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IMPROVED COMPRESSOR IMPELLER DESIGN TO OVERCOME SULPHIDE STRESS CRACKING (SSC)

Presented By:

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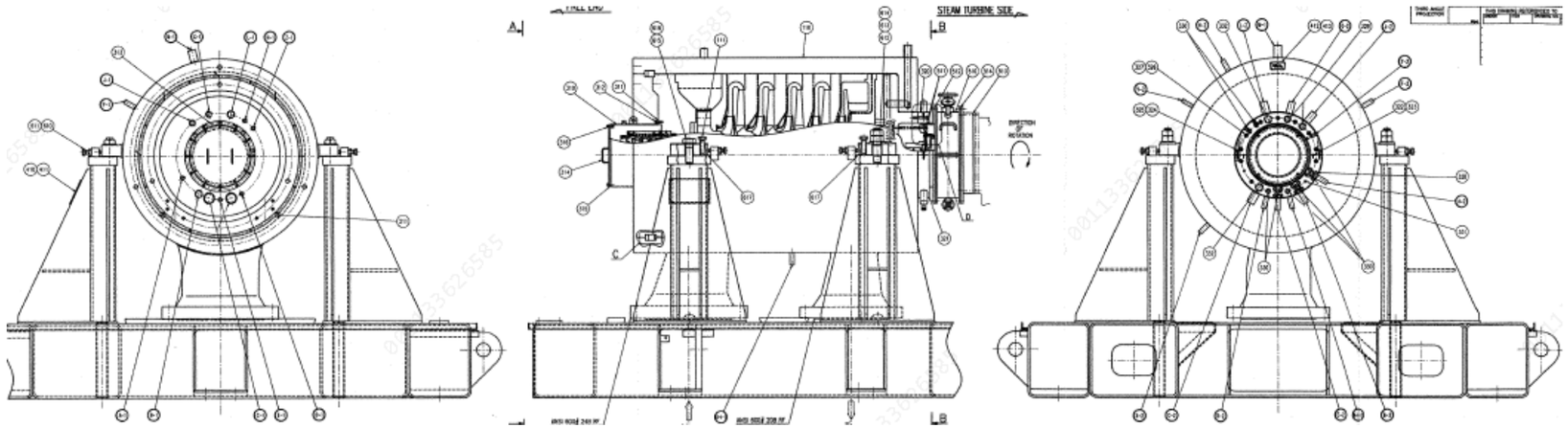
INTRODUCTION

K-5301-LP compressor is MHI centrifugal compressor containing 5 impellers to compress the synthetic gas after steam Reforming. Casing both ends are seal with Tandem dry gas seals, and safeguarded with speed control logic, Anti-surge protection , vibration and temperatures trips. Designed as per API-617 and commissioned in 2008.

