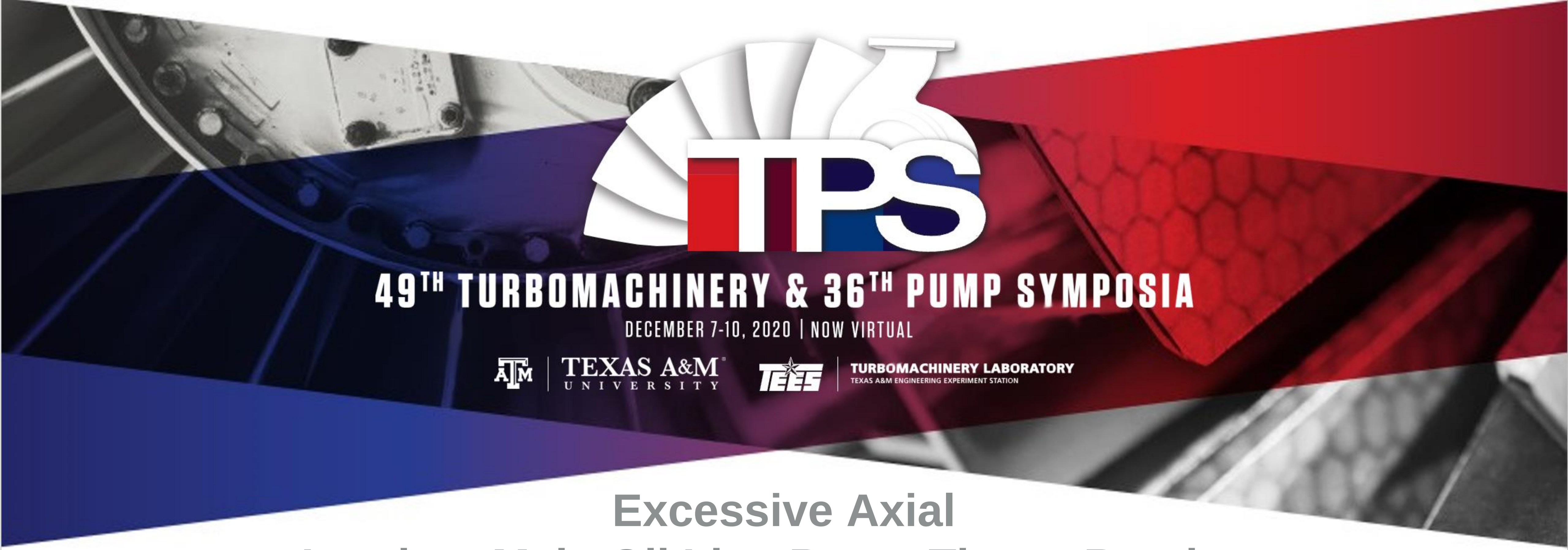

Excessive Axial Load on Main Oil Line Pump Thrust Bearing, Measurement and Control.

Martin Strachan CEng MIMechE – MDS Engineer, Bently Nevada, a Baker Hughes business
Peter Severs BEng AMIMechE – CM Technical Leader, Bently Nevada, a Baker Hughes business
Andrew Sharples CEng MIMechE – Rotating Equipment Team Leader, BP North Sea
Clive Woolsey CEng MIMechE – Rotating Equipment Engineer, BP North Sea
Timothy Vickers CEng MIMechE – Rotating Equipment Engineer, BP North Sea

Author Bios

Martin Strachan received his Master's degree in Mechanical Engineering in 2014, from the Robert Gordon University in Aberdeen, UK. Although initially covering the subsea and metallurgical fields of the Oil & Gas industry, he stepped into rotating equipment with Bently Nevada in 2016. Here he held the position of Machinery Diagnostic Services Engineer, delivering remote and on-site diagnostic support directly for operators through their Bently Nevada Supporting Service Agreements (SSA). He also spent some time as a Project Engineer for Industrial Gas Turbines with Ethos Energy Group before returning to Bently Nevada in 2019 as SSA Site Lead.

Peter Severs employment history is diverse and whilst working for Bently Nevada has worked as a field engineer, lead engineer and now as Global Condition Monitoring Technical Leader. He studied at the University of Sunderland on a day release programmed, for a Foundation Degree in Maintenance Engineering. Then went on to study for a BEng. (Hons) in Mechanical Engineering at the University of Teesside. Previously he has worked in the field of reliability and heavy industry.

