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Inappropriate Operation During Mechanical Running Test of a High-Pressure Compressor Equipped With an Hole Pattern Seal

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Responsible for providing technical support in rotordynamics and stress analysis.

Function: development and analysis of components of centrifugal compressors for oil and gas application.

Before joining the site in Switzerland in 2003 was employed for 6 years in MAN Energy Solutions, Berlin where he was involved in the design, finite element analysis, rotordynamic analysis, testing and development of centrifugal compressors.
Received his diploma (Mechanical Engineering, 1995) from the University of Valenciennes (France).

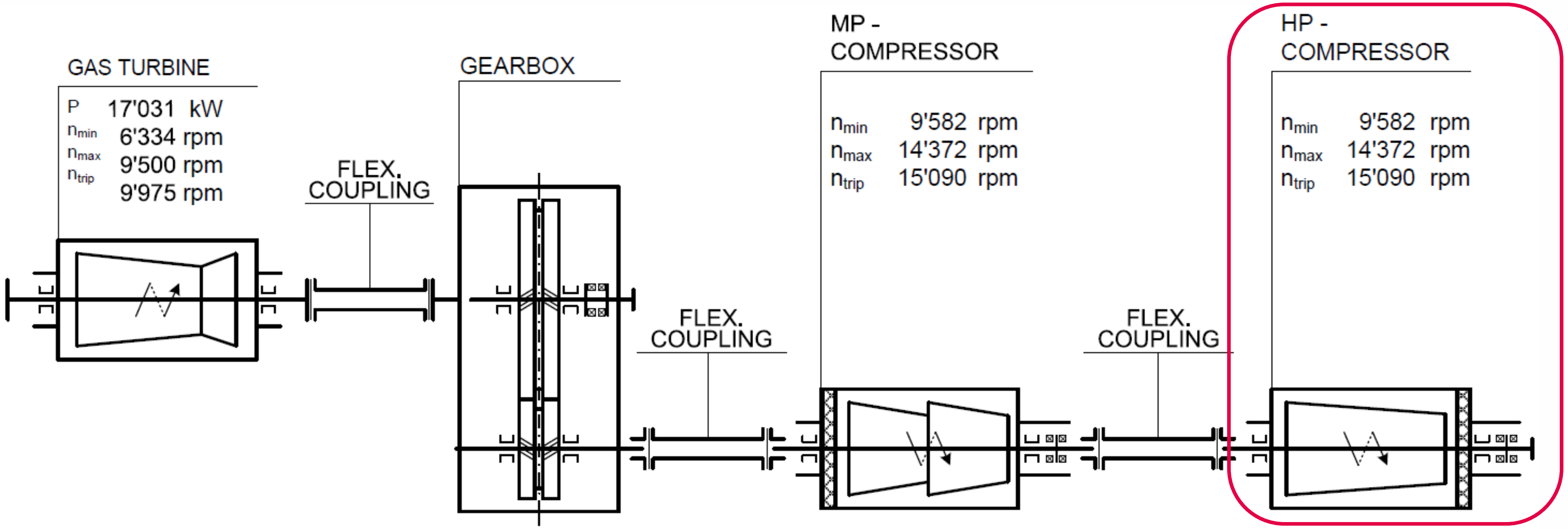
Synopsis

- During the mechanical running test of a HP centrifugal compressor, the rotor experienced a sudden increase of the radial vibrations. During run-down the compressor experienced a trip and high vibrations were recorded.
- The RCA revealed: for the manufactured clearance of the hole pattern seal the temperature level and the gradient of the pressure and temperature during the start-up was too high.
- A new hole pattern seal sleeve was manufactured with increased clearances. The duration of the start-up was increased in order to decrease the temperature gradient. After reassembly no high vibration appeared anymore.
- Generally: Operation during the mechanical test (especially at trip speed) requires careful attention if high discharge gas temperature is expected.

Outline

1. Background
2. Description
3. Findings
4. Root Cause Analysis
5. Actions
6. Measurements after modification
7. Lessons learned, Conclusion

Background – Train Arrangement, Compressor



HP – Compressor	
	7 stages, in-line
	Tilting Pad Journal Bearing
	Impeller Seals: See-through Labyrinth, stationary
	Balance Piston Seal: Hole Pattern

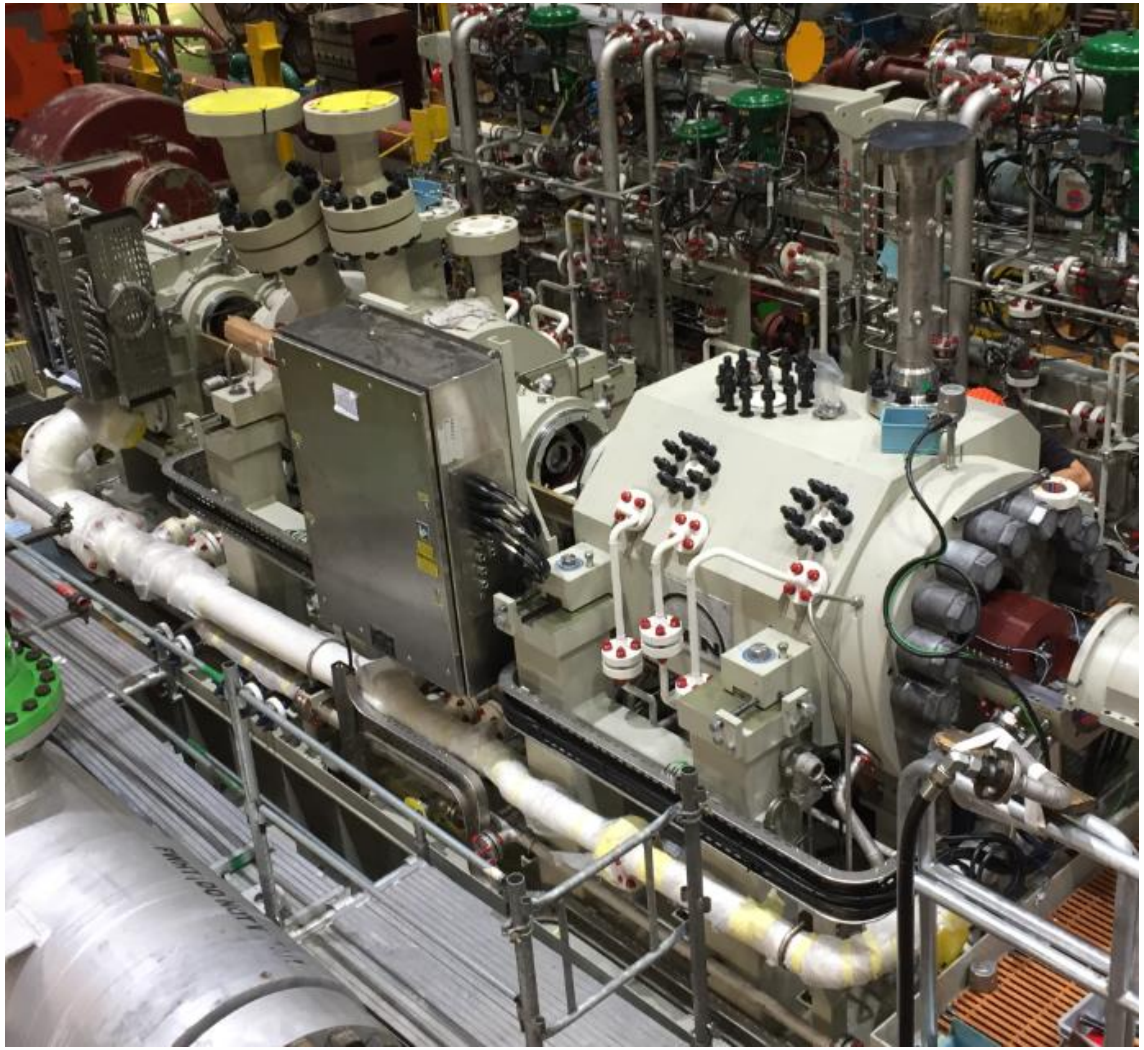
Feature HP - Compressor	SI Unit	
Suction Pressure	bara	128
Discharge Pressure	bara	386
Suction Temperature	°C	45
Discharge Temperature	°C	108
Mass Flow	kg/s	19
Gas (MW)	- (g/mol)	Natural (27)

Description

- In house mechanical test in facility test

- Sudden increase of radial vibrations on bearing probes → shut-down

- During shut-down
  - Trip
  - Vibrations up to 100 μm



Description

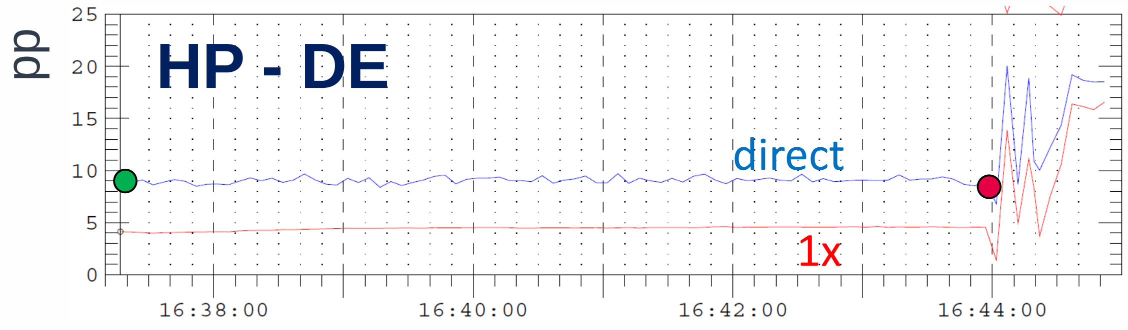
- Cartdrige was previously successfully tested
  - internal mechanical test (no load)
  - internal and official performance test
  - internal Full Load Full Pressure test

Mechanical Conditions of failed test		
	SI Unit	
Suction Pressure	bara	30
Discharge Pressure	bara	70
Suction Temperature	°C	30
Discharge Temperature	°C	190
Gas	-	N_2 (70%) + He (30%)