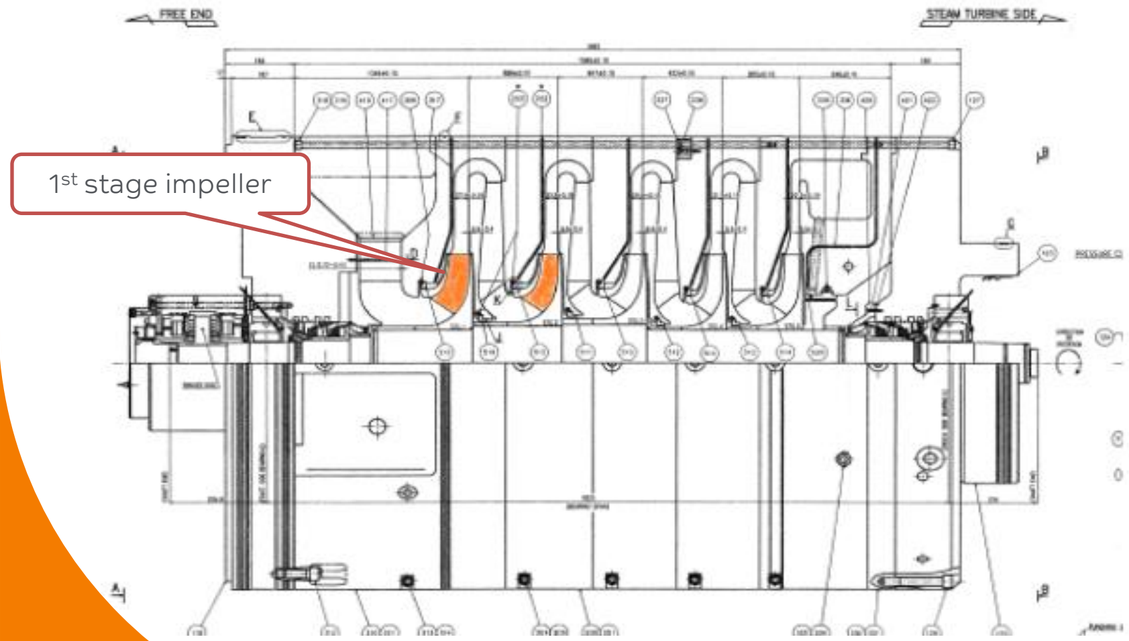


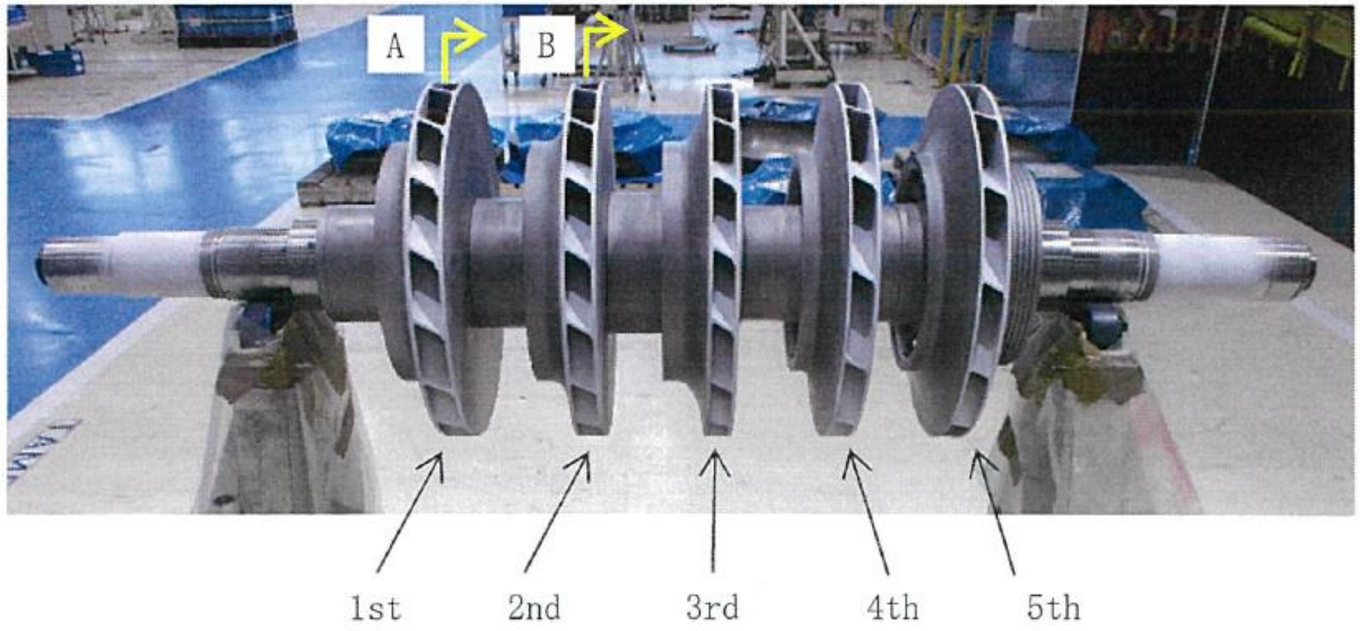
Machine type	Centrifugal Multi-stage Compressor
Number of stages	5V-5
Speed	8200 R.P.M
Required power	17 MW
Capacity	21820 M3/h
Inlet / outlet Pressure	31 / 60 Kg/cm2
Inlet / outlet Temperature	45 / 120 °C
Polytropic Head	18137 Kg-m/Kg
Polytropic Efficiency	84%

PROBLEM STATEMENT

During 2017 TAM as per maintenance strategy of K-5301-LP , internal inspection done and found yellowish color gas deposit on first two impellers, In addition detail inspection of rotor assembly at OEM shop done and multi-cracks at 2nd stage impeller were observed and repaired . In 2020 TAM , internal inspection done for other rotor and founded also with cracks in 1st and 2nd stage impellers. Investigation studies performed with involvement of MCO, SABIC - material engineering, SABIC-COE and Process Engineering and the damage mechanism were identified and concluded along with required countermeasures.

- **AR-19-0001** : Metallurgical & Corrosion Analysis (MCA) group- Jubail .
- **AR-21-0003**: Metallurgical & Corrosion Analysis (MCA) group- Jubail .
- **MCO** – fracture analysis and RCA.
- **MSR # 6921221** by SABIC material engineering.

