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TURBOMACHINERY LABORATORY
TEXAS A&M ENGINEERING EXPERIMENT STATION

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PTT Public Company Limited

SULZER PUMPS

Hydraulic Power Recovery Turbine Operational Failure and Design Enhancements

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Presenter/Author Bio

Daniel Baun:
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Dan has worked in the centrifugal pump industry in various capacities for the past 26 years. His primary areas of expertize are: Hydraulic Design, Rotor-Dynamics and Applications. Dan received his PhD in Mechanical Engineering from the University of Virginia in 2000 where his research thesis was on the subject of hydraulic generated loads within centrifugal pumps.

Kunarak Kunakulsawat: Mechanical Engineer PTT Plc
Since receiving his MSc in Aerospace Engineering from the University of Manchester, Kunarak has carried out his duties in the mechanical department of PTT at the Rayong Gas Separation facility. Kunarak has been involved with maintenance, troubleshooting and interventions on a wide variety of turbines, pumps, compressors and related process equipment

Abstract

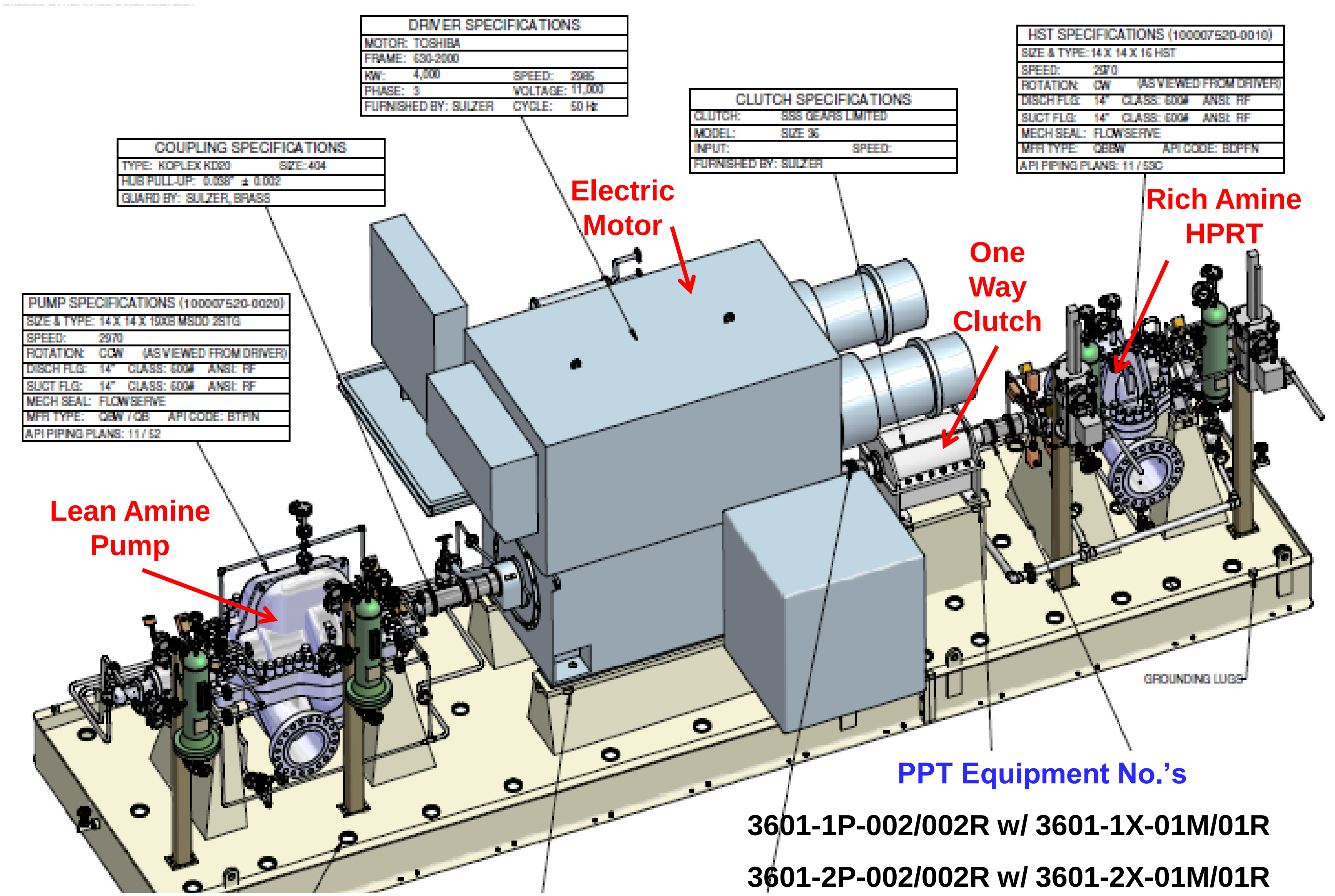
PTT operate a number of hydraulic power recovery turbines (HPRT) in their gas processing plants in Rayong Thailand. One of the newest plants incorporates some of the largest such turbines ever produced. The HPRT design under discussion includes an inlet guide vane assembly and a double flow runner required to meet system NPSHa (evolution of dissolved gases) and for axial thrust balance. Within this class of equipment, special consideration must be given to metallurgical selections, robust bearings, as well as seal designs owing to the mixed phase discharge conditions.

Within the first year of operation, several turbine issues were observed. This case study seeks to describe the nature of the issues, as well as the resulting evaluation and root cause analysis. Further the case study will describe the design improvements being implemented.