Andrew Sharples graduated from Loughborough University in 1998 with a degree in Mechanical Engineering. Having joined BP in the same year, he has since spent over 20 years in engineering roles spanning refining, petrochemicals, mid-stream and upstream areas of the Oil & Gas Industry. Starting out in the Grangemouth complex, he held a variety of positions supporting operations and projects, together with organizational change management and then as Maintenance Team Leader. In 2007 he joined BP's upstream business as a Mechanical Technical Authority and progressed to Rotating Equipment Team Leader in 2015 for the North Sea region, and recently now for Azerbaijan, Georgia & Turkey.

Clive Woolsey graduated from The Queen's University Belfast with a degree in Mechanical Engineering in 1999. He spent fourteen years as a global, oil and gas service provider for gas turbine, compressor and pump products with Wood Group GTS and EthosEnergy. Clive advanced through several technical leadership roles to the position of General Manager and Technical Director in 2012, before taking up employment with Shell UK as a senior rotating equipment engineer. Moving to BP North Sea in 2017, he acts as a senior rotating equipment specialist and recently graduated from Teesside University with an HNC in Controls and Instrumentation.

Tim Vickers has an Aerospace Engineering from the University of Bath. In the middle of his degree he worked for one year as a mechanical engineer at BMT Defense Services, a Naval Engineering consultancy. After graduating in 2012 he has worked for BP North Sea, covering engineering roles in operations, maintenance and discipline engineering.

Short Text Abstract

This case study describes the deployment of an axial load measurement and control solution for centrifugal pumps experiencing high bearing temperatures on the Non-Drive End (NDE). Through the real-time measurement of the axial load on-skid, informed and successful control of the balance line pressure was performed. Thus, the effect of the balance piston was increased and the overall load on the bearing was reduced by ~75% allowing the pumps to return to service averting the risk for the customer.

Problem Statement

- During start-up, newly commissioned centrifugal pumps on crude oil duty experienced increasing bearing temperature at the Non-Drive End (NDE) despite acceptable casing vibration.
- Further investigation determined the tapered roller NDE thrust bearing was being overloaded by the cold process fluid. The bearing axial design load was 10 kN where the theoretical calculations suggested 30 kN was more realistic. (See Appendix A for bearing information).
- With the previous pumps decommissioned, these new pumps were required to provide the export pressure into a shared pipeline and thus continue production.
- A rapidly deployed monitoring solution was required to support reduction of the axial load via balance line control and return these pumps to operation.
- Failure to do so would result in zero export from this asset until a de-rated pump-cartridge could be deployed.

Monitoring & Control Solution – Overview

- The end user and OEM, designed a dual needle valve solution to allow the balance line flow and thus effective pressure of the balance piston to be adjusted reducing the axial force on the outboard thrust bearing.
- An additional lubrication oil (LO) circulation skid was identified to provide higher volume, 0.6 liters per minute vs. 0.2 liters per minute.
- This would promote heat transfer from the bearing, allowing better absorption of thermal transients than the constant level oiler/ throw ring system.
- The LO type was changed at the NDE to increase the ratio of required viscosity vs actual viscosity at operating conditions (Kappa ratio) to 2.8 from 0.7 (See Appendix B for further information).
- On-skid data collection from a 4-20 mA transducer could be performed by an Automated Diagnostics for Rotating Equipment (ADRE), portable multi-channel analyzer with precision force sensors (or load cells).

Monitoring & Control Solution – Testing

- The load monitoring solution, utilized four button type load cells held within a machined steel ring assembly.
- Load was transmitted through the NDE hub retaining bolts into the ring and to the load cells (*Figure 1*).
- The output was amplified and fed into the multi-channel analyzer as a 4-20 mA signal.
- The application was tested at the OEM workshop verifying load transmission and compensation for bolt pre-load.