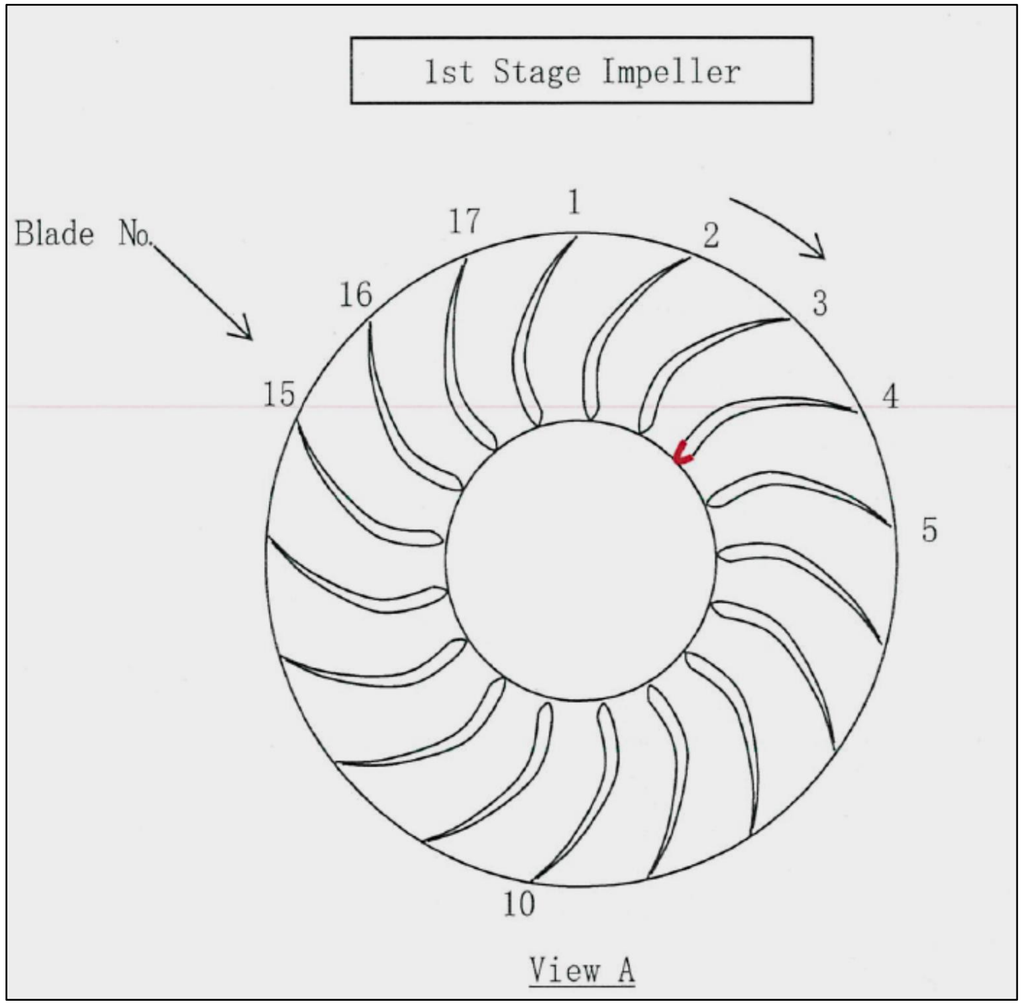


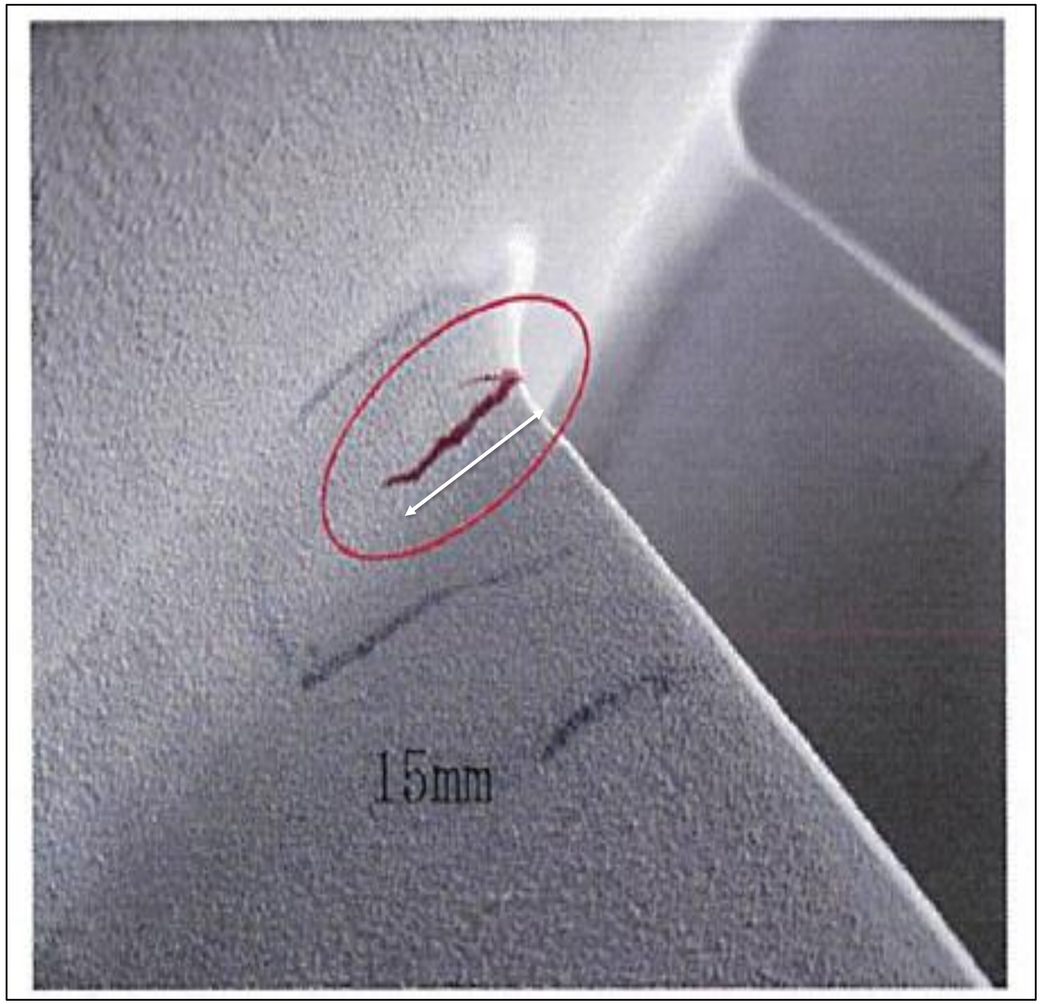


K-5301-LP ROTORS HISTORY

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Rotor serial # (L6-310)	Shipping	Commissioning & start operation	→	→	→	→	→		Rotor inspection without any impeller cracks		→	→	→	→	Rotor inspection and 1 cracks found in 1st Impeller and 17 cracks in 2nd stage impeller
Rotor serial # (L6-311)	Shipping	Preserve at warehouse					Turn Around & Rotor Replacement				Turn Around & Rotor Replacement	Rotor inspection and 15 cracks found in 2nd stage impeller		Turn Around Rotor Replacement	→

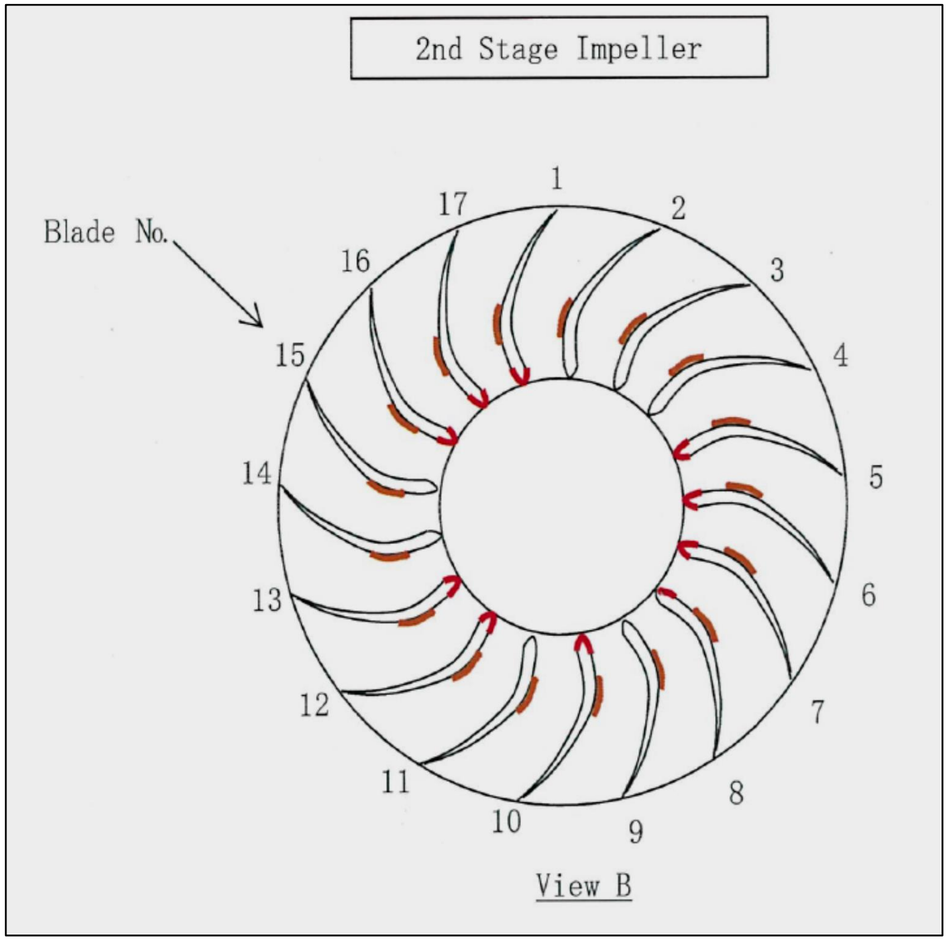
K-5301-LP CRACK FINDINGS (1ST STAGE)