Presentation Overview

- Introduction to Equipment Train
- Operating History and Component Failure
- Analysis – CFD
- Analysis – FEA
- Summary and Recommendations

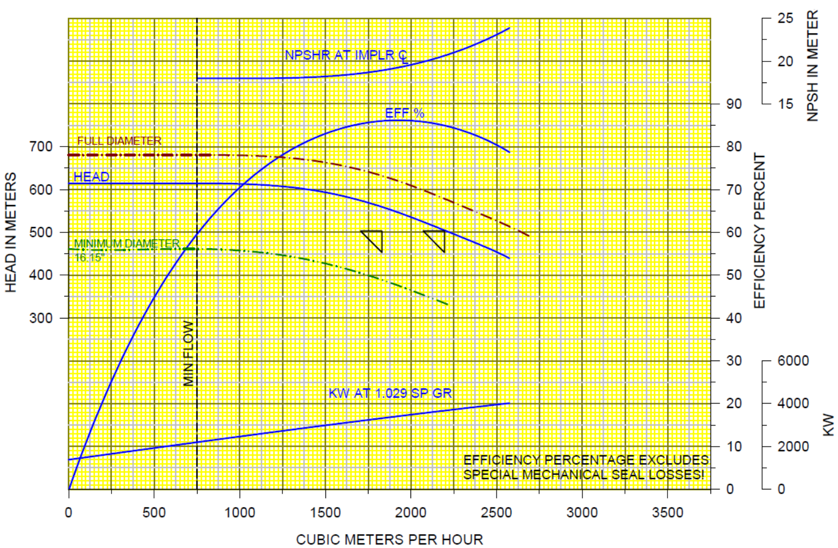
PTT Public Company, Map Taphut, Rayong, Thailand
Lean Solution (Pump-Motor-HPRT) Equipment Train

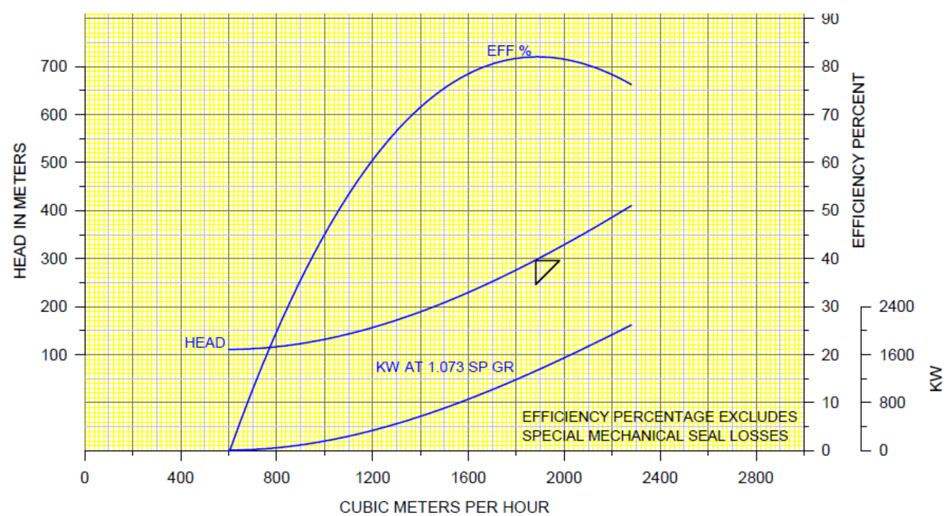


Pump/Hydraulic Power Recovery Turbine (HPRT) Equipment Train

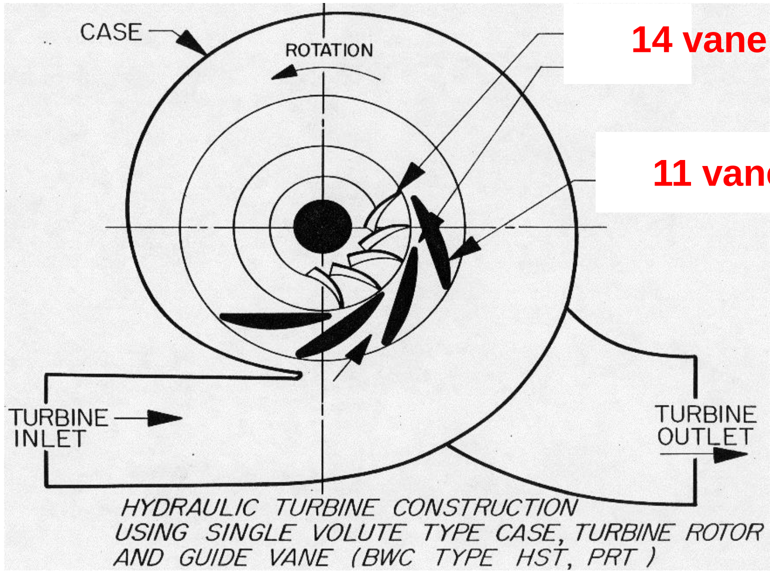
- **<u>Pump 14x14x19B</u> MSD-D (BB3 Configuration)**
  - Head: 503m
  - Flow: Rated - 2196 m³/hr, Normal -1830 m³/hr
  - RPM: 2970
  - Eff: 85 %
  - SG: 1.029
  - Power: 3693 KW
  - Product: Lean Amine

- **<u>HPRT 14x14C HST</u> (BB1 Configuration)**
  - Head: -296 m
  - Flow: 1881 m³/hr
  - RPM: 2970
  - Eff: 81.9 %
  - SG: 1.096
  - Power: 1361 KW
  - Product: Rich Amine (MDEA 50% + CO2)