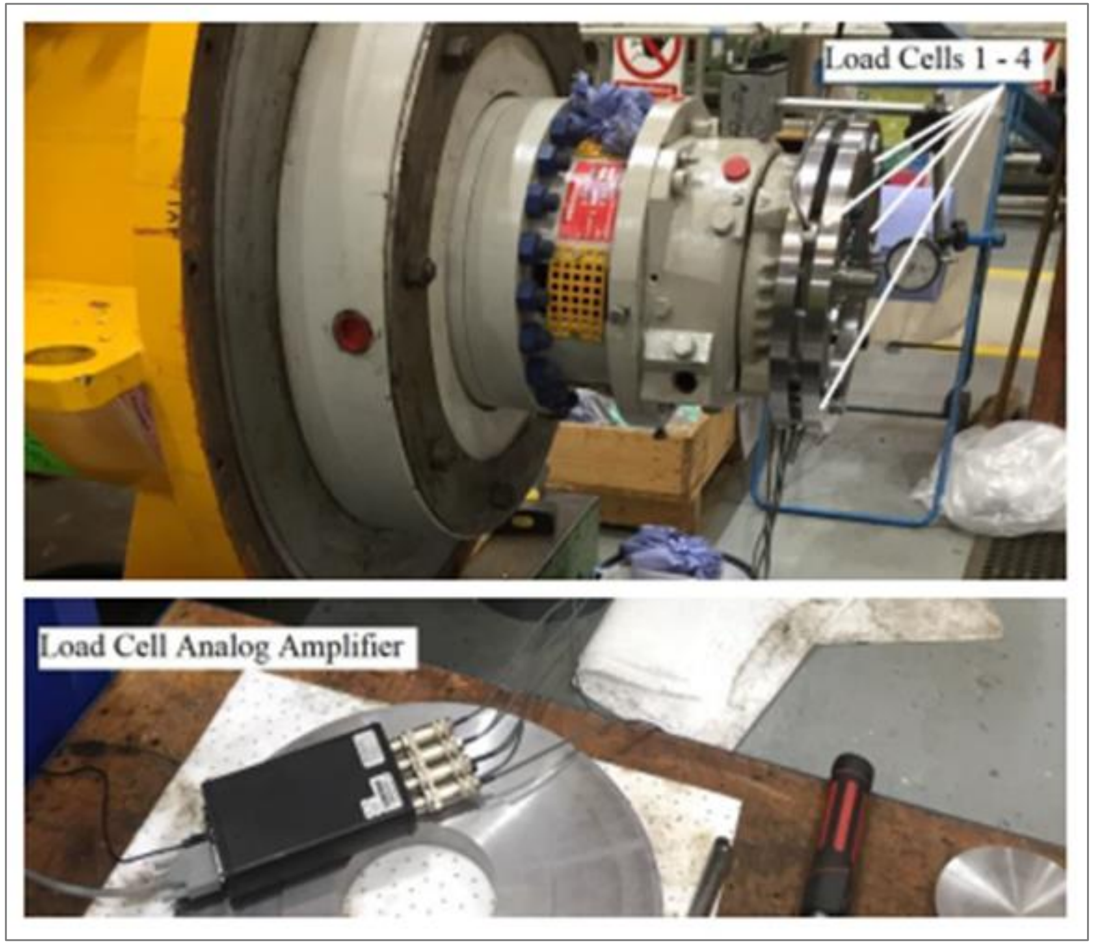

Figure 1: Load cell configuration on test pump, amplifier & individual load cell.

Monitoring & Control Solution – Safety

- The end user, were conscious of the safety implications of increasing the balance chamber pressure as this would increase the mechanical seal chamber pressure.
- A full in-depth technical review of safe operating limits was performed in compliance with end user's Management of Change (MOC) process.
- The seal system was re-evaluated to ensure the higher pressure expected was within its design limits.
- The seal pressure alarm and trip setpoints were adjusted to compensate for the higher balance chamber pressure.
- Planning of the execution of the solution was also captured to manage the risk to the wider plant and personnel.

Monitoring & Control Solution – Execution

- The load cells and analyzer were deployed in the field on-skid.
- The analyzer was configured to collect sub-second load cell data, reporting to the laptop and Machinery Diagnostic Services Engineer at the skid.
- Vibration and Temperature protection was retained by the machinery protection system and monitored in machinery management system.
- *Figure 2* shows the monitoring points for vibration, temperature and load.