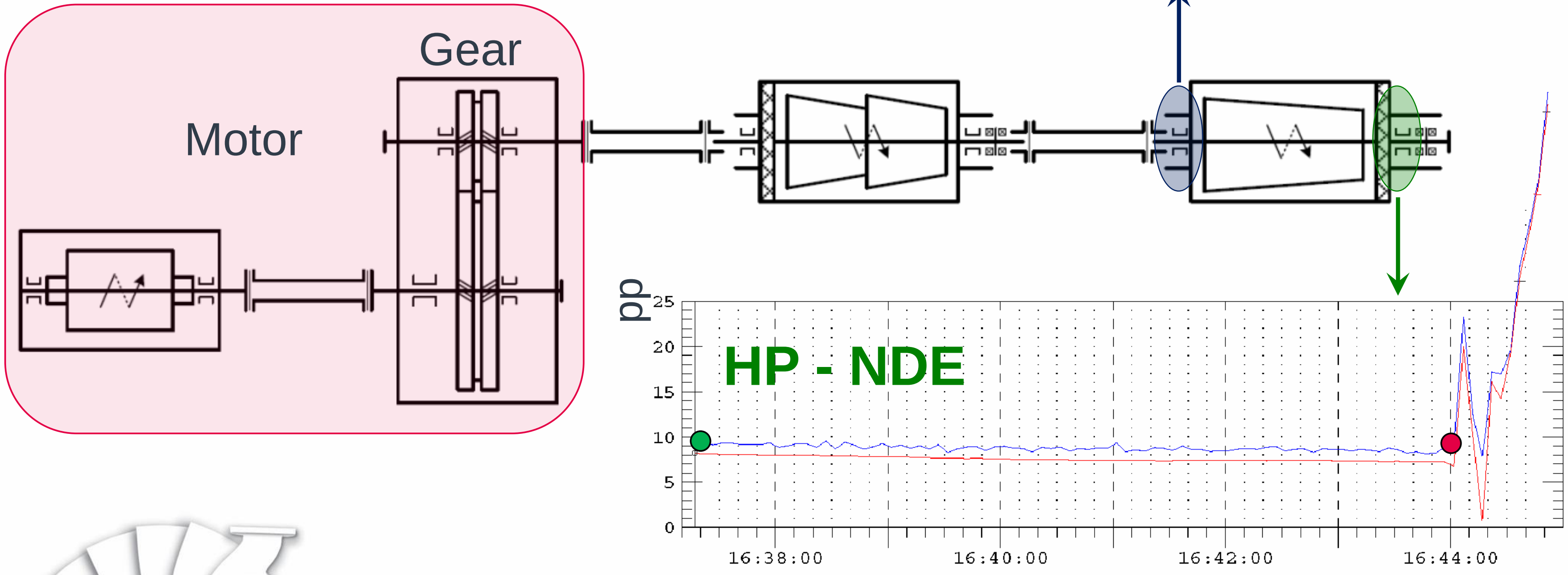
Much hotter than for the specified service (108°C) due to the N_2 mixture

- Main differences between successful and failed tests
  - Discharge temperature at max. speed approx. 20°C lower in internal test
  - Internal test: Trip speed reached after some hours of operation (compressor inner parts already warm)