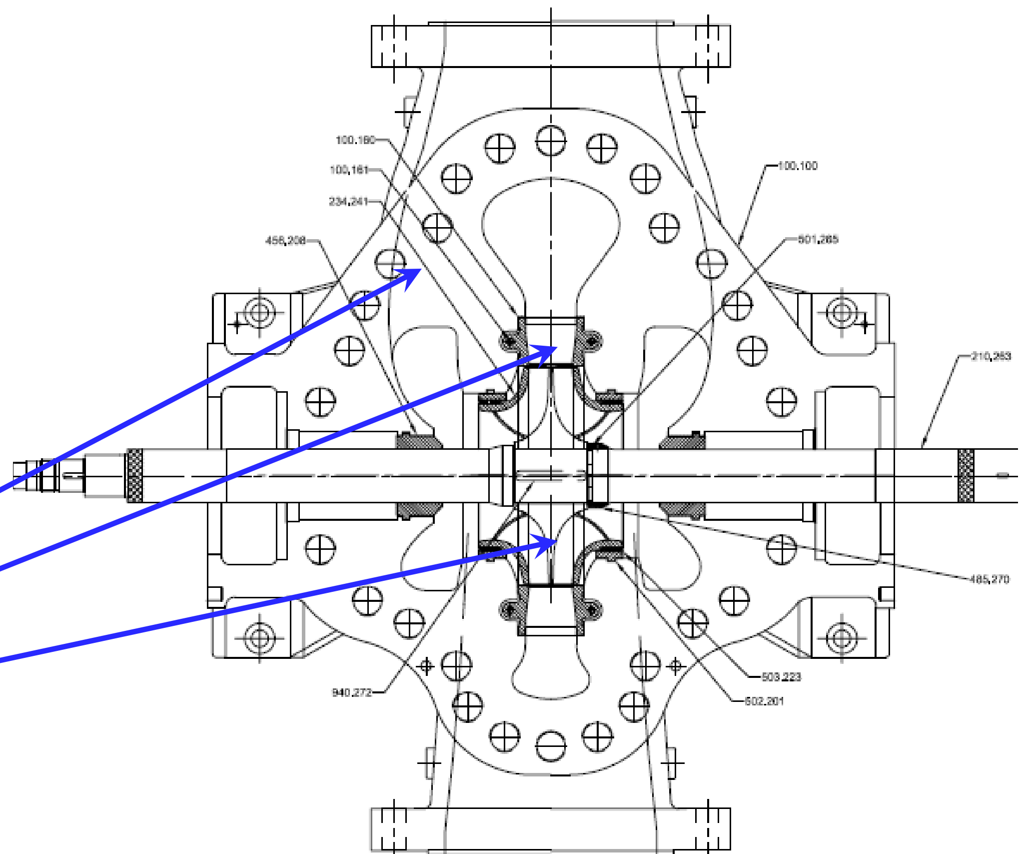


HPRT 14x14C HST – Design & Construction



14 vane Double Flow Runner

11 vane IGV



- **<u>Original Materials of Construction</u>**
  - Case: ASTM A351 Gr CF3M (316L)
  - IGV: ASTM A351 GR CF3 (304L)
  - Runner: ASTM A995 Gr. 1B (CD4MCU – Duplex SS)

Train/HPRT
Operation – Summary (ref: PTT – RCA w/ additions)

Summary

1

3601-1X-01R

- Suction Control Valve cannot be operated since Oct 2013
- Pump & Mechanical Seal: Good condition
- Ran for 2-3 days during commissioning

2

3601-2X-01M

- October 2013: High Vibration
  - Check Alignment, Bearing, Mechanical Seal
- December 2013: High Vibration (Stop unit)
- Overhaul, as found
  - Guide vane support damage
  - Impeller crack
- Unit ran approximately 3 months

3

3601-2X-01R

- Started unit January 2014:
- Shut down on High Vibration March 2014
- Overhaul, as found
  - Guide vane support damage
  - Impeller cracks
  - Split ring and split ring collar missing

4

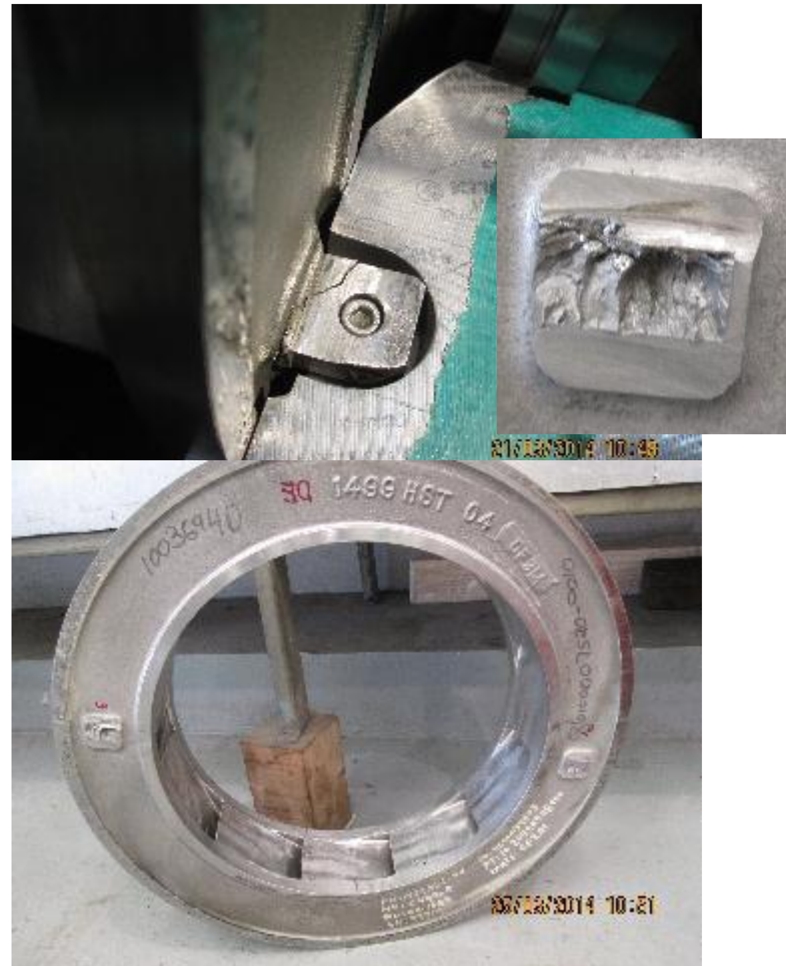
3601-1X-01M

- Unit online since Oct 2013
- High Vibration March 2014 – still on line as backup

