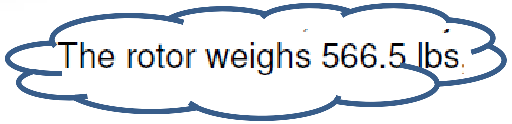
SUBJECT: Lateral Rotor Dynamic Analysis of the 3 Compressor for Petronas Carigali Sdn Bhd.

SUMMARY:

This report documents the lateral rotor dynamic analysis of the compressor for d. The rotor exhibits acceptable sensitivity to unbalance. The first critical speed occurs at 5900 to 5920 RPM with minimum clearance. The first critical speed occurs at 5460 to 5980 RPM with maximum clearance. The second critical speed occurs at 21220 to 21260 RPM with minimum clearance and at 22090 to 22130 RPM with maximum clearance. The critical speeds have acceptable lateral separation margins based on the operating speed range of 7788 RPM to 11682 RPM. The rotor dynamics of this unit is satisfactory per API Standard 617, Seventh Edition .

Spare Rotor – lateral analysis report

Description	Original Rotor	Spare Rotor
Installation date	Commissioned in 2013 and in service until Q4 2018	Replaced in Q4 2018 & failed in March 2019
Design 1st Critical Speed (CS)	**4800 rpm** (no details specify for minimum & maximum clearance	**5460 – 5980** maximum clearance 5900 – 5920 minimum clearance
Actual 1st Critical Speed	**5000 – 5100 rpm**	**5700 – 5800 rpm**
Idling speed	• **5840 rpm** (during in operation)	
Other information	• Spare rotor **weight different** about 10% 566 lbs (original) . vs 510 lbs (spare) • Past record original bundle went for impeller trim / minor modification to address discharge temp issue • It was suspected that the clearance used for spare rotor is towards maximum value	



The rotor weighs 566.5 lbs.

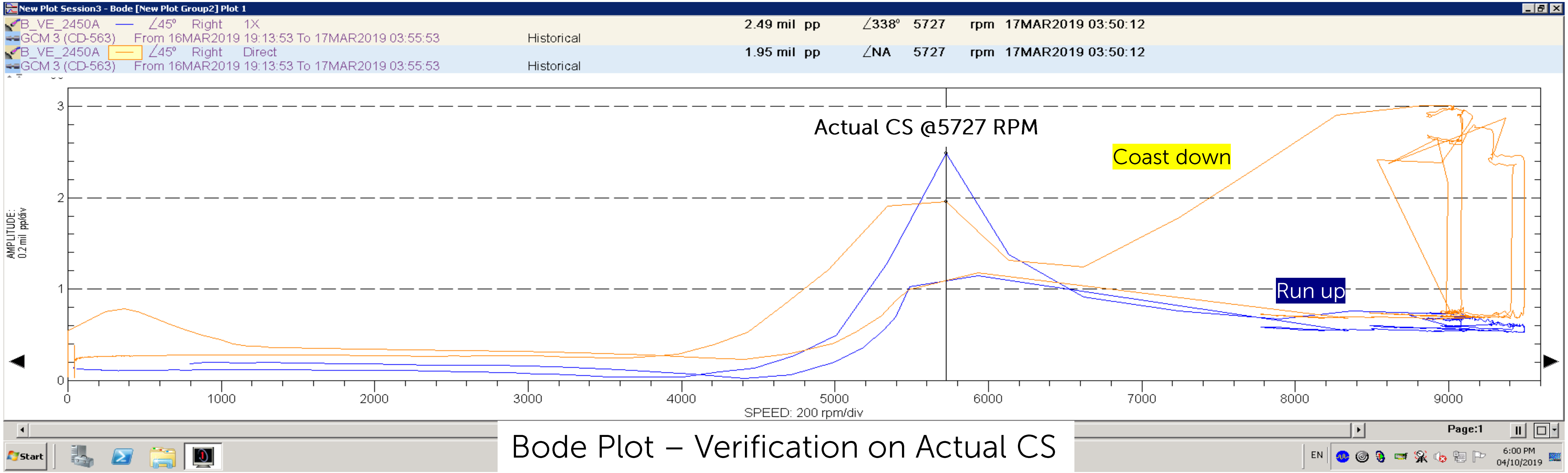
VS

MAINTENANCE WEIGHTS
ROTOR------------------------ 510 LBS. (231 KGS.)