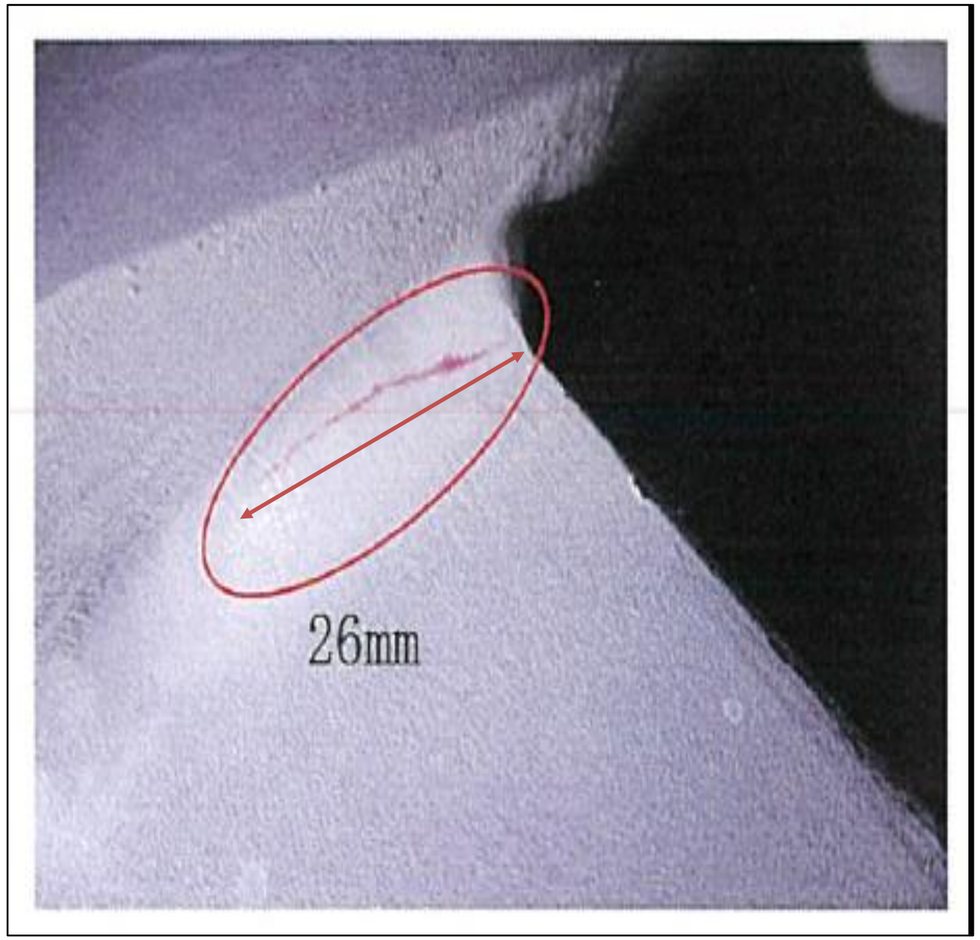




Crack in vane # 4 of 1st stage impeller as of 2020 TA

K-5301-LP CRACK FINDINGS (2ND STAGE)



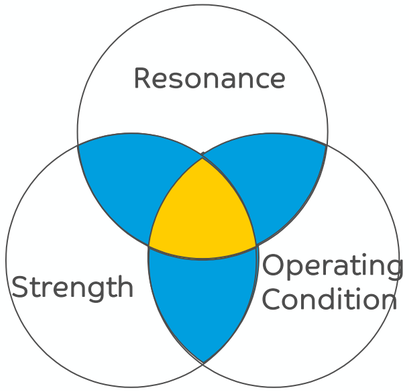


Crack in vane # 7 of 2nd stage impeller as of 2020 TA

POSSIBLE CAUSES FOR IMPELLERS CRACKS

Based on RC investigation and analysis result performed with OEM, the most possible causes for founded cracks are:

- Inadequate Impellers design with respect to resonance safety margin .
- Impeller miss material selection and fabrication .
- Up normal operating condition (overloading , oscillate loading , surging , liquid ingress , gas impurities and deviation from design components.