HPRT (14x14C HST) Typical Failures

- Runner Exit Vane Failure
  - 3-5 Adjacent Runner Vanes on DE

- IGV Assembly Retention Tab Failure



HPRT Runner Vane Metallurgical Failure Analysis
(ref: SVT Engineering Consultants FN02-1370997.1)

- Inter granular crack(s) originating from Sigma Phase Embrittlement compromised runner mechanical properties and resulted in fatigue failure
- Source of Sigma Phase:
  - Improper heat treat after Foundry weld repair on runner vanes (gates/risers location ??) lead to formation of Sigma Phase in heat affected zone.
  - Required Heat Treatment for ASTM A995 Gr. 1B (CD4MCU – Duplex SS)
    - Heat soak to minimum 1040 °C followed by rapid cool down to avoid precipitation of sigma phase at grain boundary.

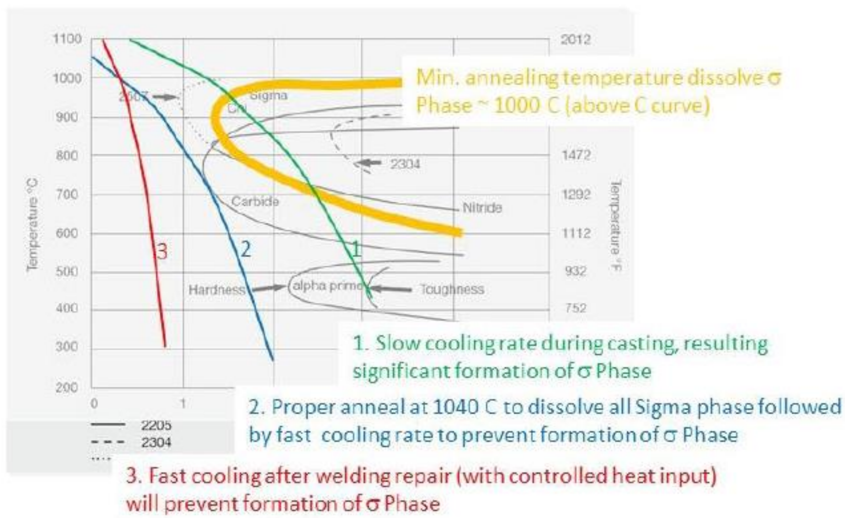
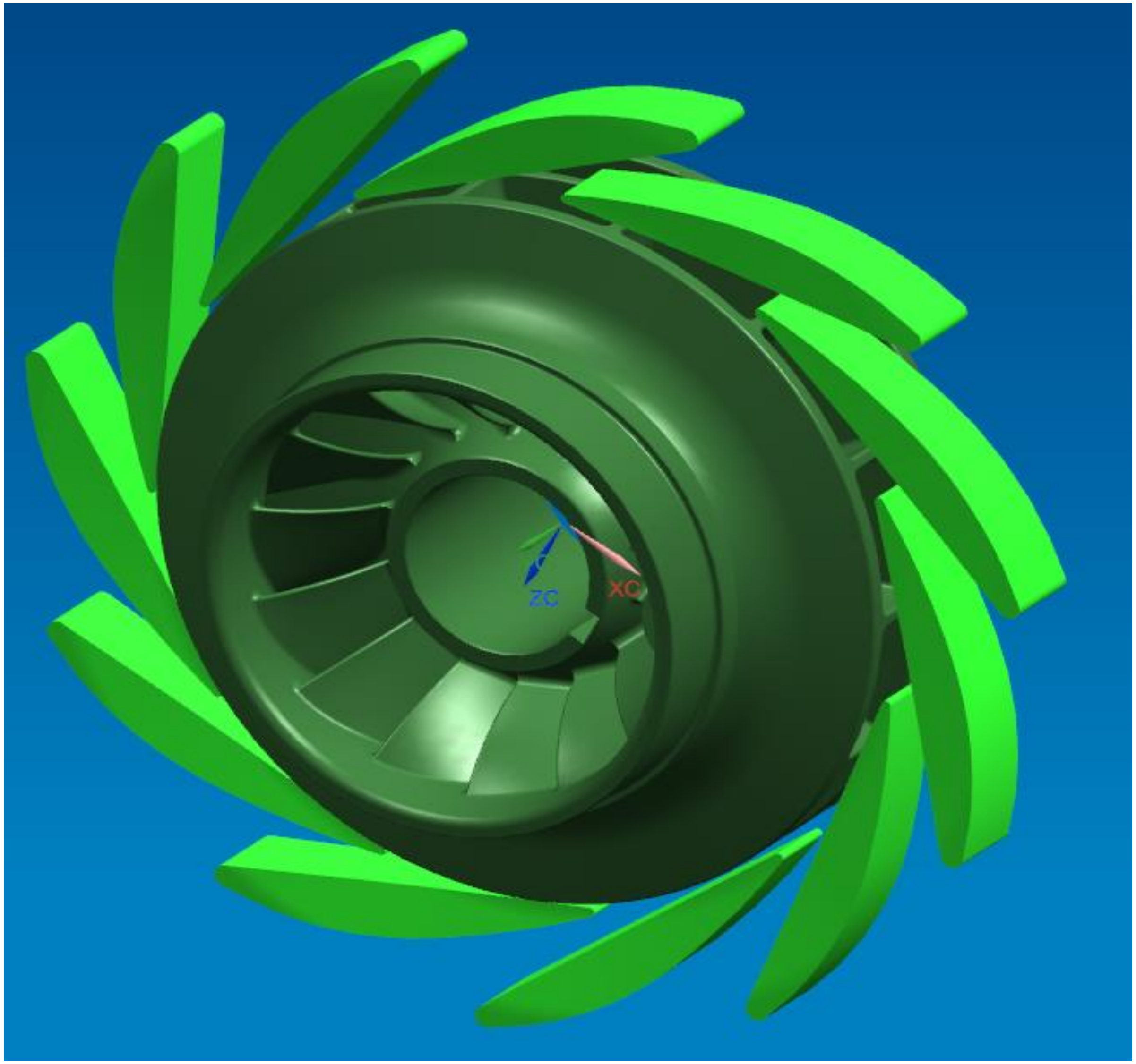


Figure 6-3 Figure of the cooling curve of the cast duplex steel for avoiding Sigma phase formation during casting and the weld repair.