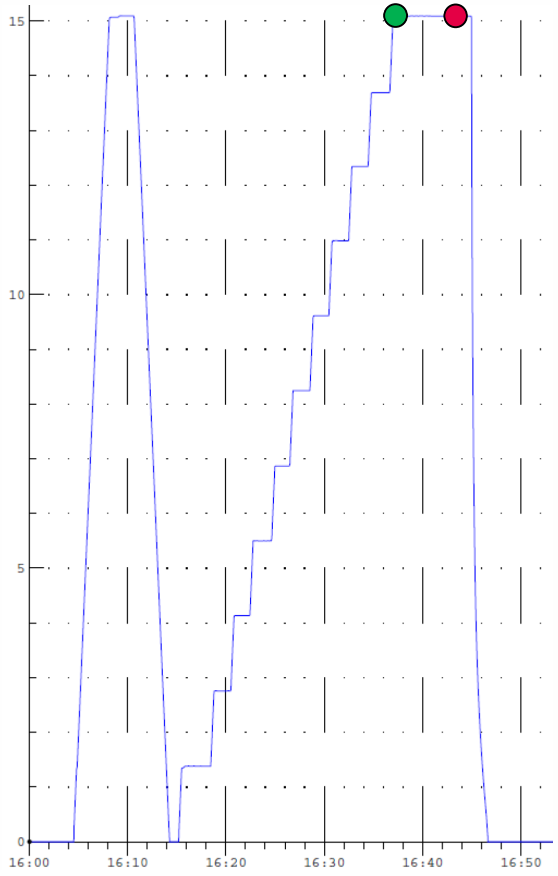
Findings – Lateral Vibrations



Testbed equipment

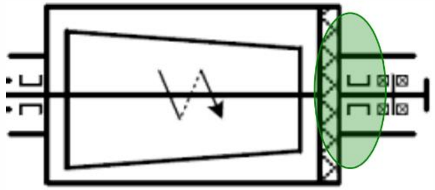


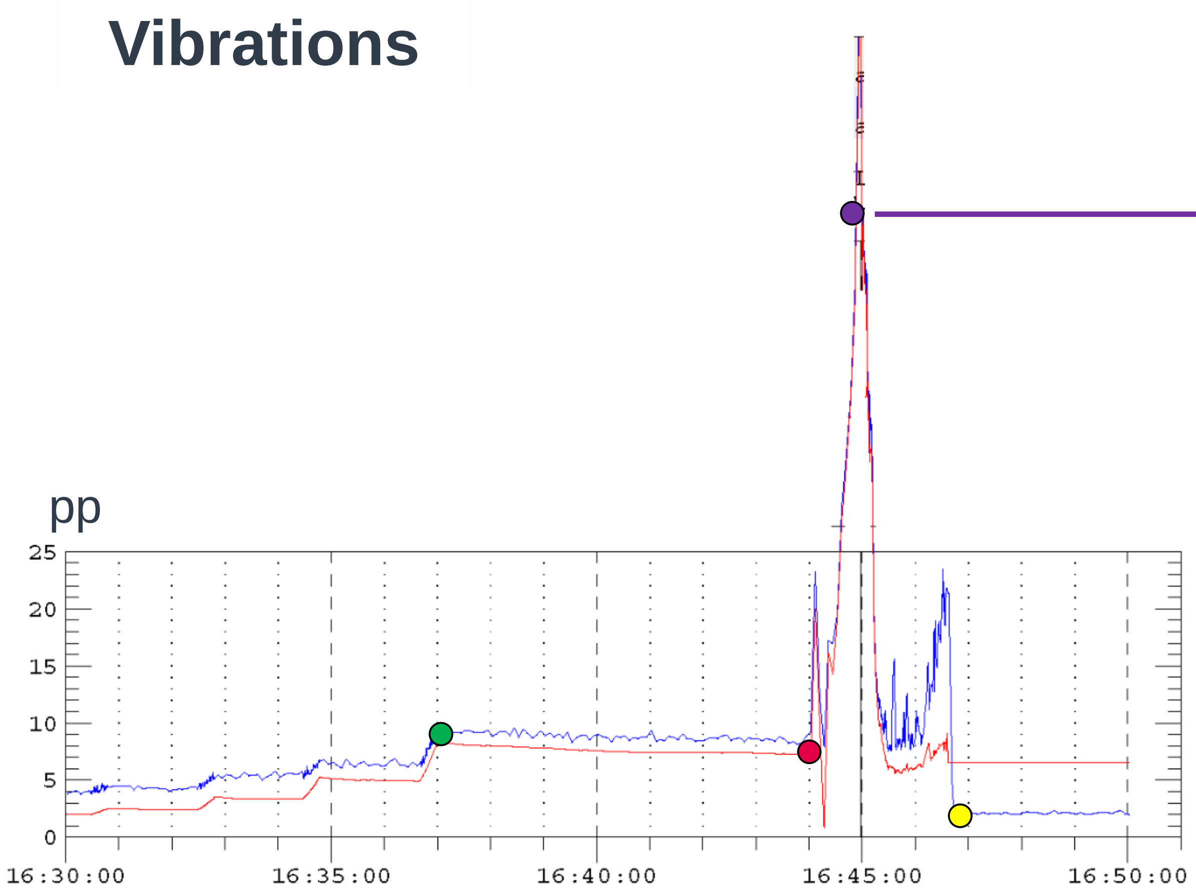
Speed

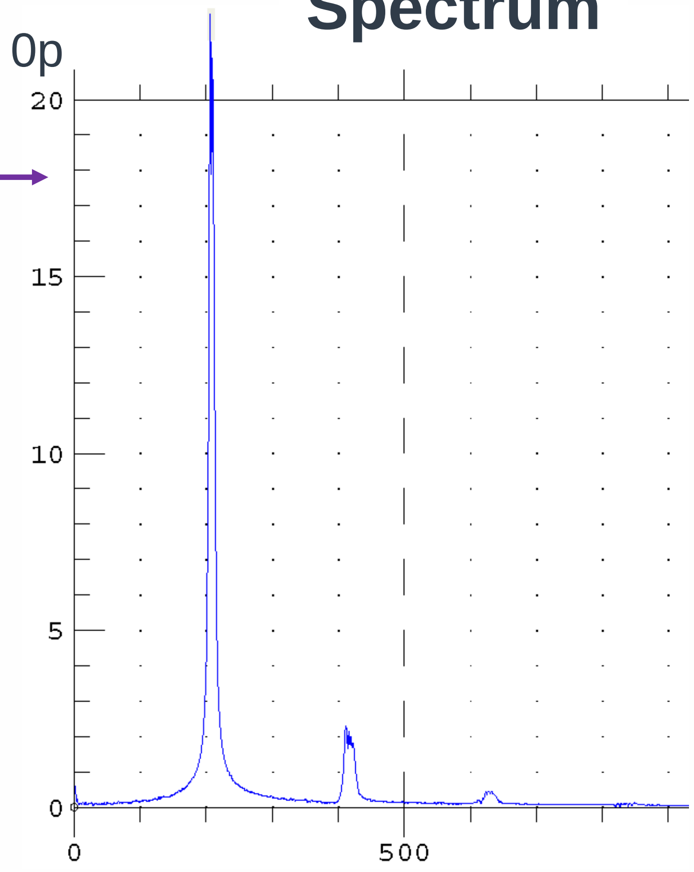


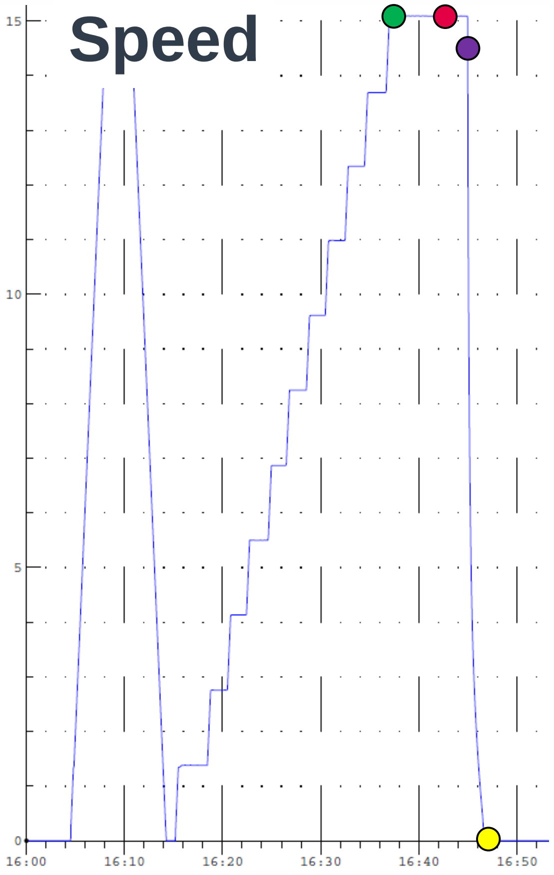
→ Sudden increase of vibrations at DE (20 µm) and NDE (> 100 µm)

Findings – Lateral Vibrations (HP – NDE)





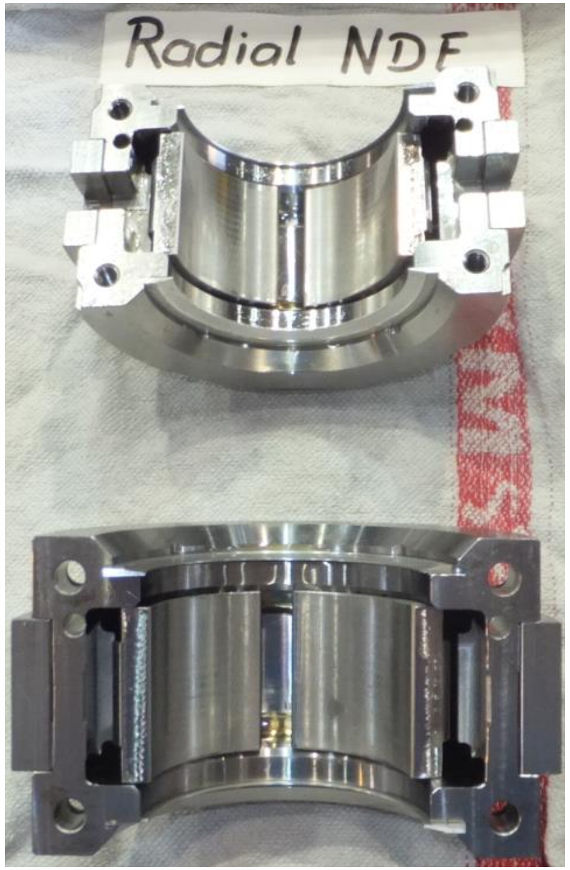




→ Synchronous vibration

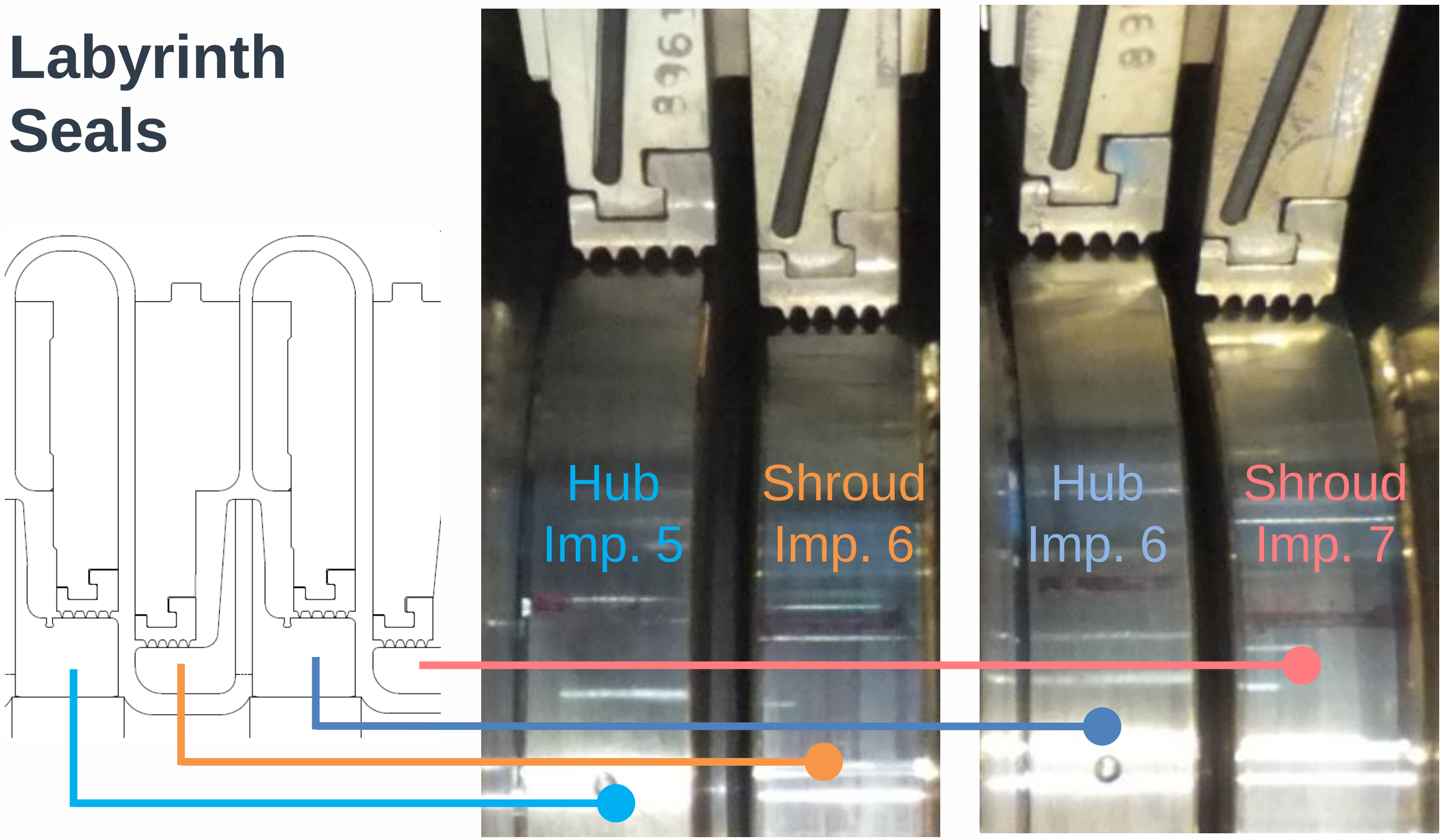
Findings – Machine Parts

Bearings



No abnormality, no mark ✓

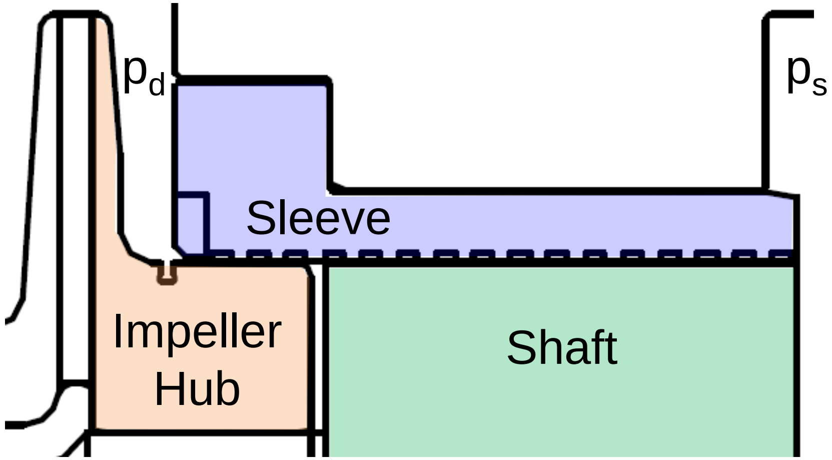
Labyrinth Seals

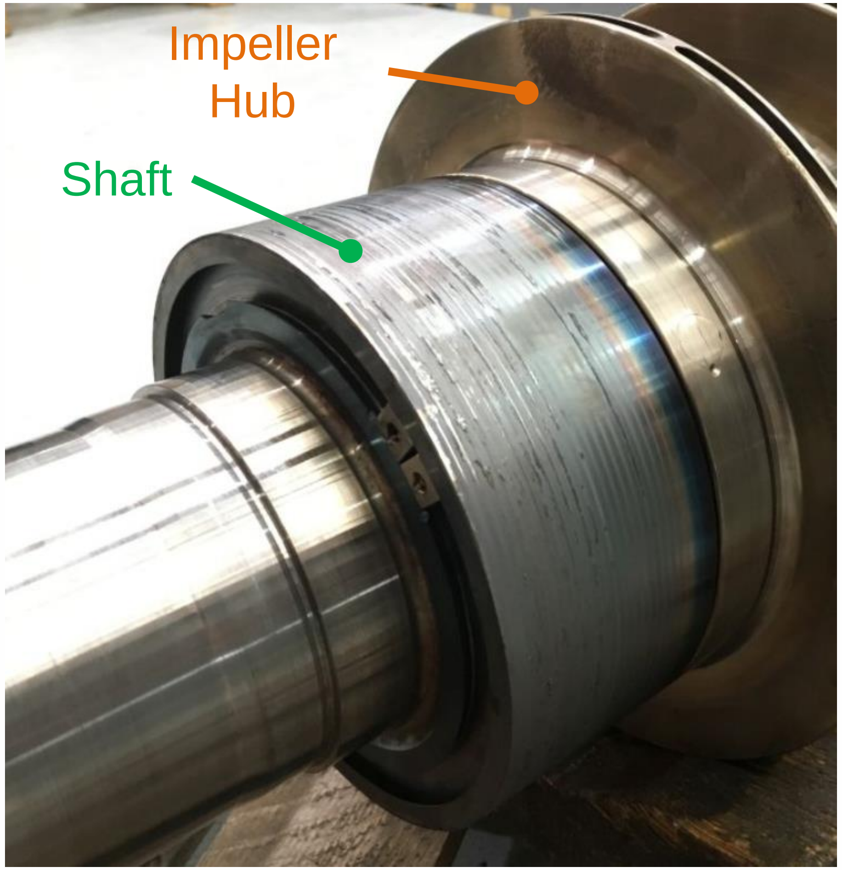


No abnormality, no mark ✓

Findings – Machine Parts

Balance Piston (Hole Pattern Seal)