Original rotor

Spare rotor

Finding on Rotor 1st Critical Speed Changes



New Plot Session3 - Bode [New Plot Group2] Plot 1

B_VE_2450A	—	∠45°	Right	1X	2.49 mil pp	∠338°	5727	rpm	17MAR2019 03:50:12
GCM 3 (CD-563)	From 16MAR2019 19:13:53 To 17MAR2019 03:55:53			Historical					
B_VE_2450A	—	∠45°	Right	Direct	1.95 mil pp	∠NA	5727	rpm	17MAR2019 03:50:12
GCM 3 (CD-563)	From 16MAR2019 19:13:53 To 17MAR2019 03:55:53			Historical					

Bode Plot – Verification on Actual CS

Spare rotor: lower mass & max clearance

Actual 1st critical around **5700-5800 rpm**

Unit **idling** speed is **5840 rpm**

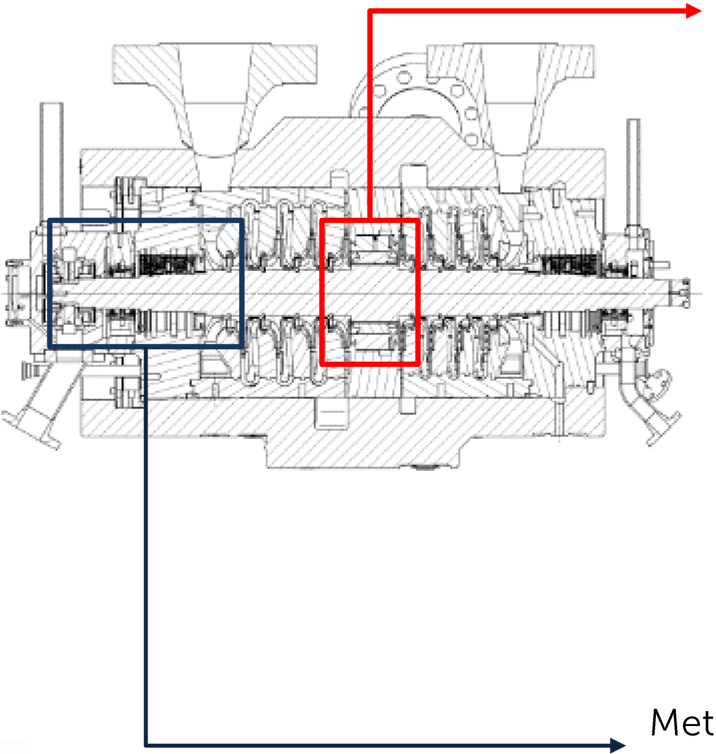
Idle scenario: During **startup**, cool down **stop**, **trip to idle**