HPRT 14X14C HST Runner Analysis - CFD

- CFD Domain – (Steady State)
  - IGV & Runner single blade passage w/ inlet and exit segments
  - Steady State w/ Stage Interface
- CFD Set-Up
  - ANSYS CFX (RANS Solver)
  - Single Phase
- CFD Domain – (Transient)
  - Complete IGV, Runner, w/ inlet and exit segments.
  - GGI – Full Time Transient



HPRT 14X14C HST CFD Steady State Analysis - Torque & Vane Pressure Loading Estimates

- Runner and Guide Vane Steady Reaction Torque
  - Integration of surface pressure distribution plus shear stress distribution.
- Runner Torque from CFD:

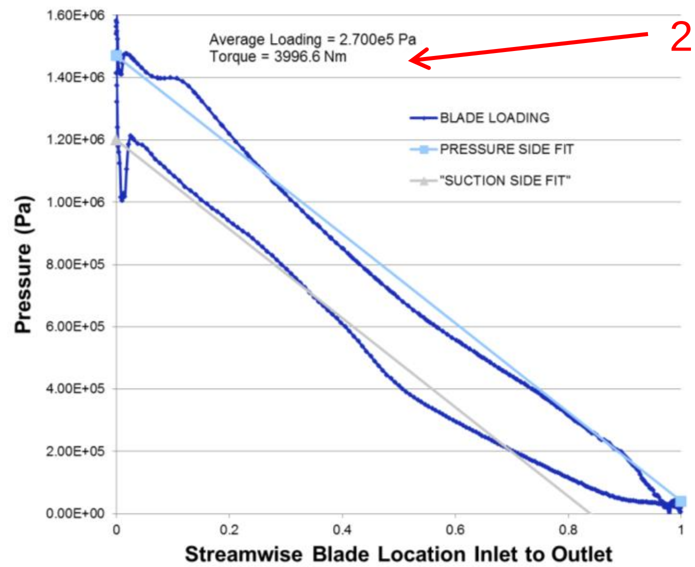
$$T_{CFD} = 3997 \text{ [Nm]}$$

- Runner Torque @ Rated Power:

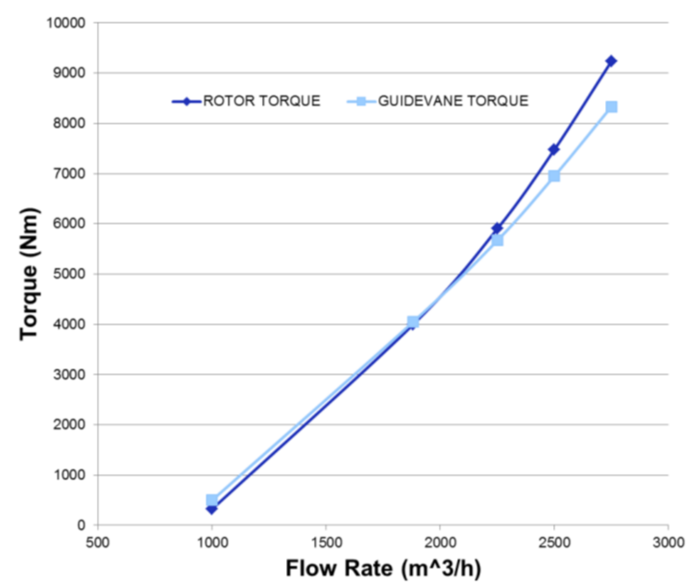
P = T*ω = 1,361 [KW]