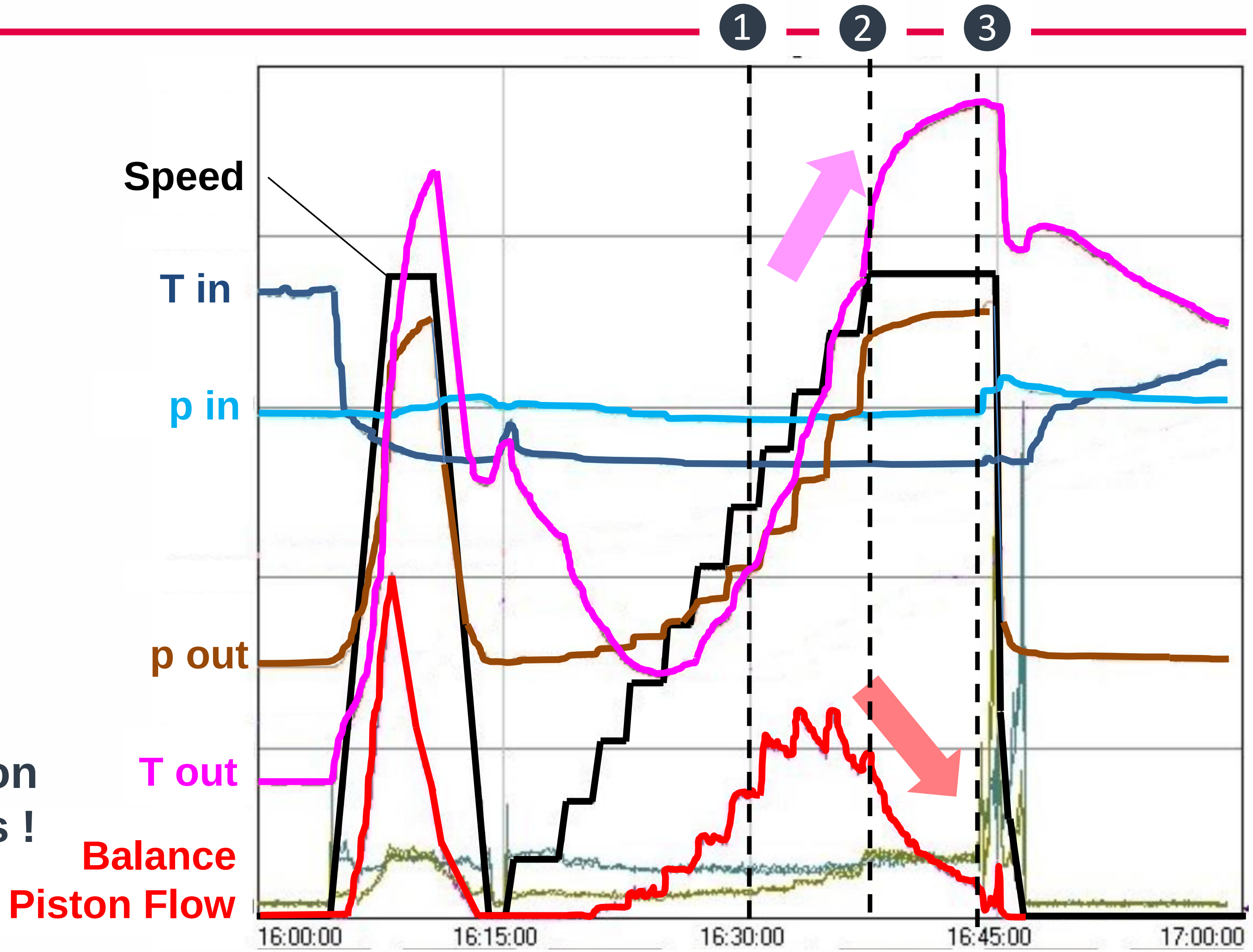


- Sleeve removed from shaft (possible only after heating)
- Traces of rubbing at suction pressure end

Root Cause Analysis – Operation Data

Feature		❶	❷	❸
Speed	rpm	9'614	15'090	
p_{in}	bara	29	30	30
p_{out}	bara	46	70	71
T_{in}	°C	27	27	27
T_{out}	°C	82	176	191

- Trip Speed (at 15'090 rpm)
- Constant inlet conditions (p_{in}, T_{in})
- Increase of p_{out}, T_{out}
- **Continuous decrease of balance piston leakage flow until 0 kg/s !**



Findings – Summary

- Phenomenon linked with leakage flow at balance piston
  - Not caused by rotordynamic instability
  - Not caused by foreign particle

- **What is the behavior of the clearance at balance piston at operating conditions ?**

  → FE Analysis of assembly Casing - Shaft

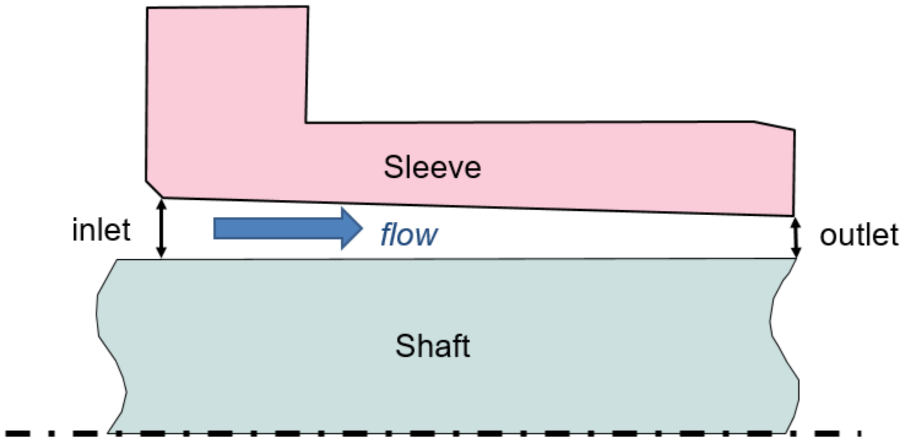
Root Cause Analysis – FEA

Particularities of Hole Pattern Seal

- In order to ensure the rotordynamic stability

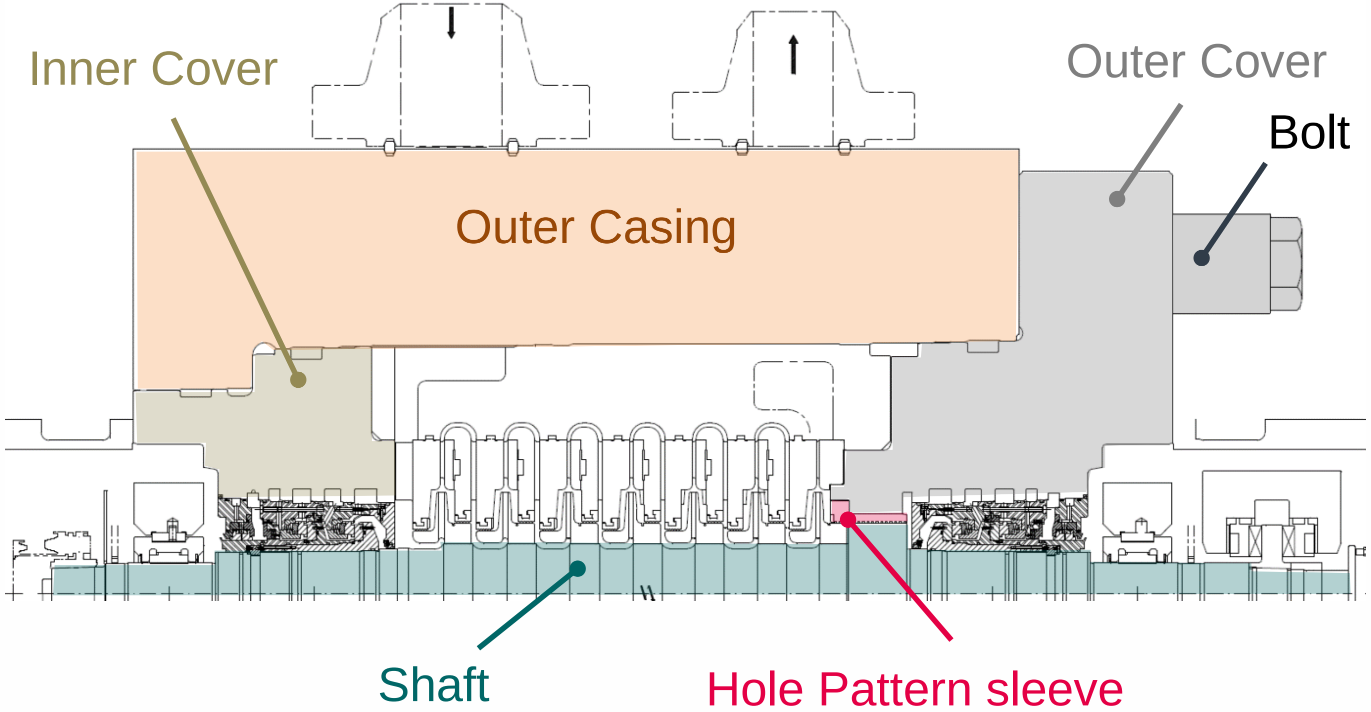
  → Clearance of seal must be kept convergent at all operating conditions