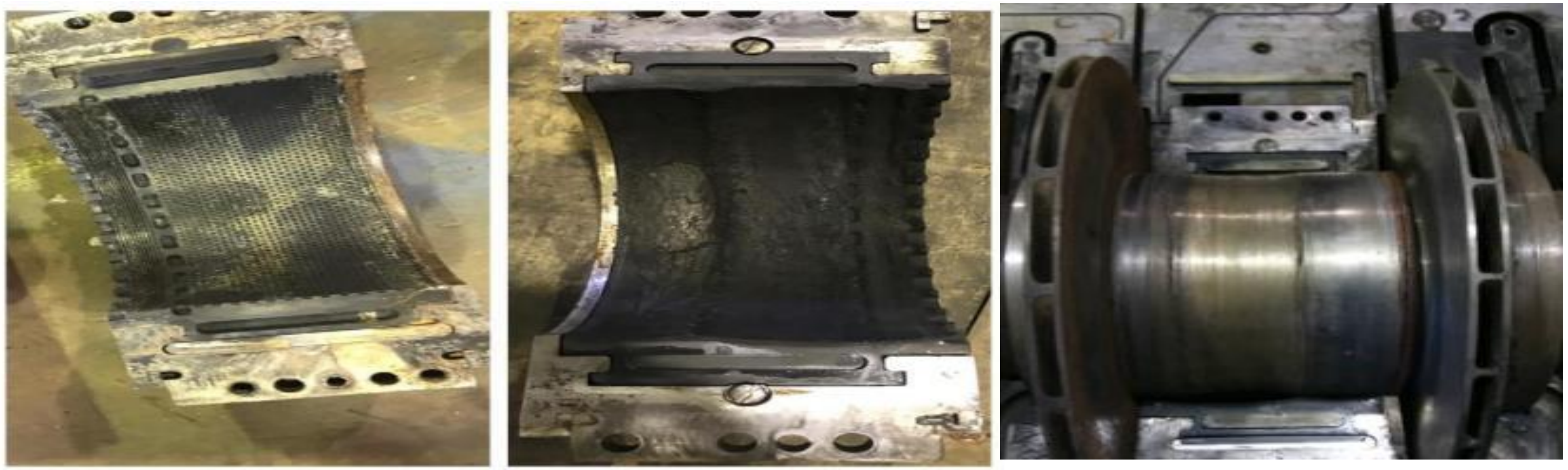
Expected period in idle from Dec 18 to Mar 19 > **60 minutes**

Separation Margin (SM) is about **2% only !!**

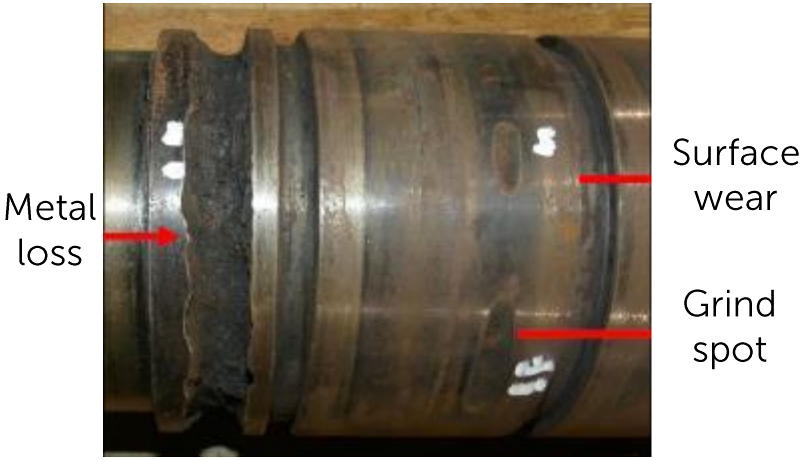
Possible Causes #4 – Excessive Clearance of Internal Component

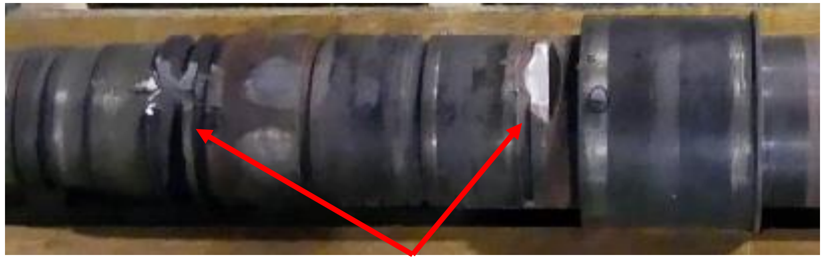
Excessive clearance at **center seal due to rubbing**





3rd & 4th stage compressor centre seal (honey comb) badly rubbed & sleeve materials loss