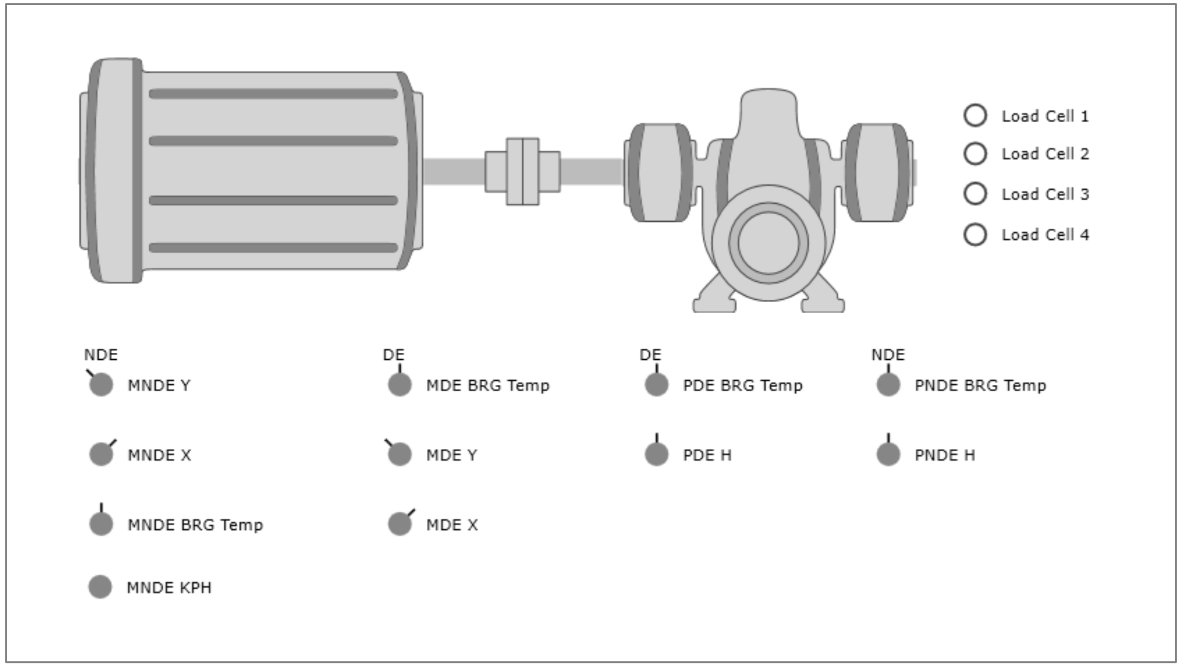

Figure 2: Machine train instrumentation setup including additional load cells.