  → Convergent conical clearance (inlet larger than exit) already manufactured

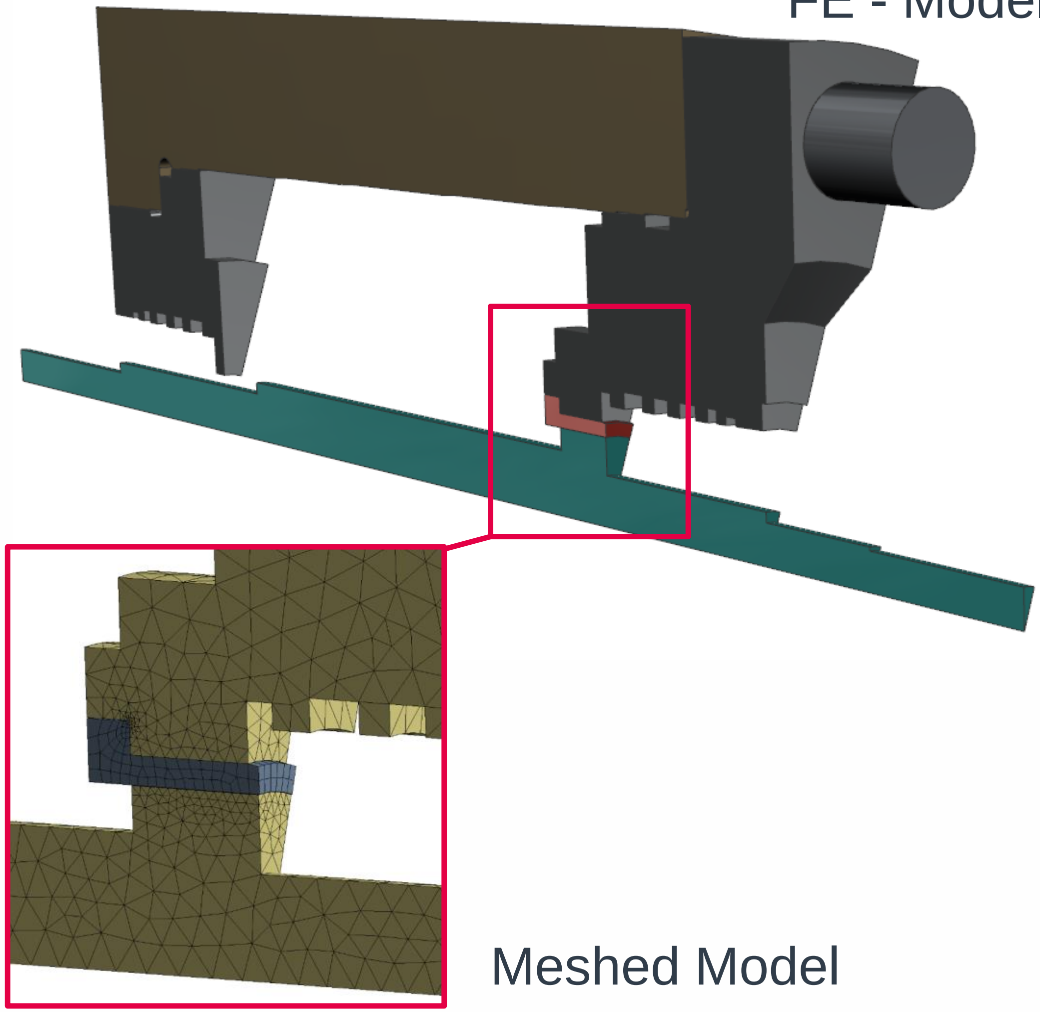


- Loads which determine the clearance in operation (considered in the FEA)
  - Pressure (casing, sleeve)
  - Temperature (casing, sleeve)
  - Centrifugal forces (shaft)

Root Cause Analysis – FEA



Cross Section



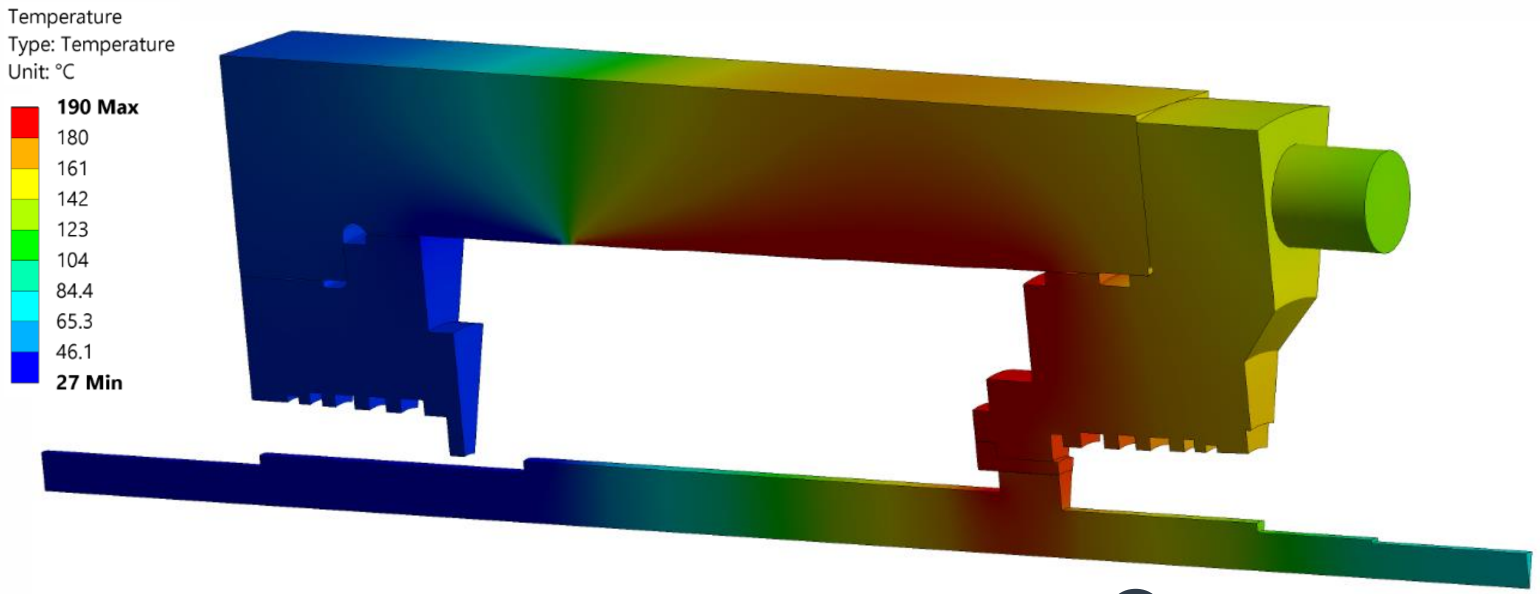
FE - Model

Meshed Model

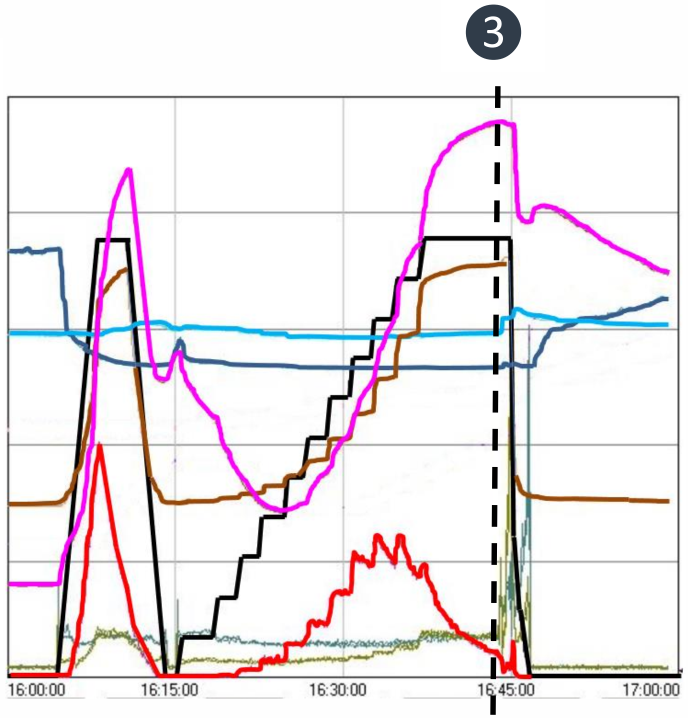
Root Cause Analysis – FEA

1. Analysis : Static Calculation

- Boundary Conditions at ❸ : p_{in}= 30 bar, T_{in}= 27°C, p_{out}= 71 bar, T_{out}= 190 °C, n= 15’090 rpm