T = 1,361,000 / {2,970*2*π/60}

$$T_{Rated} = 4180 \text{ [Nm]}$$

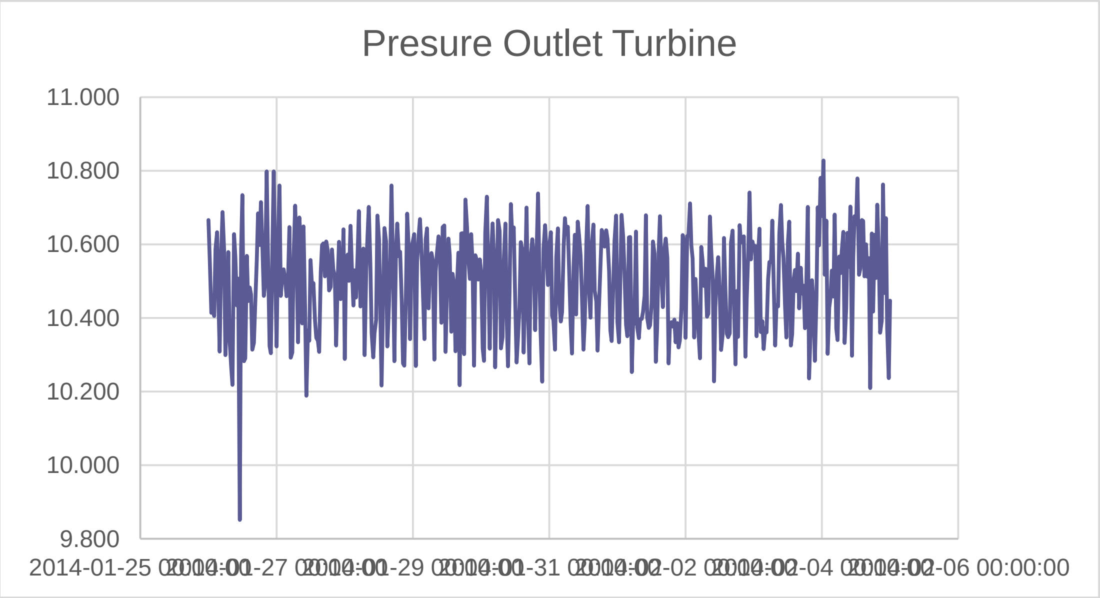


270 kPa Average Loading

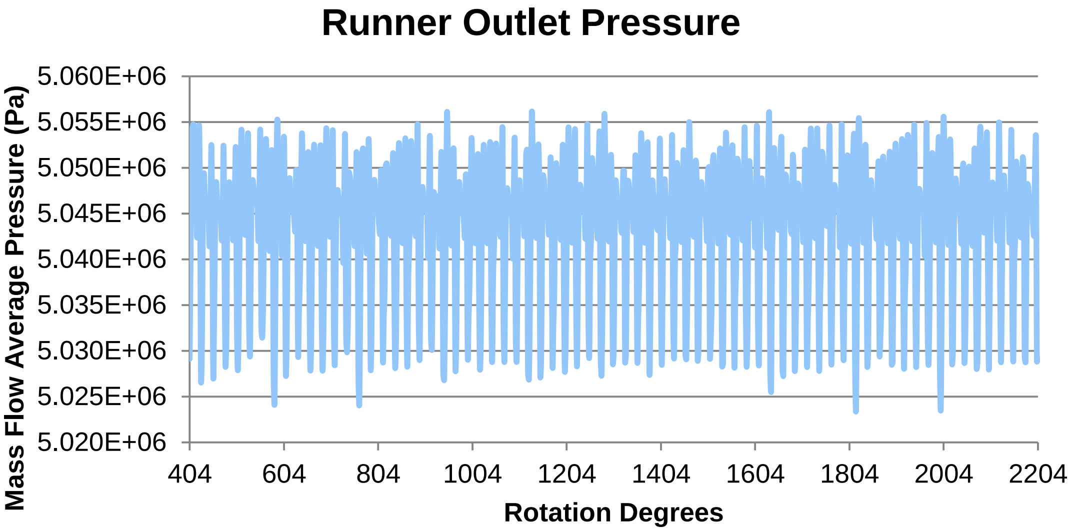


HPRT 14X14C HST CFD Transient Analysis – Runner Exit Dynamic Pressure

- Measured (PTT) HPRT outlet pressure trend.
  - peak-to-peak pressure variations in range of 0.3 – 0.4 bar (4.5 – 6 psi)
    - i.e. 17,250 – 20,700 Pa (2.5 psi to 3 psi) amplitude.

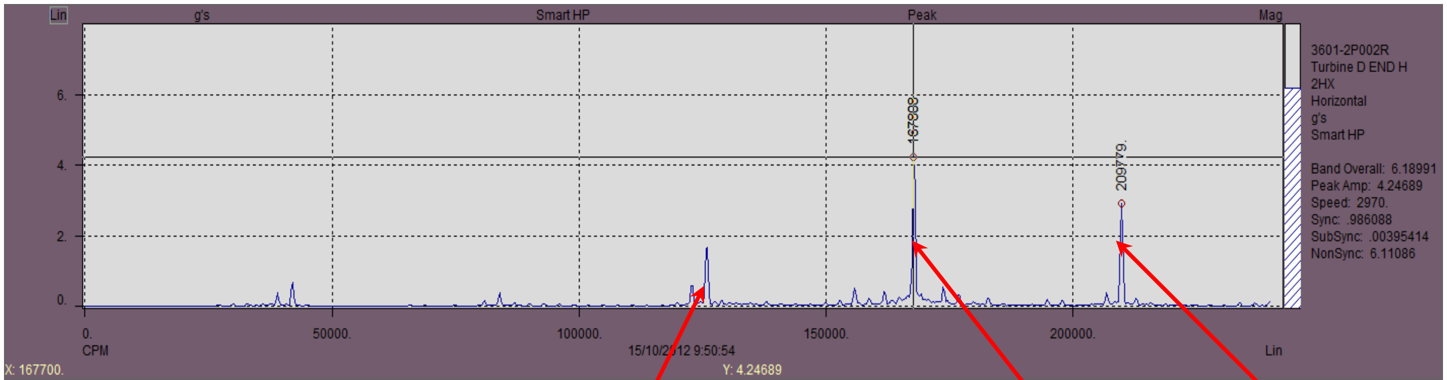


- CFD estimated HPRT outlet pressure trend.
  - peak-to-peak pressure variation in the range of 30,000 Pa (4.4 psi)
    - i.e. 15,000 Pa (2.2 psi) amplitude.