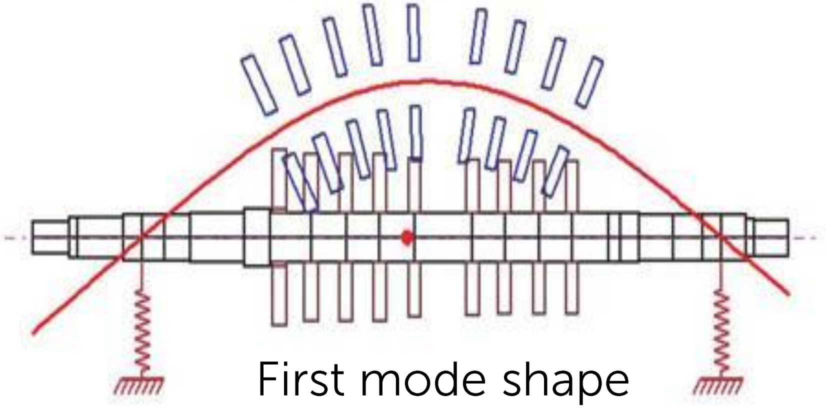
Shaft Rotor – damage area

Conclusion & Recommendation

No	Possible Causes	Conclusion	Recommendation
1	Hydrodyamic instability from fluid film	Not a concern	No further action. Maintain lube oil parameters & quality
2	Aerodynamic induced instability	Minor concern & less significant	Rectify passing & broken check valves
3	Aerodynamic induced instability	Concern (erosion & pitting on internal components due to process gas contaminants)	Replace affected compressor components, improve compressor materials (refer to next slide)
4	Rotor dynamic instability (self-excitation)	Main concern (idling speed vs. critical speed is <2% of separation margin	Change compressor idling speed to avoid coinciding with rotor 1st critical speed
5	Excessive clearance on internal parts/components	Main concern (consequent from no#4 and accelerated due to contaminants)	As of no#4, address source of moisture & H2S in process gas, improve compressor materials (refer to next slide)

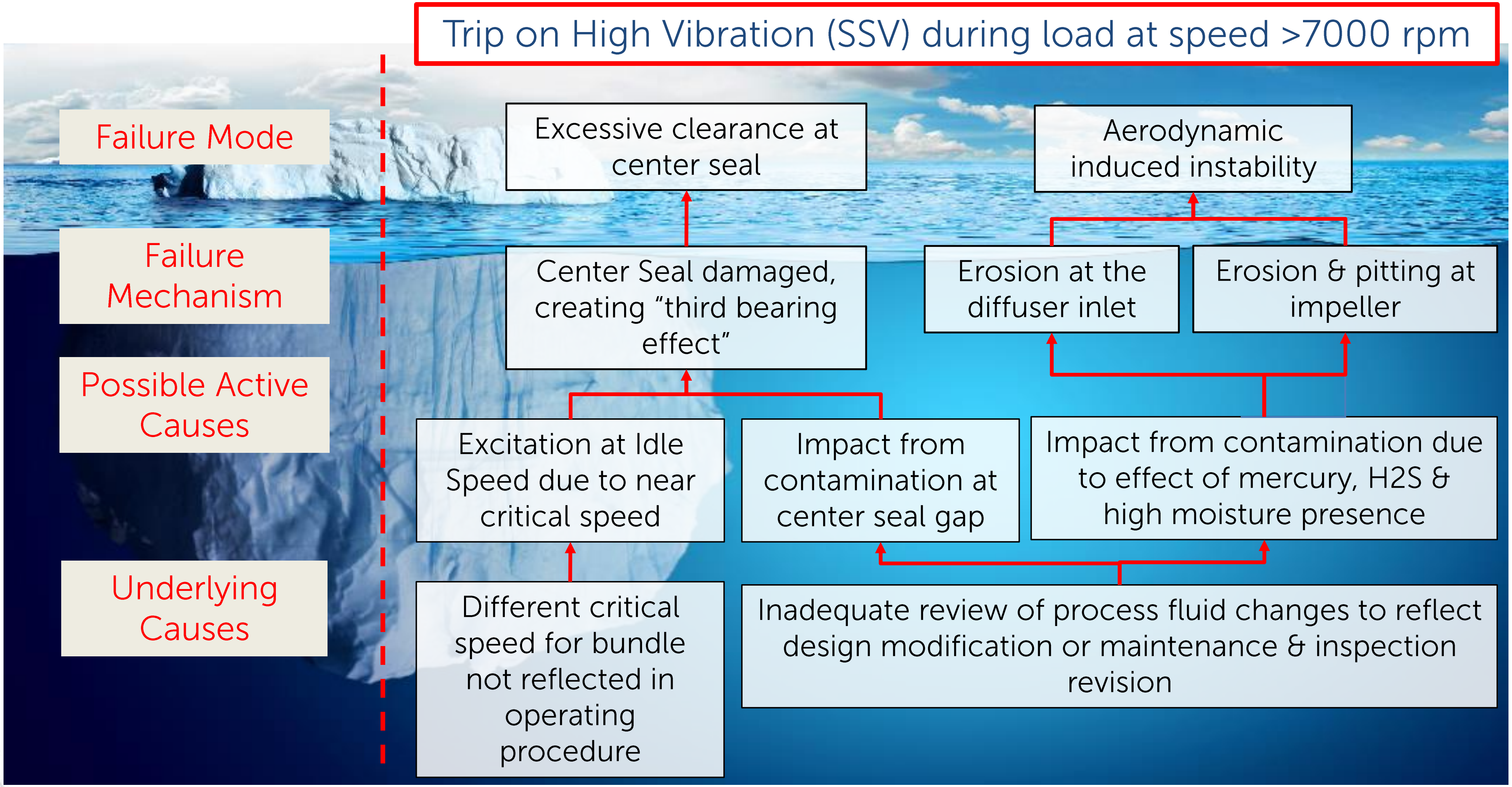
Conclusion & Recommendation (cont.)