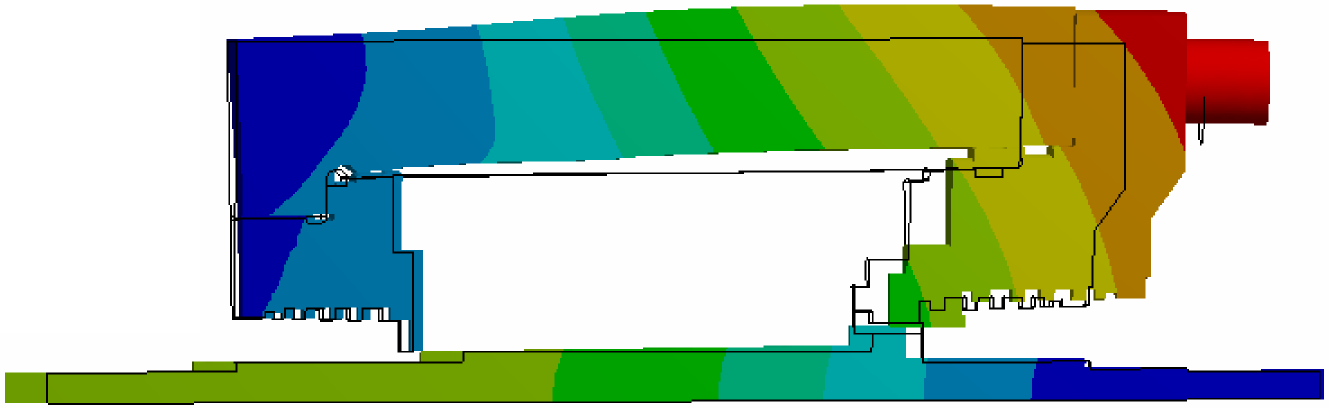


Temperature Distribution at ❸

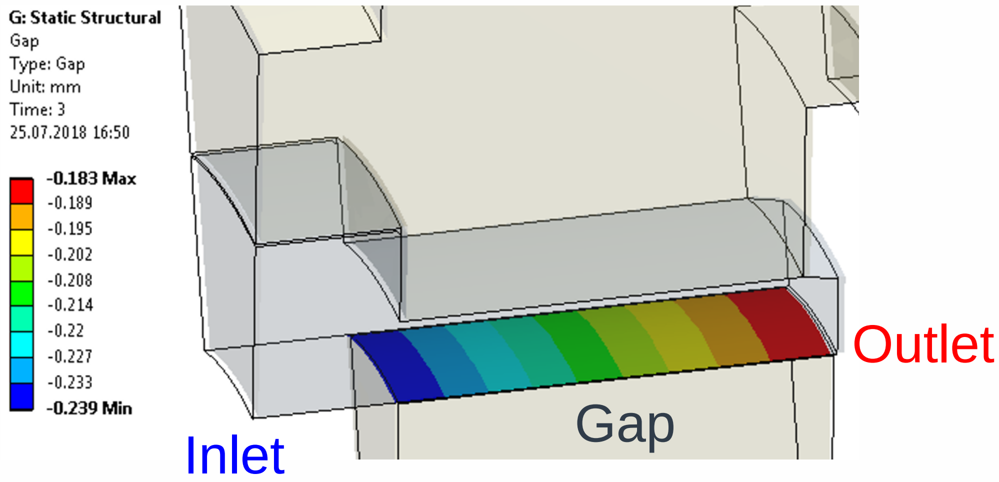


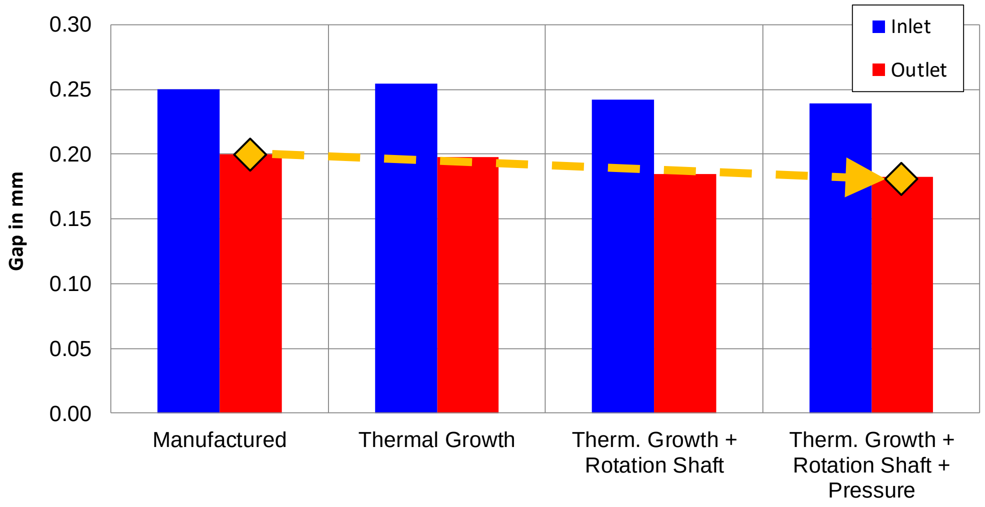
Root Cause Analysis – FEA

1. Analysis : Static Calculation (Results)



Overall Deformation



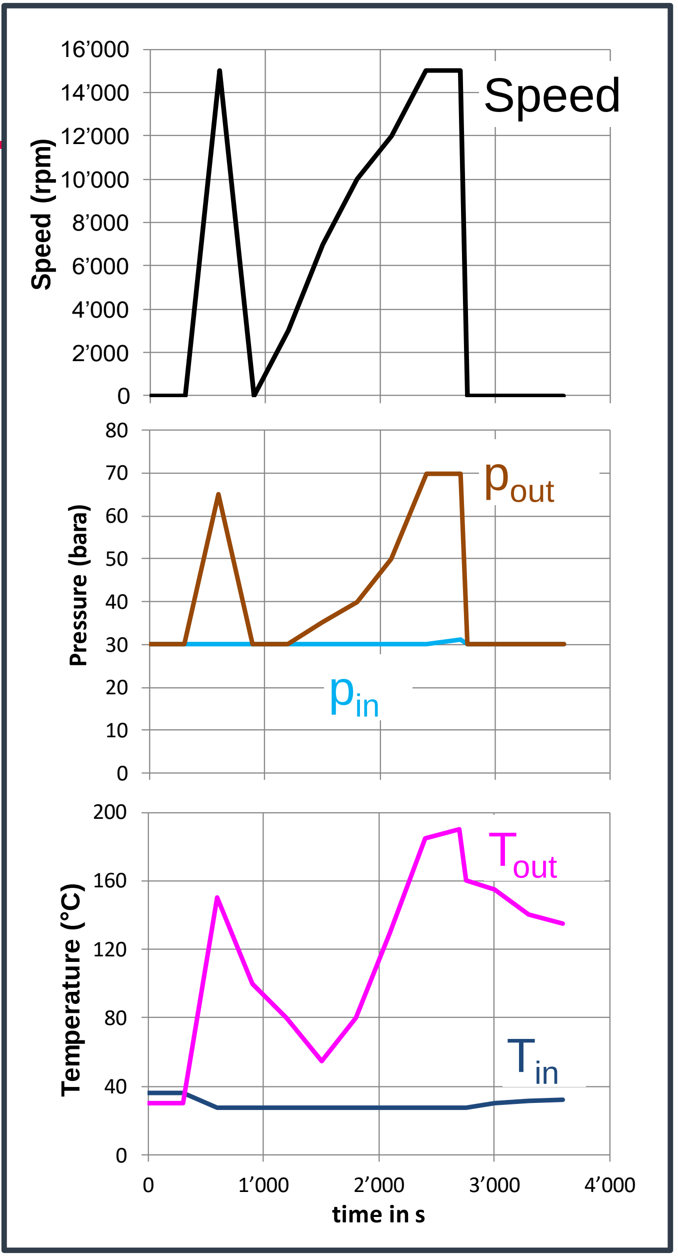


- Reduction of min. clearance from 0.20 mm (manufactured) down to 0.18 mm (operation)
- Clearance still high enough

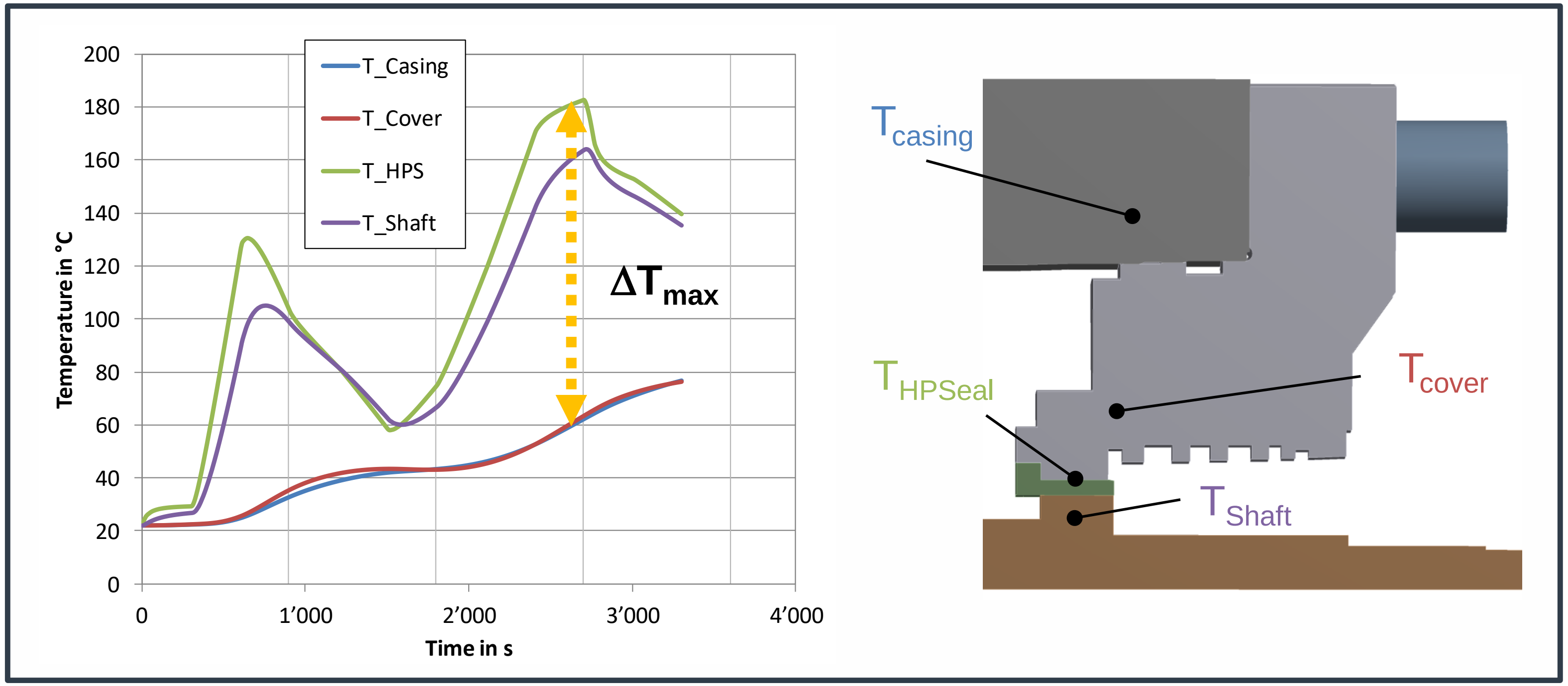
Root Cause Analysis – FEA

2. Analysis : Transient Calculation

Simulation of operation (16:00 – 16:45 : 2’700 s)