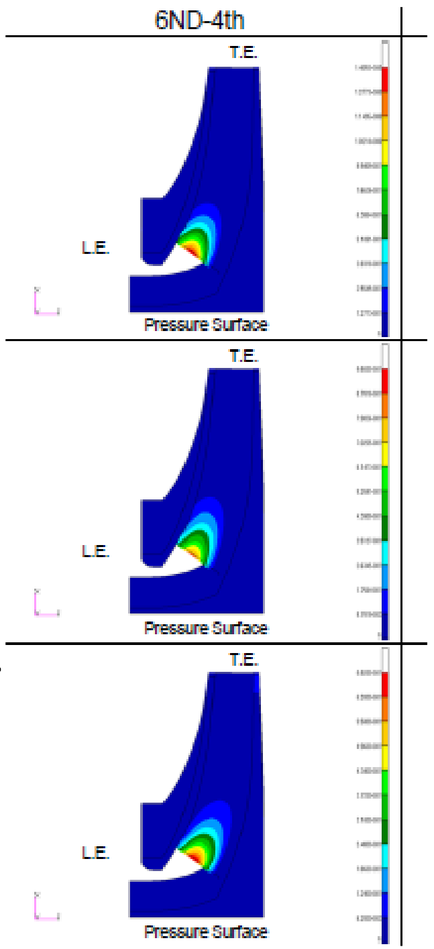


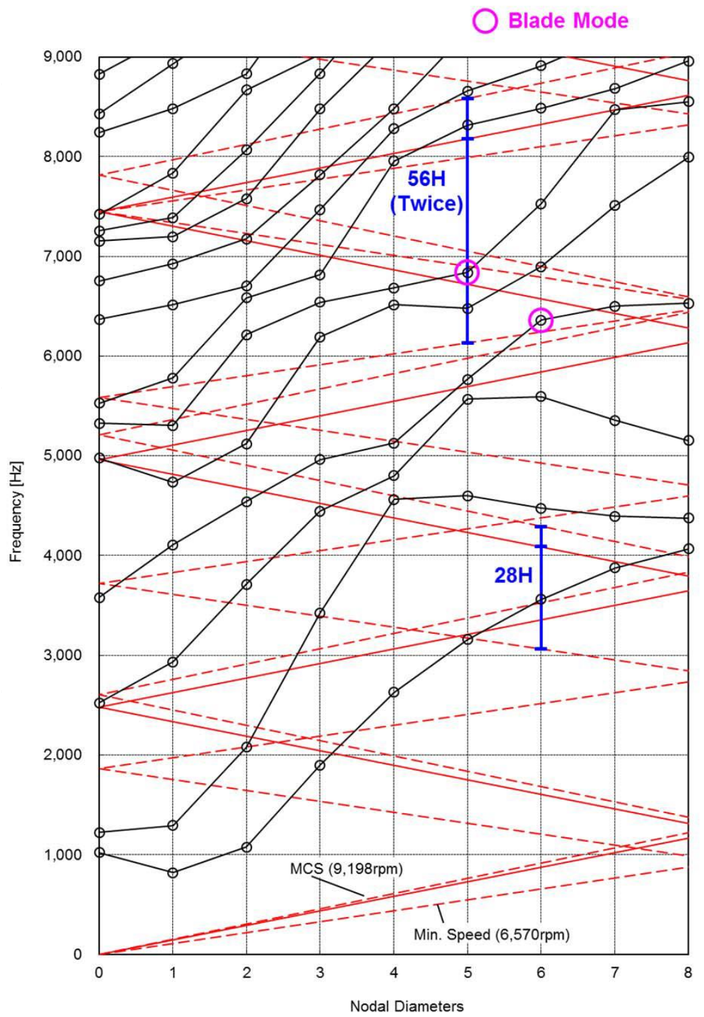
POSSIBLE CAUSES FOR IMPELLERS CRACKS

- **Inadequate Impellers design with respect to resonance safety margin .**

  - Engineering study was done for 2nd impeller on Syn. Gas Compressor LP, especially focused on the influence of resonance.
  - Impeller natural frequency and vibratory mode was evaluated by FE analysis.
  - Concerned vibratory mode (blade mode) is 6ND-4th, and its separation margin is 48.2%. It was confirmed that 6ND-4th is surely avoided.
  - Wake flow (28H and 56H) harmonics was evaluated by dynamic flow analysis at design point.
  - Suspected resonance conditions have enough large safety factor for fatigue limit.

Therefore, it is unlikely that the impeller was damaged just only by the influence of blade-row interference.





POSSIBLE CAUSES FOR IMPELLERS CRACKS

❑ Impeller miss material selection and fabrication

- With use of XRF and C/S analyzers in SABIC Jubail analytical lab , confirmed the base material and hardness level are matching SNCM431 as in Data sheet. However, the hardness at weldment is slightly higher than limits .

Table 10: Hardness value measurements for the cracked vanes

indentation #	Vane #2	Vane #9	Vane #14	Vane #14 Weld
1	329	329 (Weld)	325	436.1
2	333.1	344.2 (Weld)	281.6	441.5
3	327	343.3 (Weld)	303.5	477.5
4	340.7	303.7	288.7	432.7
5	337.3	323.3	314.7	473.7
6	338.1	320.5	306.4	
7	347.7	317.8	316.2	
8	340.7		309.8	
9			339	
10			328.1	
11			339.9	
Average measured hardness (HV0.5)	336.7	325.9	313.9	452.3
Average measured HB (converted)	319	309	298	427
Reference hardness SNCM 431 (HB)	269 – 321			

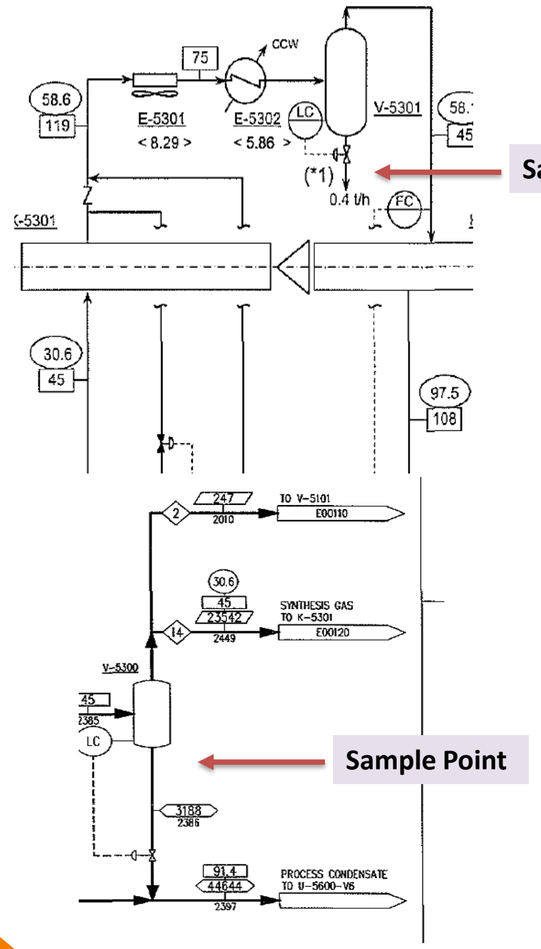
Table 1: Chemical Composition by XRF and C/S Analyzers for Vane# 02

Element	Vane# 02 Conc. %	Reference SNCM 431
Al	Tracing	
Cr	0.794	0.6 – 1.0
Co	0.041	
Cu	0.046	
Fe	Balance	
Mn	0.664	0.6 – 0.9
Mo	0.244	0.15 – 0.30
Nb	Tracing	
Ni	1.835	1.6 – 2.0
P	Tracing	0.03 max
S*	0.035	0.03 max
C*	0.279	0.27- 0.35
Si	0.276	0.15 – 0.35
Ti	Tracing	
V	Tracing	

*Carbon/sulfur analyzer

POSSIBLE CAUSES FOR IMPELLERS CRACKS

Up normal operating condition (liquid ingress , gas impurities and deviation from design components).



Sample Point

Sample Point

To Analyze Cd , PH , Na , Cl , Si , Fe , TDS & TSS for V-5301

Sample #: 23766412	Product:		Grade:		Batch/Lot:
25/01/21 8:22	pH	7.57		-	No Specs
25/01/21 8:22	Conductivity	4720.00	←	µS/cm	No Specs
25/01/21 8:22	Silica	0.02		mg/L	No Specs
25/01/21 8:22	Chloride	4.81	←	mg/L	No Specs
25/01/21 8:22	Sodium (Na)	3.87	←	mg/L	No Specs
25/01/21 8:22	Total Dissolved Solids (TDS)	3162.00		mg/L	No Specs
25/01/21 8:22	Total Suspended Solids (TSS)	<0.01		mg/L	No Specs
25/01/21 8:22	Iron (Fe)	0.02		mg/L	No Specs

Description : To Analyze Cd , PH , Na , Cl , Si , Fe , TDS & TSS for V-5301

To Analyze Cd , PH , Na , Cl , Si , Fe , TDS & TSS for V-5300

Sample #: 23766409	Product:		Grade:		Batch/Lot:
25/01/21 8:22	pH	7.48		-	No Specs
25/01/21 8:22	Conductivity	11120.00	←	µS/cm	No Specs
25/01/21 8:22	Silica	0.04		mg/L	No Specs
25/01/21 8:22	Chloride	1.53	←	mg/L	No Specs
25/01/21 8:22	Sodium (Na)	1.70	←	mg/L	No Specs
25/01/21 8:22	Total Dissolved Solids (TDS)	7450.00		mg/L	No Specs
25/01/21 8:22	Total Suspended Solids (TSS)	<0.01		mg/L	No Specs
25/01/21 8:22	Iron (Fe)	0.06		mg/L	No Specs