- Presence of moisture, contaminant & H2S led to component deterioration and damage not only to upstream facilities such as piping/scrubber but also to compressor internal components
- Such debris & contaminants unfortunately pass thru & stuck at critical area ie. center seal clearance creating some rubbing effect
- In addition, the situation worsen when spare compressor installed in 2018 having different rotor 1st critical speed which is 5727 rpm vs. 4800 rpm (original)
- This resulting rotor resonate whenever unit at idle speed (5840 rpm, <2% seperation margin). The rotor resonance at 1st CS with first mode shape will have largest deflection on the center leading to more exposure towards rubbing and causing severe damage to center seal
- Excessive clearance at damaged center seal behave like “third bearing” effect and causing machine experiencing stall and/or aerodynamic instability as observe from <u>sub-synchronous vibration (SSV)</u>



First mode shape

Conclusion & Recommendation (cont.)



Trip on High Vibration (SSV) during load at speed >7000 rpm

Failure Mode
- Excessive clearance at center seal
- Aerodynamic induced instability

Failure Mechanism
- Center Seal damaged, creating "third bearing effect"
- Erosion at the diffuser inlet
- Erosion & pitting at impeller

Possible Active Causes
- Excitation at Idle Speed due to near critical speed
- Impact from contamination at center seal gap
- Impact from contamination due to effect of mercury, H2S & high moisture presence

Underlying Causes
- Different critical speed for bundle not reflected in operating procedure
- Inadequate review of process fluid changes to reflect design modification or maintenance & inspection revision

Solutions Implementation

Process gas supply

- Temporary shut-in flowing well with high moisture / H2S / mercury concentration [completed]
- Periodic process gas sampling & analysis [completed]

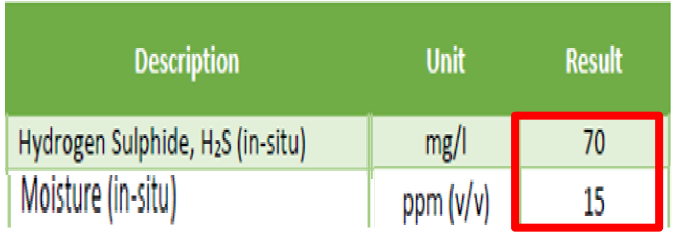
Suction scrubber

- Scrubber efficiency adequacy review & simulation [completed]
- Level control function test & periodic calibration to avoid liquid carry over [completed]

Operation / Process

- Replaced passing & parted check valves [completed]
- Periodic compressor draining during start-up after long standby [completed]

Result:

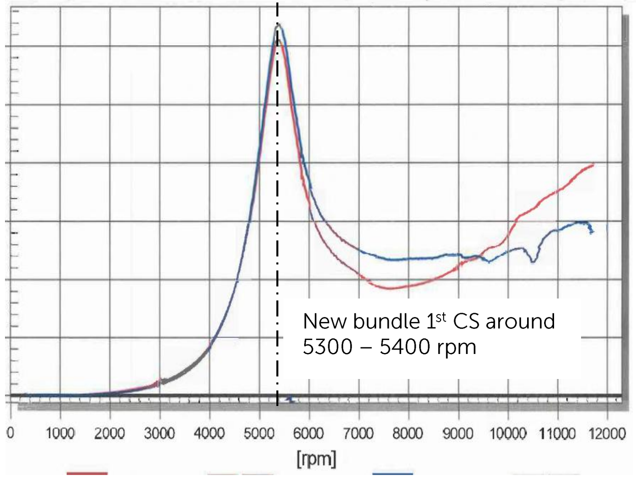


Description	Unit	Result
Hydrogen Sulphide, H_2S (in-situ)	mg/l	70
Moisture (in-situ)	ppm (v/v)	15

- H2S concentration reduce from +110 mg/l to +/-70 mg/l (35% reduction)
- Moisture content reduce from 5100 ppm to 15 – 100 ppm (>90% reduction)

Solutions Implementation (cont.)

Amplitude/Phase over Speed (Bode Diagram)



New bundle 1st CS around 5300 – 5400 rpm

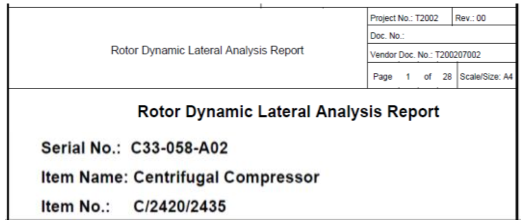
15% SM from 5400 rpm = 6210 rpm

Adjust compressor idling from 5840 rpm to 6420 rpm (>15% separation margin)

[completed]

Request **documentation on rotor dynamic** with OEM for each bundle purchase

[completed]



Rotor Dynamic Lateral Analysis Report	Project No.: T2002	Rev.: 00
	Doc. No.:	
	Vendor Doc. No.: T200207002	
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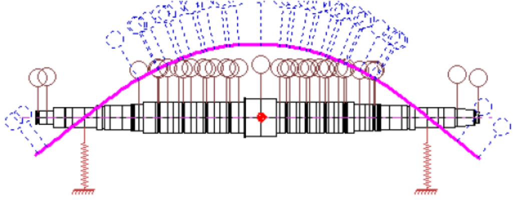
Rotor Dynamic Lateral Analysis Report

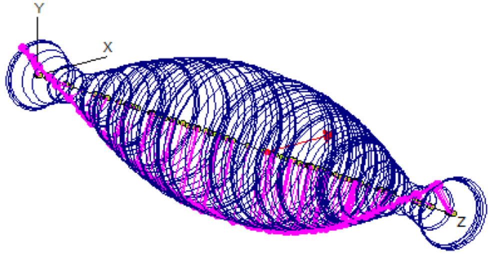
Serial No.: C33-058-A02

Item Name: Centrifugal Compressor

Item No.: C/2420/2435

Critical Speed Mode Shape, Mode No.= 1
Spin/Whirl Ratio = 1, Stiffness: (Kxx+Kyy)/2
Critical Speed = 5600 rpm = 97.76 Hz