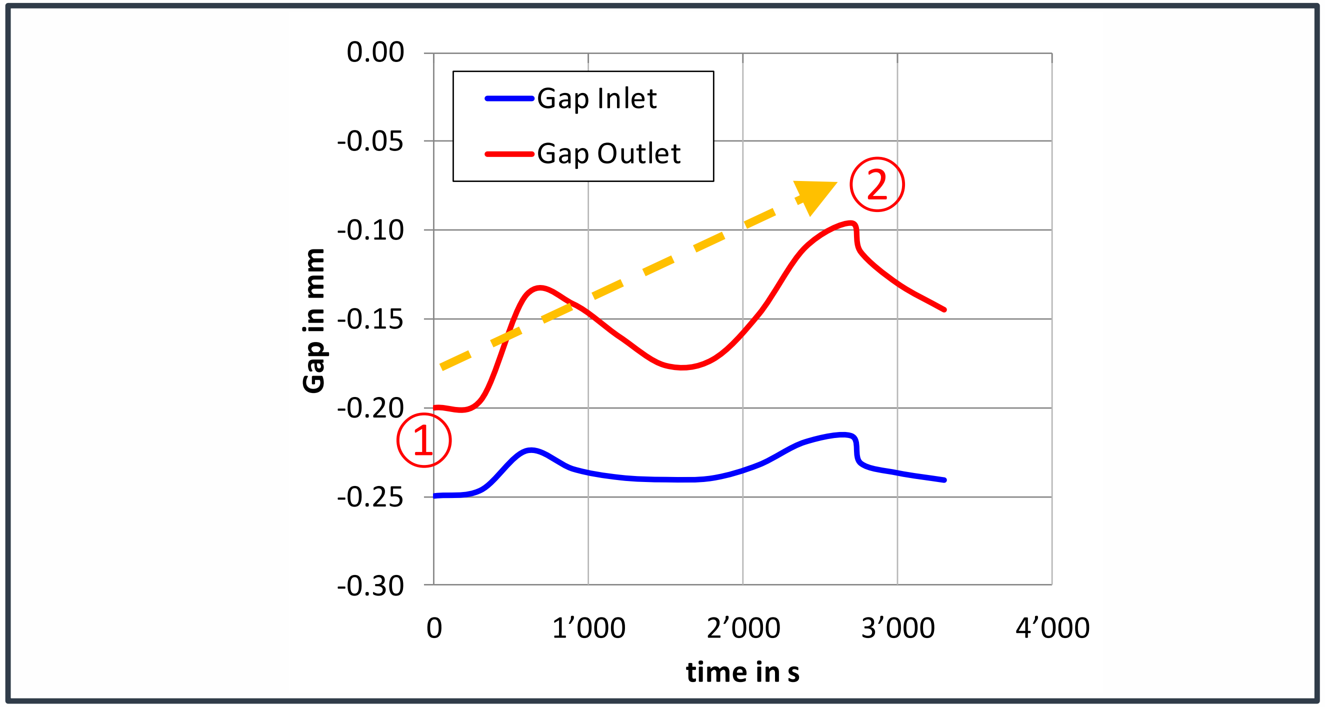
FEA Results

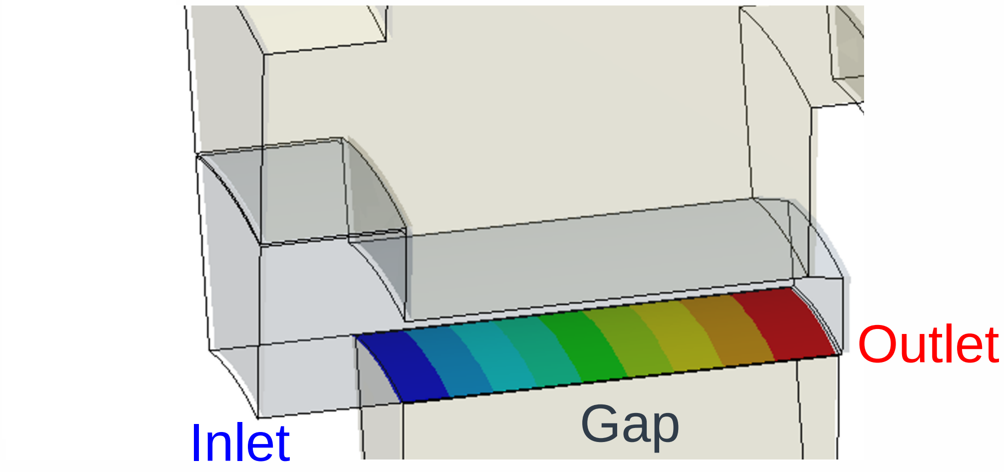


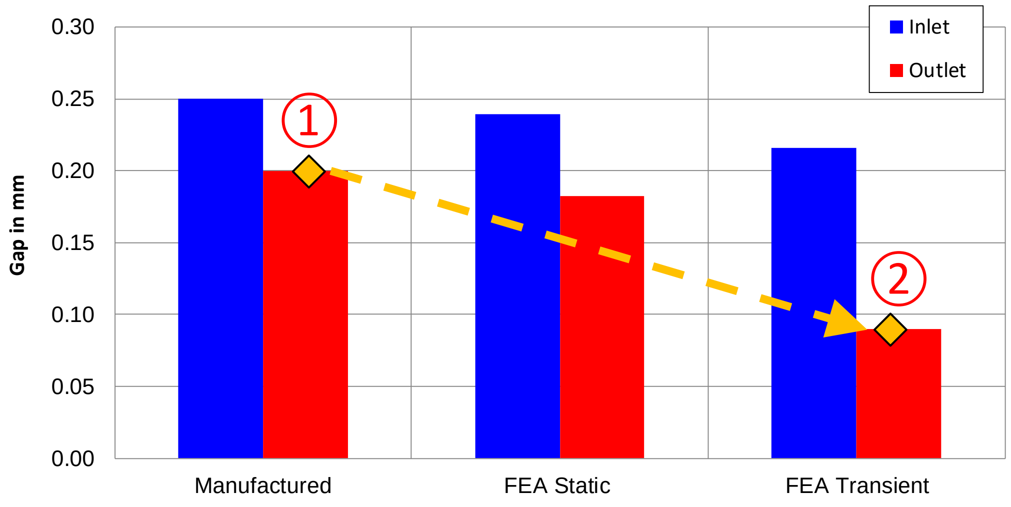
- Hole Pattern Seal and Shaft warm up much quicker than Casing and Cover → High Temperature Difference !

Root Cause Analysis – FEA

2. Analysis : Transient Calculation (Results)





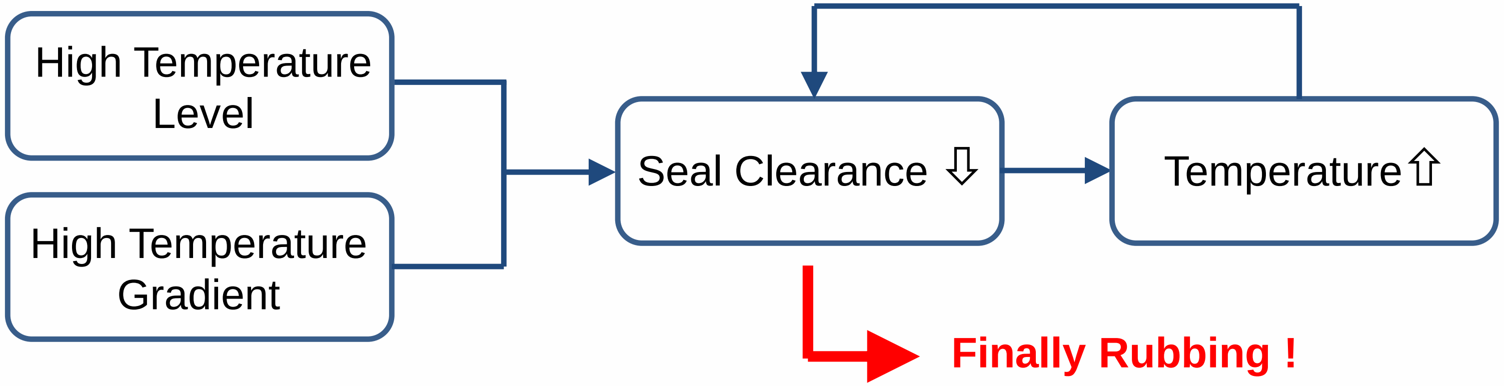


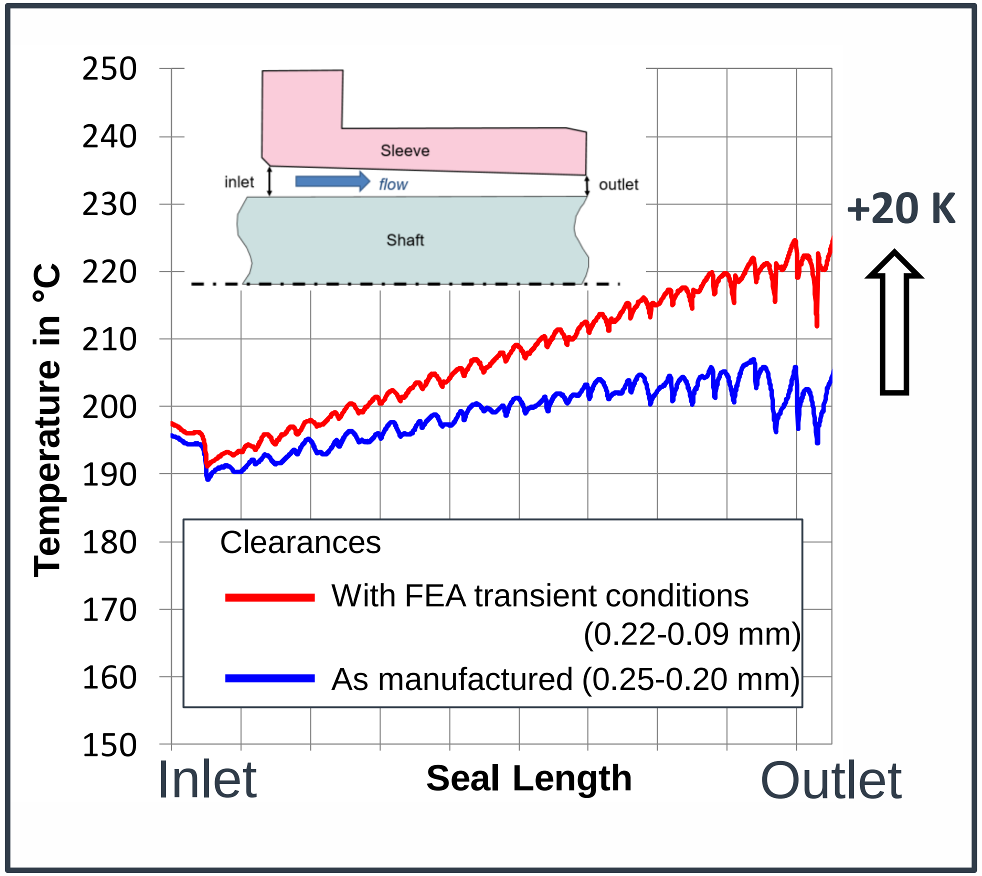
- Due to High Temperature difference between Sleeve/Shaft and Cover/Casing
  → Significant reduction of clearance at outlet !