Description : To Analyze Cd , PH , Na , Cl , Si , Fe , TDS & TSS for V-5300

POSSIBLE CAUSES FOR IMPELLERS CRACKS

AR-E-3621OUT - E-3621Out (Process Condensate of METH-3)

Sample #: 23777638 **Product:** **Grade:** **AR-PROCESS**

27/01/21 20:44	pH	**9.29**		-
27/01/21 20:44	Conductivity	**207.00**	←	µS/cm
27/01/21 20:44	Total Dissolved Solids (TDS)	**138.00**		mg/L
27/01/21 20:44	Silica	**0.02**		mg/L
27/01/21 20:44	Chloride	**0.03**	←	mg/L
27/01/21 20:44	Sodium (Na)	**1.15**	←	mg/L
27/01/21 20:44	Iron (Fe)	**0.02**		mg/L
27/01/21 20:44	Total Suspended Solids (TSS)	**<0.01**		mg/L

Description : to analyze Cd , PH , Na , Cl , Si , Fe , TDS & TSS

Possible causes for impellers cracks:

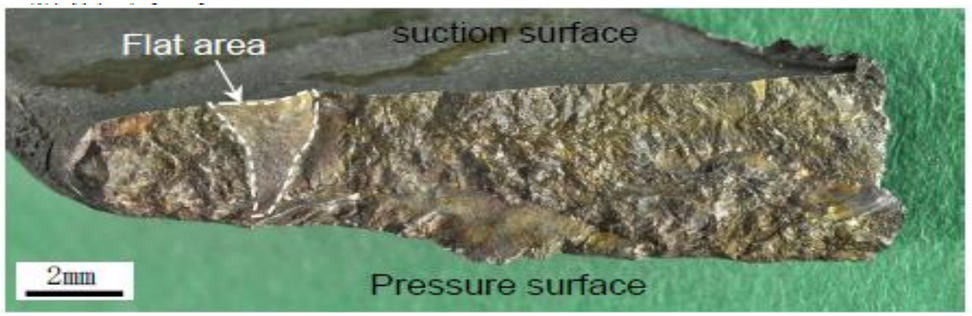
Up normal operating condition (liquid ingress , gas impurities and deviation from design components).

Table EPMA analysis result of fracture surface of 1st stage

	Detected Elements (wt%) ※1																			
	C※2	O	Na	Mg	Al	Si	P	S	Cl	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Nb+Ta	Cd	Ba
1-4-A	27.4	7.6	0.2	0.3	2.4	0.9	-	0.4	0.5	1.9	0.1	0.1	9.9	0.4	42.7	2.3	1.7	0.3Nb	0.3	0.6
1-4-B	28.3	11.5	-	0.2	0.8	0.5	0.1	1.5	0.1	0.8	-	-	9.2	0.4	38.8	2.0	1.4	0.3Nb	4.3	-
17-4PH	≦0.07	-	-	-	-	≦1.00	≦0.025	≦0.010	-	-	-	-	15.00～17.50	≦1.00	Bal.	3.00～5.00	3.00～5.00	0.15～0.45	-	-

Table EPMA analysis result of fracture surface of 2nd stage

	Detected Elements (wt%) ※1																	
	C※2	O	Na	Mg	Al	Si	P	S	Cl	Ca	Ti	Cr	Mn	Fe	Ni	Mo	Cd	Ba
2-5-A	12.2	36.8	B-Rank	-	0.1	0.2	-	0.1	0.1	0.2	B-Rank	0.3	0.7	48.8	-	-	0.4	-
2-5-B	10.2	41.3	-	-	0.1	0.1	-	0.3	-	0.1	-	0.6	0.7	45.8	-	-	0.8	-
SNCM431	0.27～0.35	-	-	-	-	0.15～0.35	≦0.030	≦0.030	-	-	-	0.60～1.00	0.60～0.90	Bal.	1.60～2.00	0.15～0.30	-	-

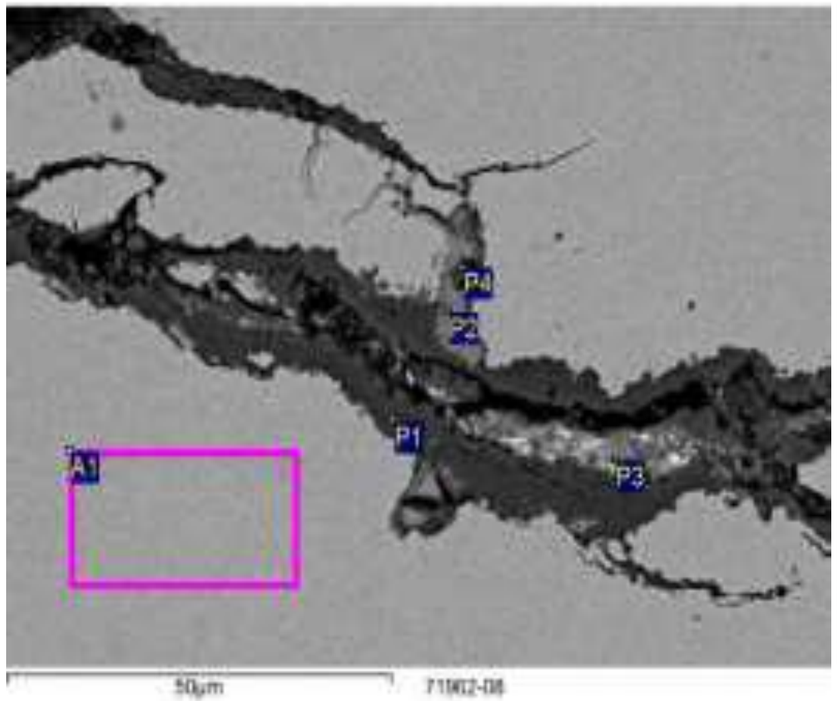


- O, Fe, C are the major observed components in fracture area.
- Na ,Mg ,Al ,Cl ,Ca ,Ti ,Cd observed as minor and are not included in Rotor materials . Its added from process gas impurities .