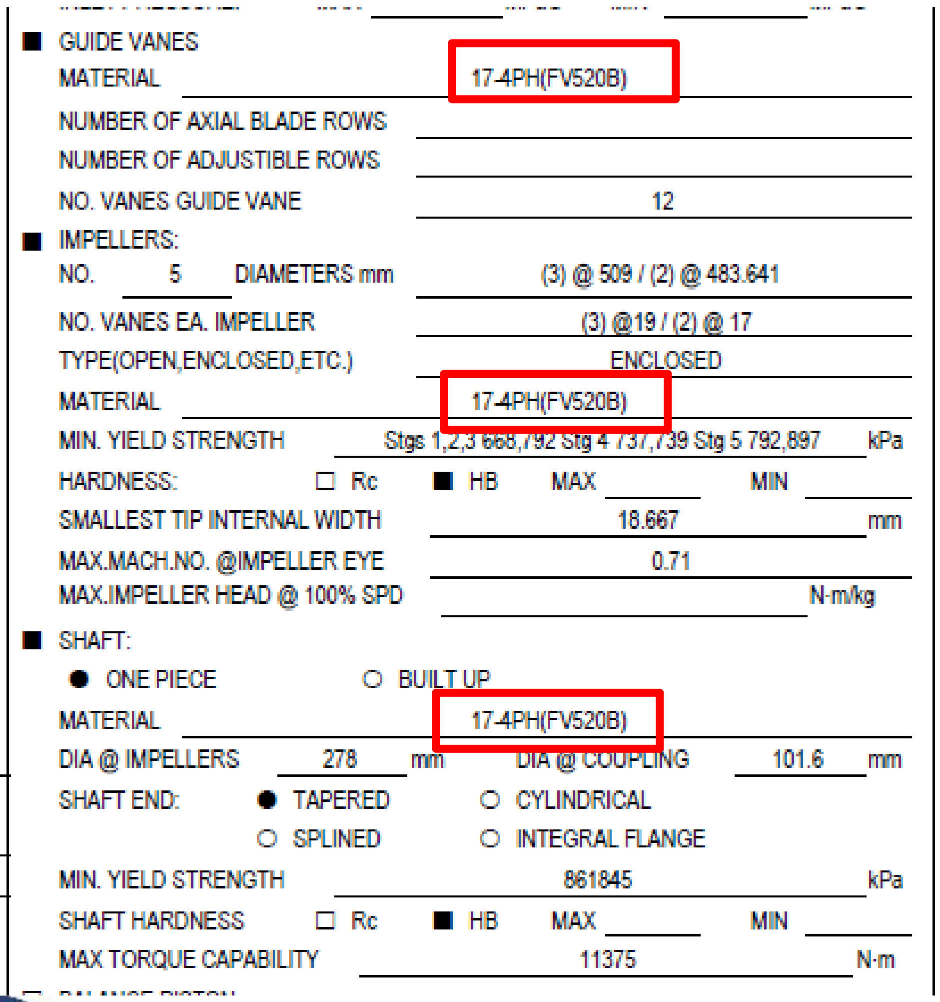
Bundle replacement with **better materials** grade SS 17-4PH, NACE compliance [completed]

Compressor related rectification

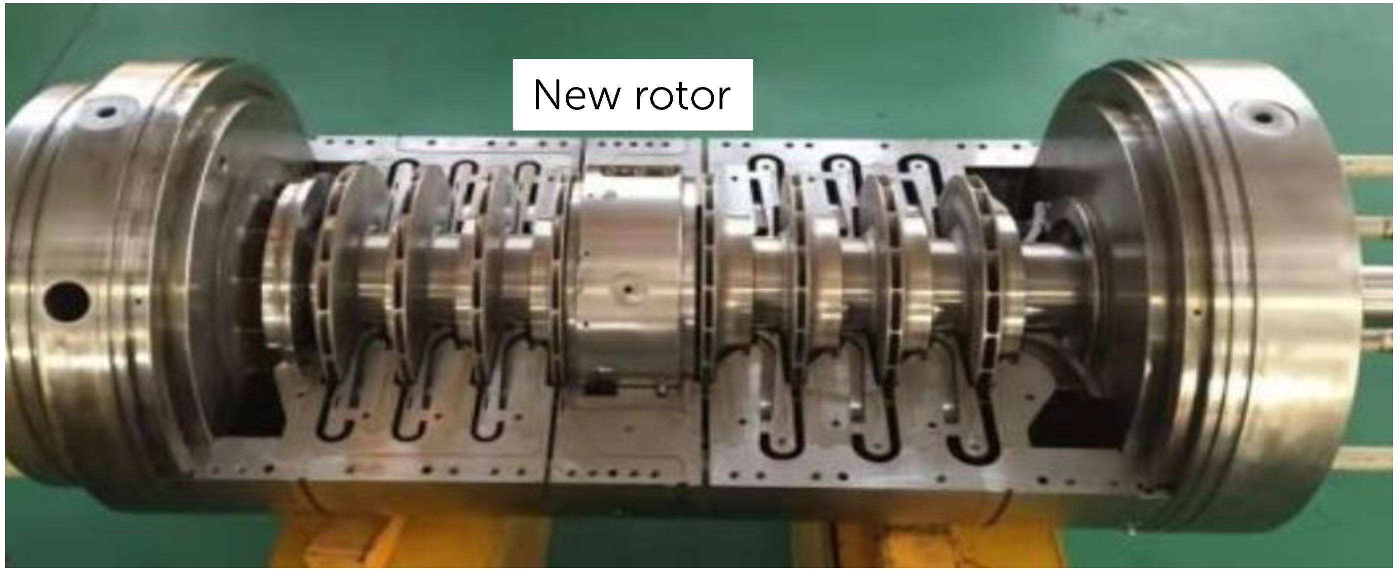
Revise practice to **capture actual critical speed** data every start-up post maintenance work