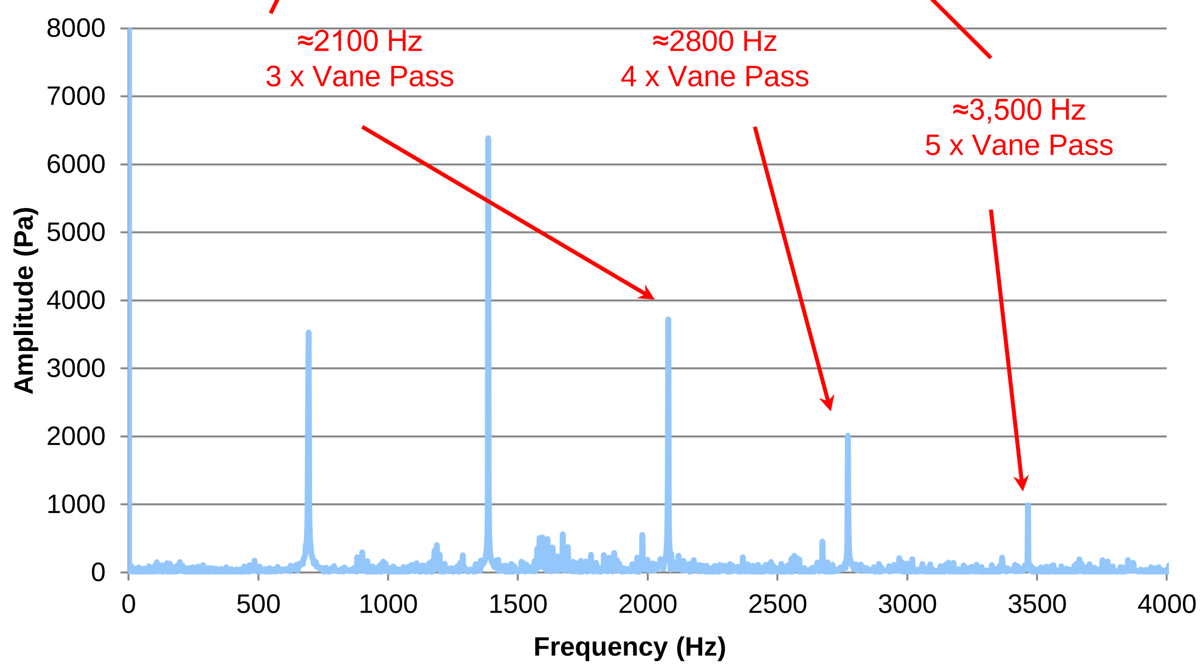


HPRT 14X14C HST CFD Transient Analysis – Runner Exit Dynamic Pressure

Measured Housing Vibration (g's)

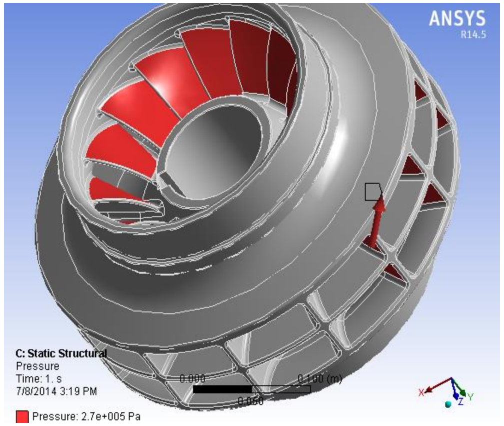


- CFD estimated HPRT outlet pressure spectra
  - 1x (700 Hz) 3500 Pa
  - 2x (1400 Hz) 6400 Pa
  - 3x (2100 Hz) 3800 Pa
  - 4x (2800 Hz) 2000 Pa
  - 5x ((3500 Hz) 1000 Pa

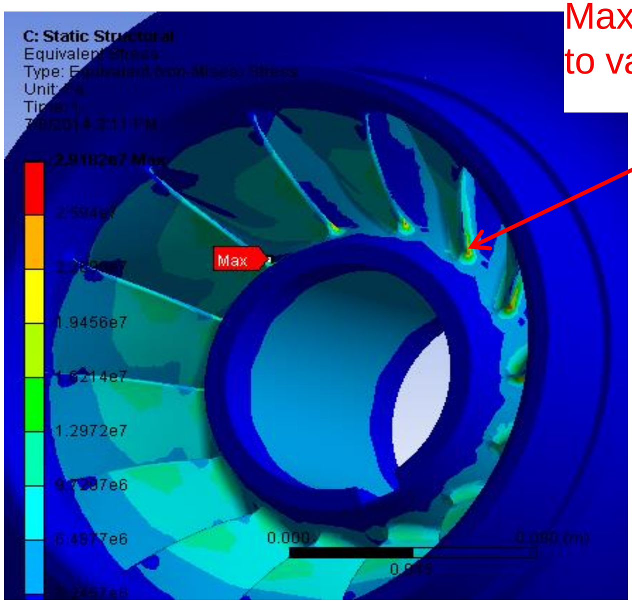


14X14 HST Runner FE Analysis Results - Equivalent (von-Mises) Stress

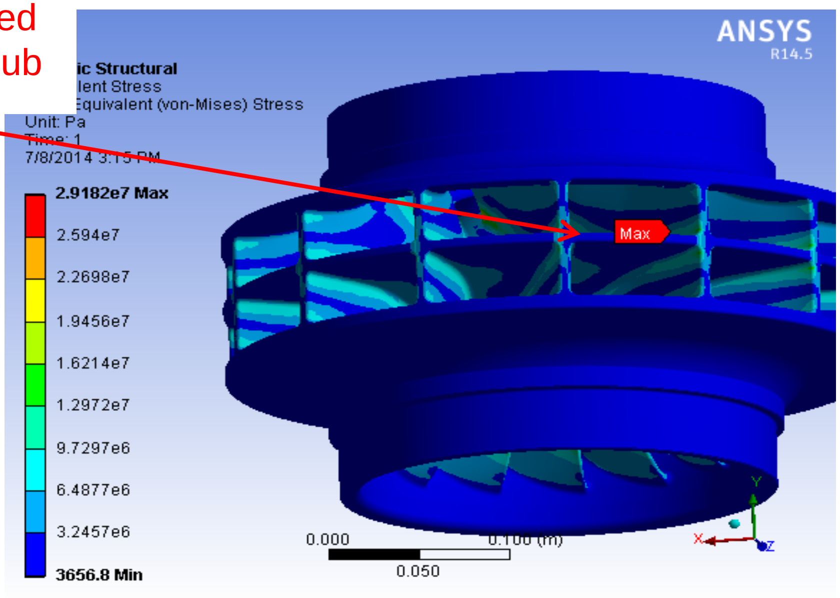
- 270 kPa blade pressure loading from CFD analysis