Root Cause Analysis

3. Analysis : Other Considerations

- High temperature and high gradient temperature increase
  → Reduction of clearance
- Reduction of clearance
  → Increase of Leakage Flow Temperature





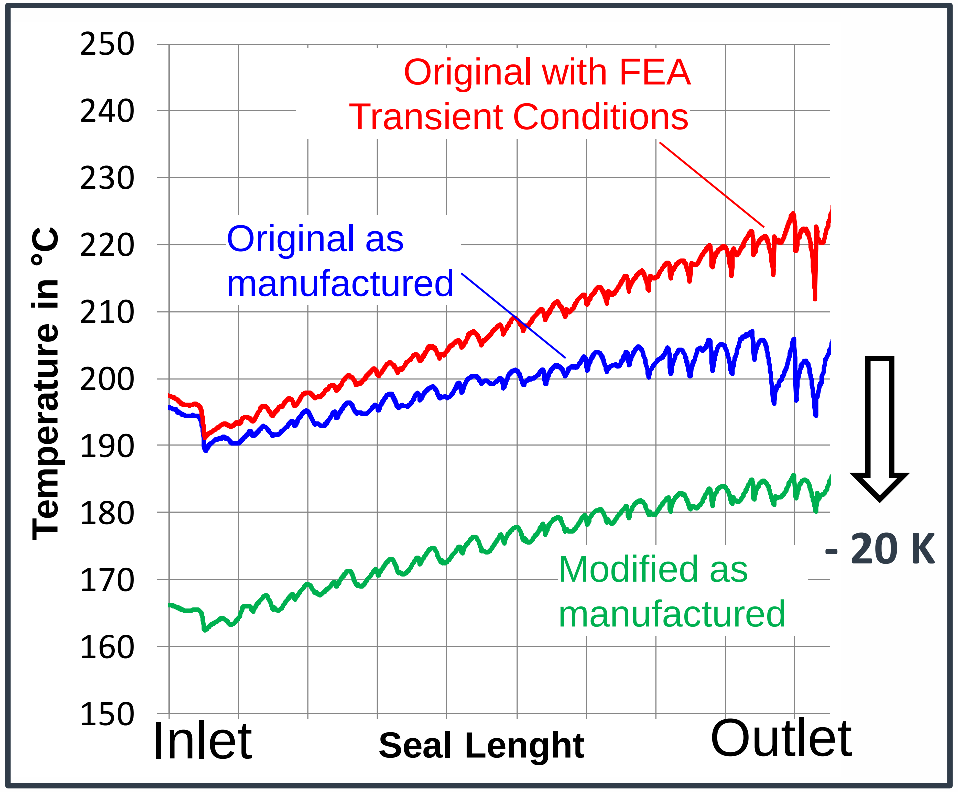
- Due to the reciprocal action «reduction seal clearance» and «increased flow temperature», the gap between sleeve and shaft decreases till rubbing

Actions

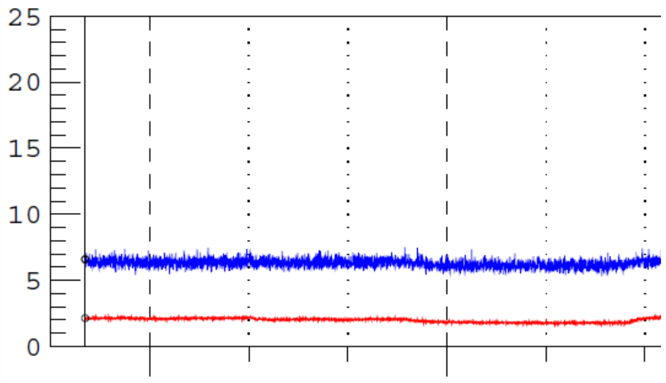
1. Gas composition modified
   → Decrease of discharge temperature
   Original: 70% N_2 + 30% He
   Modified: 50% N_2 + 50% He

2. Start-Up conditions modified : duration of start-up increased
   → gradient of increased pressure and temperature reduced
   → uniform temperature distribution in casing

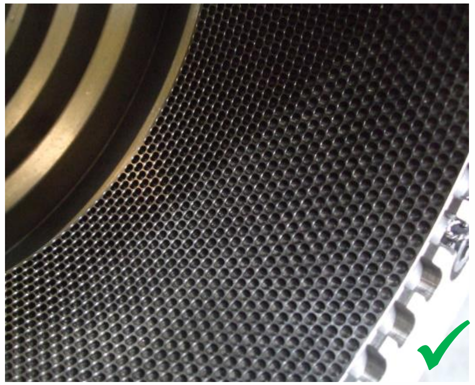
3. Replacement of Hole Pattern sleeve with a new manufactured with slightly increased clearances



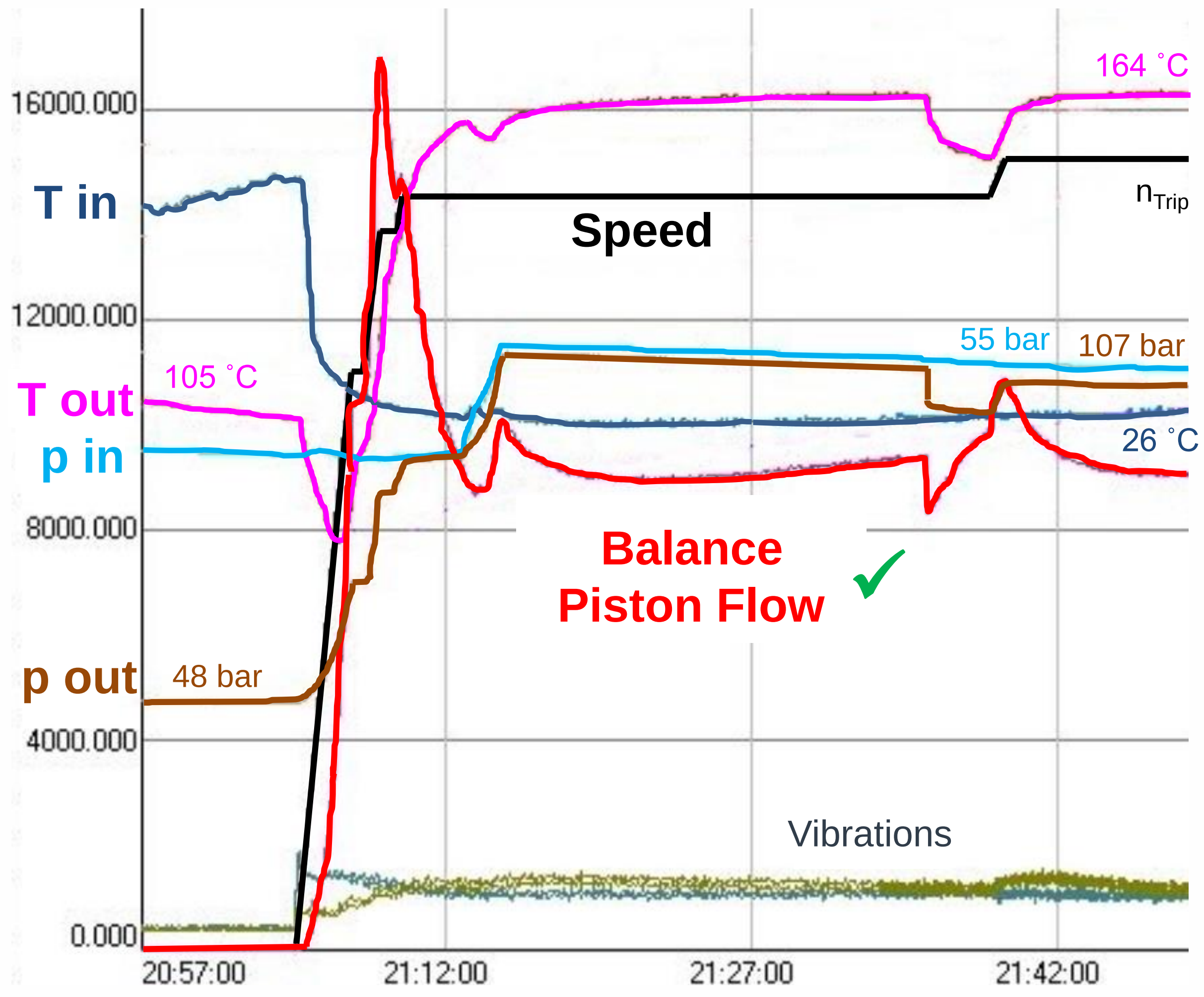
Measurements after modifications



Vibrations @ NDE (μm, pp) ✓



Inspected Hole Pattern Sleeve after test ✓



- Leakage flow stable
- All vibrations low and stable
- Mechanical Test successful
- No rubbing at Hole Pattern Seal

Lessons learnt / Summary

- When discharge temperature in shop test conditions exceeds the values in operation at site → careful attention

- If necessary mechanical running test procedure shall be modified to better reflect the temperature level and gradient of operation at site.

- Leakage at balance piston shall be continuously monitored during the test.

Case Study – Hole Pattern Seal

Thank you !

Questions ?