SULFUR AMOUNT FOUNDED IN 2017 CRACKS

2019 SABIC Analysis Report

Spectrum	C	O	Al	Si	S	Cr	Mn	Fe	Ni	Cu	Cd
P1	30.24	46.75					0.33	22.68			
P2	48.86	3.41			15.54		27.37	4.82			
P3	36.04	24.08	0.31	0.67	5.44	0.49		12.93			20.05
A1	8.11			0.33		0.88	0.66	88.26	1.77		
P4	8.30	2.23			21.99	0.76	5.74	58.50	1.15	1.32	

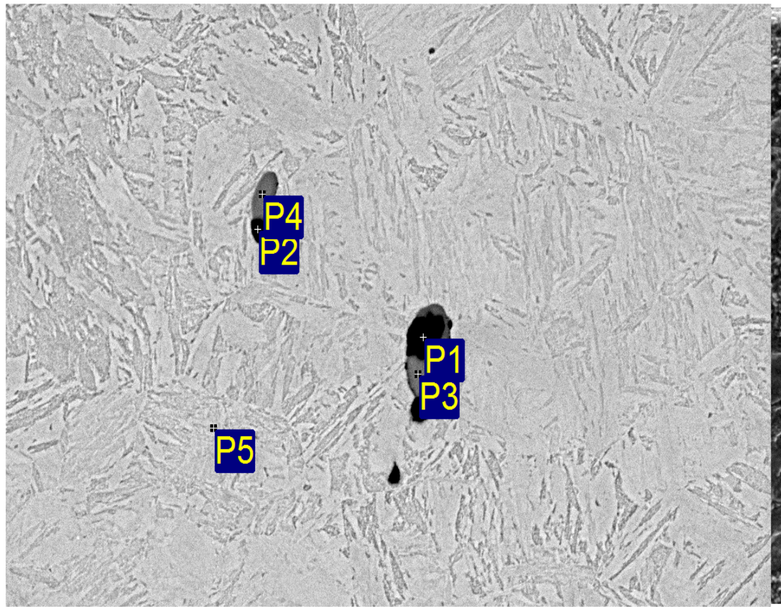


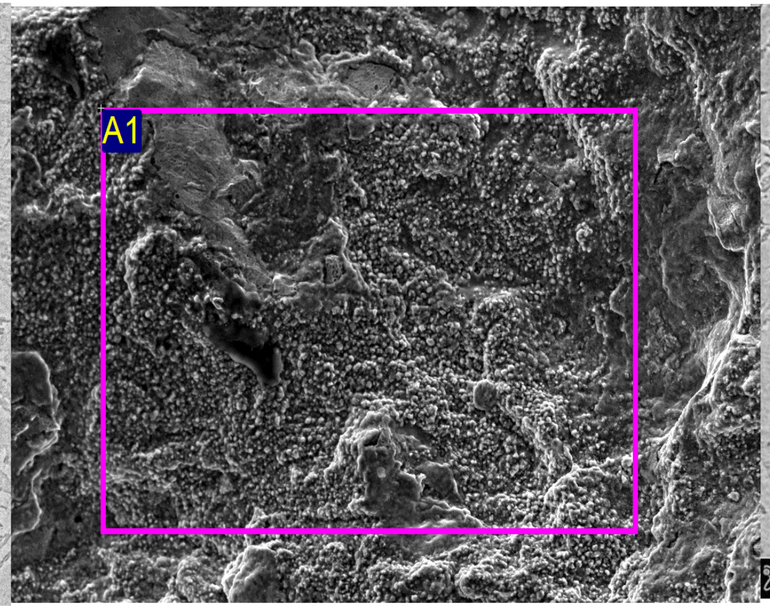
Significant amounts of S were detected inside cracks indicating that the failure mechanism is sulphide stress cracking (SSC), cracking is trans-granular crossing the grains.

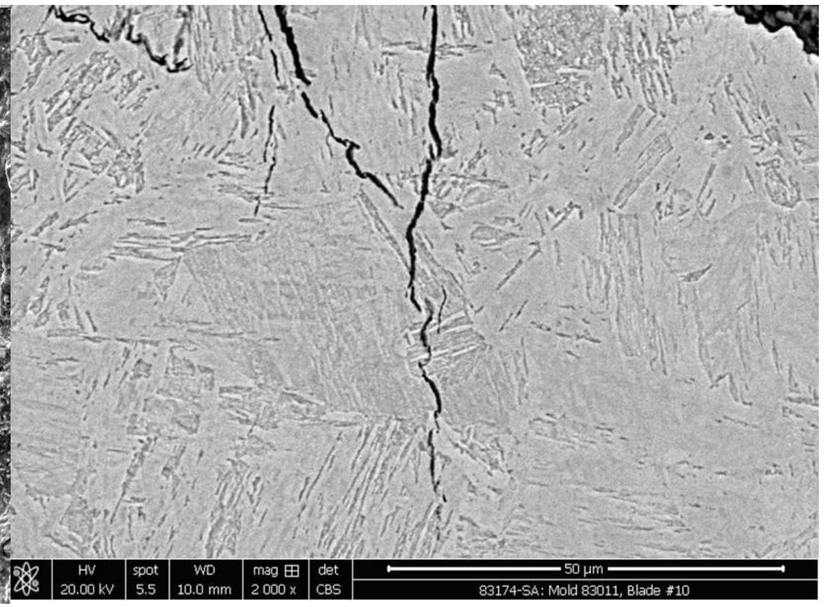
SULFUR AMOUNT FOUNDED IN 2020 CRACKS

2021 SABIC Analysis Report

Spectrum	C	Si	S	Cr	Mn	Fe	Ni	Total
P1	14.19		31.74		51.97	2.11		100.00
P2	15.11		31.42		51.35	2.13		100.00
P3	9.49	0.42		0.85	0.66	87.30	1.29	100.00







Significant amounts of S were detected on the fracture surface and cracking is trans-granular with limited branching indicating that the failure mechanism is sulphide stress cracking.

ANALYSIS CONCLUSION

MCO:

- Considering the observation of quasi-cleavage fracture and branch of cracking, it is considered that the impeller damage was caused by **Hydrogen Embrittlement cracking (HE)** due to hydrogen sulphide containing environments.
- In addition, the variability of process gas condition is suspected because this rotor was operated without any failure from 2008 to 2013.