- Max von-Mises Stress Approx. 29 MPa
  - < 6% of Yield Stress for CD4MCu (Duplex SS)
  - < 4.5% of Yield Stress for CB7Cu-1 (17-4 pH H1150)



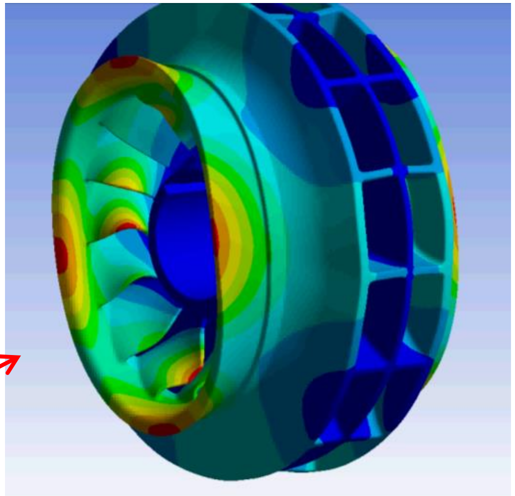
Max stress localized to vane fillets on hub

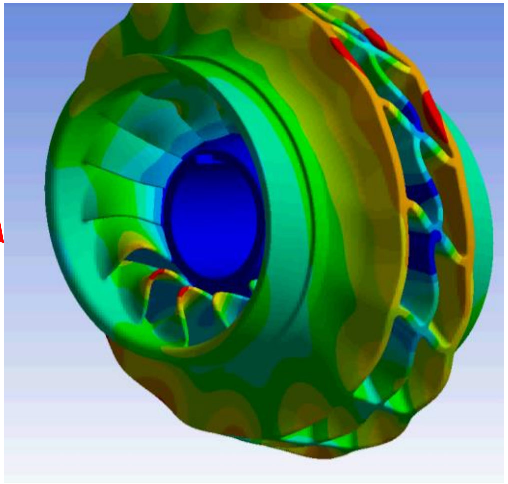


HPRT 14X14C HST Runner FE Analysis Results-Modal Shapes & Natural Frequencies

- Many runner structural natural frequencies in the range of 1 – 2 KHz.

Mode	Eigenfrequency (Hz) In Air	In Water (*0.46)	Comments	Nodal Diameters
1	1834	844	Outer Shroud twist about Shaft Axis	0
2	1852	852	Rocking about Transverse Axis	1
3	1860	856		
4	2068	951	Twist about Shaft Axis	0
5	2326	1070	Egg Shape on Eye Shroud	2
6	2329	1071		
7	3265	1502	Axial Movement of Shroud	0
8	3465	1594	Out of Phase Rocking about Traverse Axis	1
9	3475	1599		
10	3733	1717	Tri-lobal on Eye Shroud - out of phase	3
11	3734	1718		
12 & 13	4311	1983	Egg Shape on Eye Shroud - in phase	2
14	4759	2189	middle shroud twist relative to hub	1





  - Not possible to know exact frequency of any mode during operating due to fluid added mass and damping.

- Possibility exists that a runner structural vibration mode is excited by:
  - IGV – Runner hydrodynamic interaction
  - System Excitation source:
    - water hammer (valve closure)
    - system surge (compliance resulting from gas/vapor pockets

HPRT 14x14C HST – Structual Summary

- HPRT runner failures typically occurred after 2-3 months of operation.
  - All runner vane failures were isolated to 3 – 5 adjacent vanes on DE side of HPRT runner.
- Runner vane steady stresses due to steady torque transmission is very low (approx. 5% of material YS).
- Possibility that a runner structural mode was excited, however, amplitude of the stress cycles are expected to be very low due to low amplitude pressure transients at runner exit.
- Unlikely that dynamic loading from rotor-stator interaction during normal operation cased fatigue failure of HPRT runner vanes.
  - Consider a 2 kHz mode:
    - 10^7 stress cycles are accumulate in less than 1.5 hours of operation.
    - If a 2 kHz. runner structural mode was excited during normal operation and the stress amplitude were high, the runner vanes should have failed due to fatigue in approximately 2 hours.

HPRT 14x14C HST Runner – Summary

- Likely cause(s) of HPRT Runner vane failures:
  - High amplitude system pressure transient (water hammer or surge) provided impulsive excitation with sufficient energy to excite runner vane mode(s) and lead to high cycle fatigue failure.
  - Reduced material strength resulting from sigma phase embrittlement resulting from improper post weld heat treatment on affected vanes.
- Recommended Design Enhancements:
  - Change Runner MOC (material of construction) from Duplex SS, ASTM A995 Gr 1B CD4MCu, to precipitation hardened SS, ASTM A747 Gr CB7 Cu1.
    - 35% increase in yield strength (larger strength margin against system upset conditions).
    - Less risky heat treatment process to easily facilitate weld repair.

14x14C HST Guidevane – Summary

- Likely cause(s) of HPRT IGV retention tab failures:
  - High amplitude system pressure transient (water hammer or surge) leading to over stress/fatigue of IGV retention tabs.
  - Loosing of retention screws – IGV free to vibrate/move
  - Improper shimming resulting in high assembly stresses
- Recommended Design Enhancements:
  - Change guide vane MOC (Material of construction) from ASTM A351 Gr CF3M, to Precipitation hardened SS, ASTM A747 Gr CB7 Cu1.
    - >50% increase in yield strength for increased strength margin against possible system upset conditions.
  - Increase retention tab sectional area (x4) and retention bolt size (x4) and increase fillet radii at juncture to side plates
    - for increased mechanical design robustness against possible system upset conditions.