[completed]

Solutions Implementation (cont.)

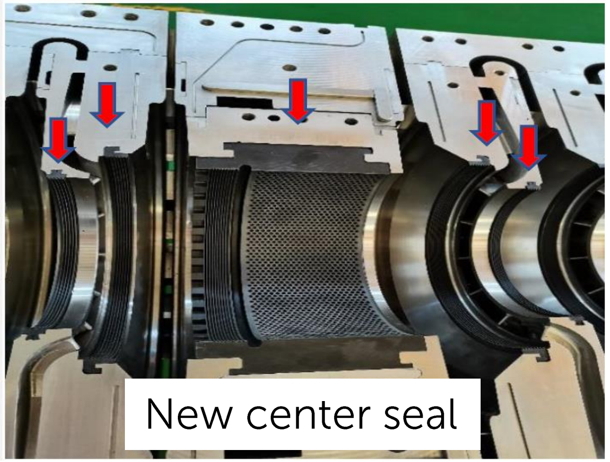


■ GUIDE VANES
MATERIAL 17-4PH(FV520B)
NUMBER OF AXIAL BLADE ROWS
NUMBER OF ADJUSTIBLE ROWS
NO. VANES GUIDE VANE 12
■ IMPELLERS:
NO. 5 DIAMETERS mm (3) @ 509 / (2) @ 483.641
NO. VANES EA. IMPELLER (3) @19 / (2) @ 17
TYPE(OPEN,ENCLOSED,ETC.) ENCLOSED
MATERIAL 17-4PH(FV520B)
MIN. YIELD STRENGTH Stgs 1,2,3 668,792 Stg 4 737,739 Stg 5 792,897 kPa
HARDNESS: ☐ Rc ■ HB MAX MIN
SMALLEST TIP INTERNAL WIDTH 18.667 mm
MAX.MACH.NO. @IMPELLER EYE 0.71
MAX.IMPELLER HEAD @ 100% SPD N-m/kg
■ SHAFT:
● ONE PIECE ○ BUILT UP
MATERIAL 17-4PH(FV520B)
DIA @ IMPELLERS 278 mm DIA @ COUPLING 101.6 mm
SHAFT END: ● TAPERED ○ CYLINDRICAL
○ SPLINED ○ INTEGRAL FLANGE
MIN. YIELD STRENGTH 861845 kPa
SHAFT HARDNESS ☐ Rc ■ HB MAX MIN
MAX TORQUE CAPABILITY 11375 N-m



New rotor

New compressor bundle



New center seal

Bundle replacement using better material: 17-4PH

Summary & Lesson Learnt

13th May 19

Unit back online

- Solutions implemented

Feb 2022

Running

- No SSV, vibration acceptable at >8000 rpm

Running normal close to 2 years !!

- Process fluid such as gas composition recommended to be verified on periodic interval (i.e., yearly basis) for any significant changes. This input is critical to ensure any intervention required for centrifugal compressor safe operation

- Idle speed & running speed need to meet API requirement with >15% seperation margin from rotor critical speed to avoid vibration related impact

- SSV may be contributed from several factor, thus proper elimination process is deemed necessary to narrow down the root cause that create excitation force

- Out of clearance for center seal create “third bearing” effect & stall that resulted in high SSV amplitude

Thank You