SABIC:

- Crack morphology and position as well as detection of S in the fracture surface and inside cracks, indicate that the failure mechanism is **sulphide stress cracking (SSC).**
- **SSC is a form of hydrogen embrittlement (HE)** that occurs as a result of absorption of atomic hydrogen originating from corrosion process in the presence of liquid water and hydrogen sulphide(API 571).
- Low alloy steels and martensitic stainless steels like the materials used in the 1stand secondary impeller are susceptible to SSC 'if hardness is not controlled to a low enough level' (API 571). NACE MR0103 specifies a maximum hardness of 237HB for alloy steels and 33HRC for 17-4PH for hydrogen sulphide containing environments. The hardness of the failed impellers are higher than these NACE limits.
- SSC is strongly temperature dependent with most failures occurring in the 5-50˚C range and cracking susceptibility decreasing with rising temperatures above 50˚C (Twigg, 1984). Thus, the inlet temperature of around 40-50˚C, provides more suitable conditions for SSC than the outlet temperature of around 120˚C. This is a possibly explanation why cracking is only occurring in the 1stand 2ndstages which are near the inlet.

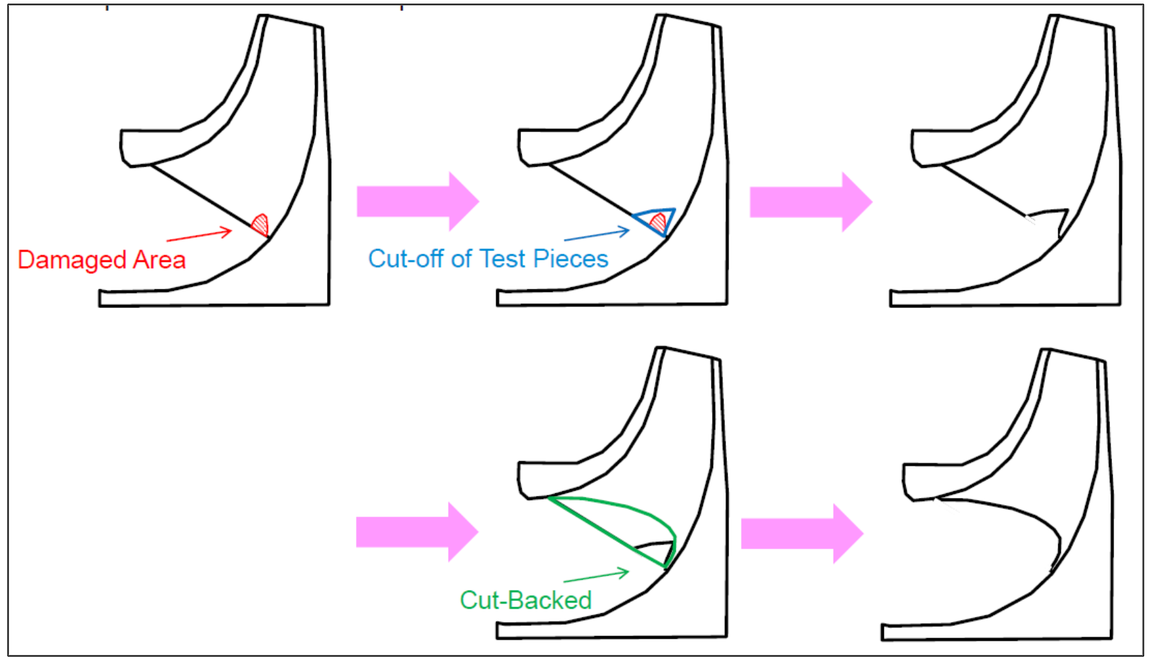
IMPELLERS CRACKS ROOT CAUSE

Root Cause	Damage Mechanism
High sulfur concentration in make up gas more than original design limits	Lead to sulphide stress cracking (SSC)
High chloride concentration in make up gas more than original design limits	Lead to stress corrosion cracking (SCC)

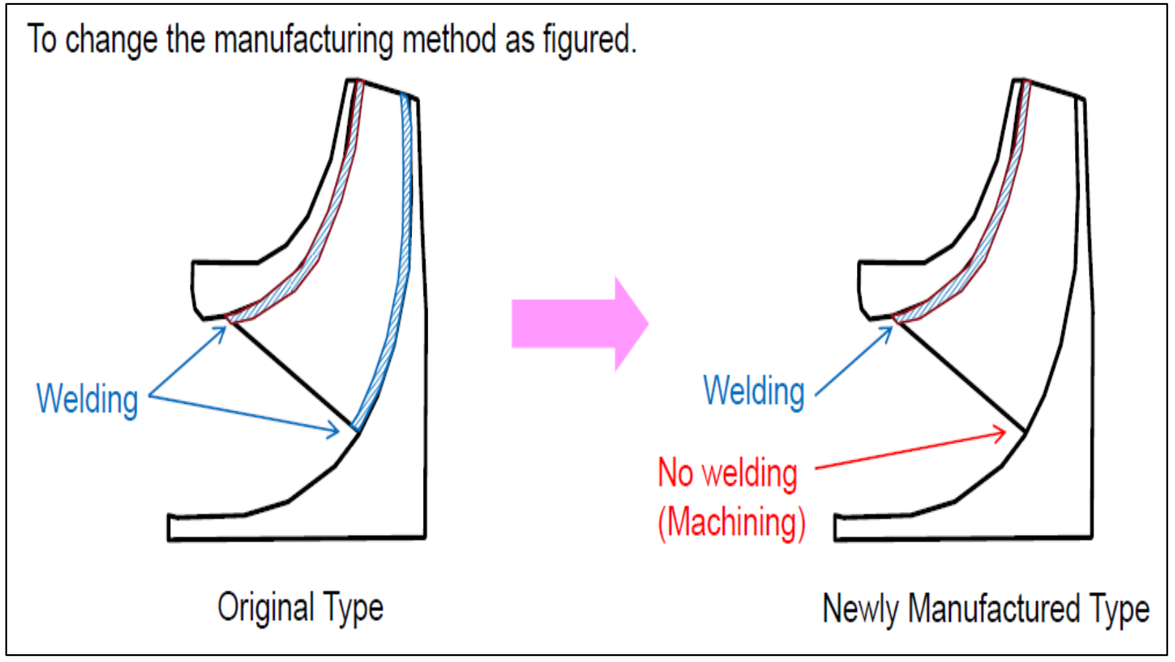
RECOMMENDATIONS

- Control suction temperature to K-5301-LP between 45~50 °C in all session to reduce condensate impact (Dew point of SG : 41°C, Suction temperature to be raised to 48~50°C if possible as it will reduce the aqueous phase in gas more.
- Control level of V-5300 & V-5301 below 25 ~ 20 % during start up and normal operation .
- Increase Process condensate recycling with fresh water that support reduce Cl , Na impurities.

- **Short Term** : Repair the rotor with cut back the 1st stage impeller and rebalance it.



- **Long Term**: Modify both 1st & 2nd stage impeller to weld less (17-4 PH SS) material with reduced hardness ≤ 33 HRC.



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