Monitoring & Control Solution – Execution

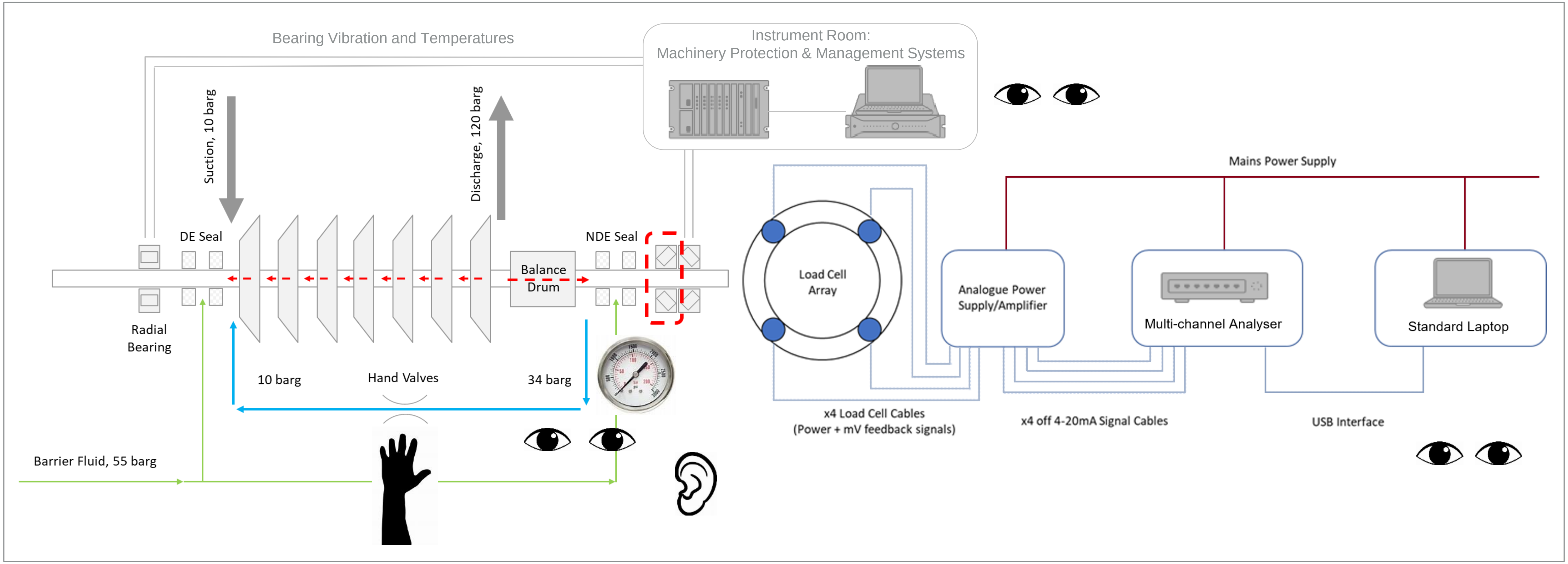

Figure 3: Overview of the full solution – with Manual adjustment of Needle Valves in response to Balance Chamber Pressure, Thrust Load monitoring setup with Engineer feedback in response to valve changes and the Vibration and Temperature monitoring and protection system.

Monitoring & Control Solution – Results

- The machine train was started operated in full recycle.
- The load monitoring system reported an initial axial load of 22.6 kN. This was greater than the bearings allowable 10 kN.
- The balance line pressure control valves (PCVs) were adjusted initially reducing the load to 21.7 kN.
- Further adjustments reduced the load to 13.3 kN or by 40% (*Figure 4*).

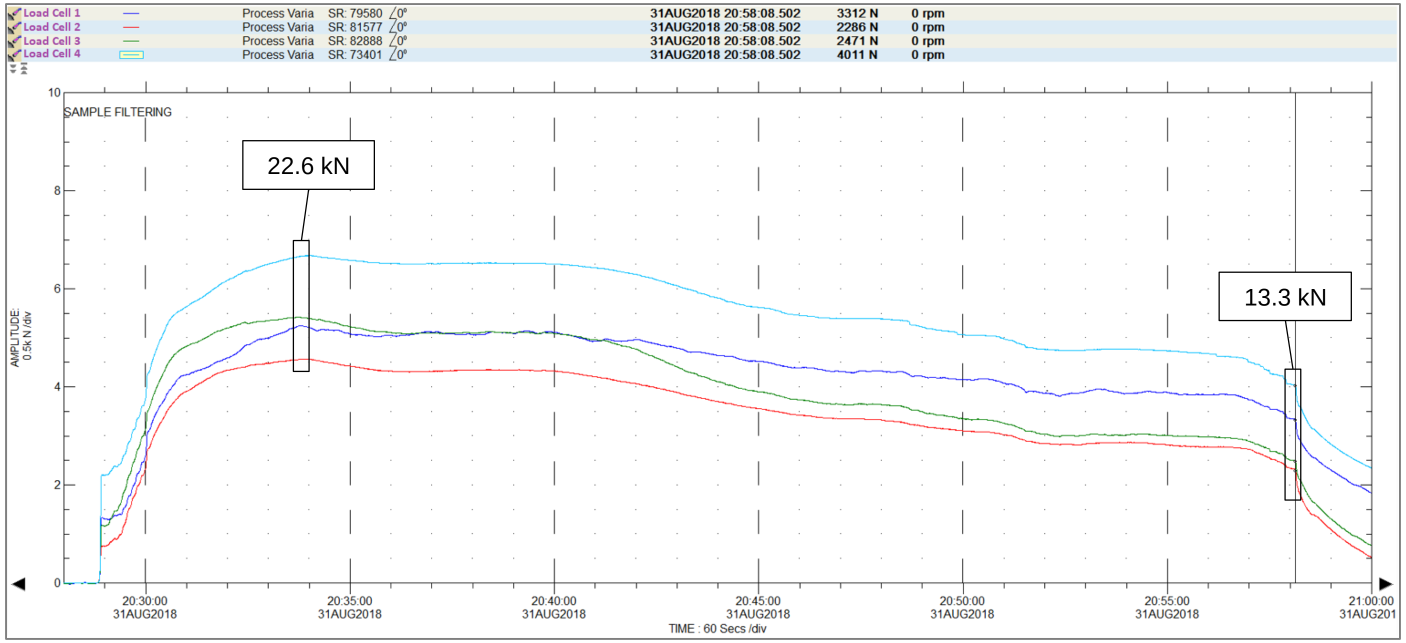

Figure 4: Pump NDE Axial Load (Individual) Trends, Test Run 1.

Monitoring & Control Solution – Results

- This subsequently reduced the NDE bearing temperature from 82°C to 74°C prior to a process related trip event *(Figure 5).*

- Note each bearing had an independent LO system and the DE retained the constant level oiler/ throw ring system .

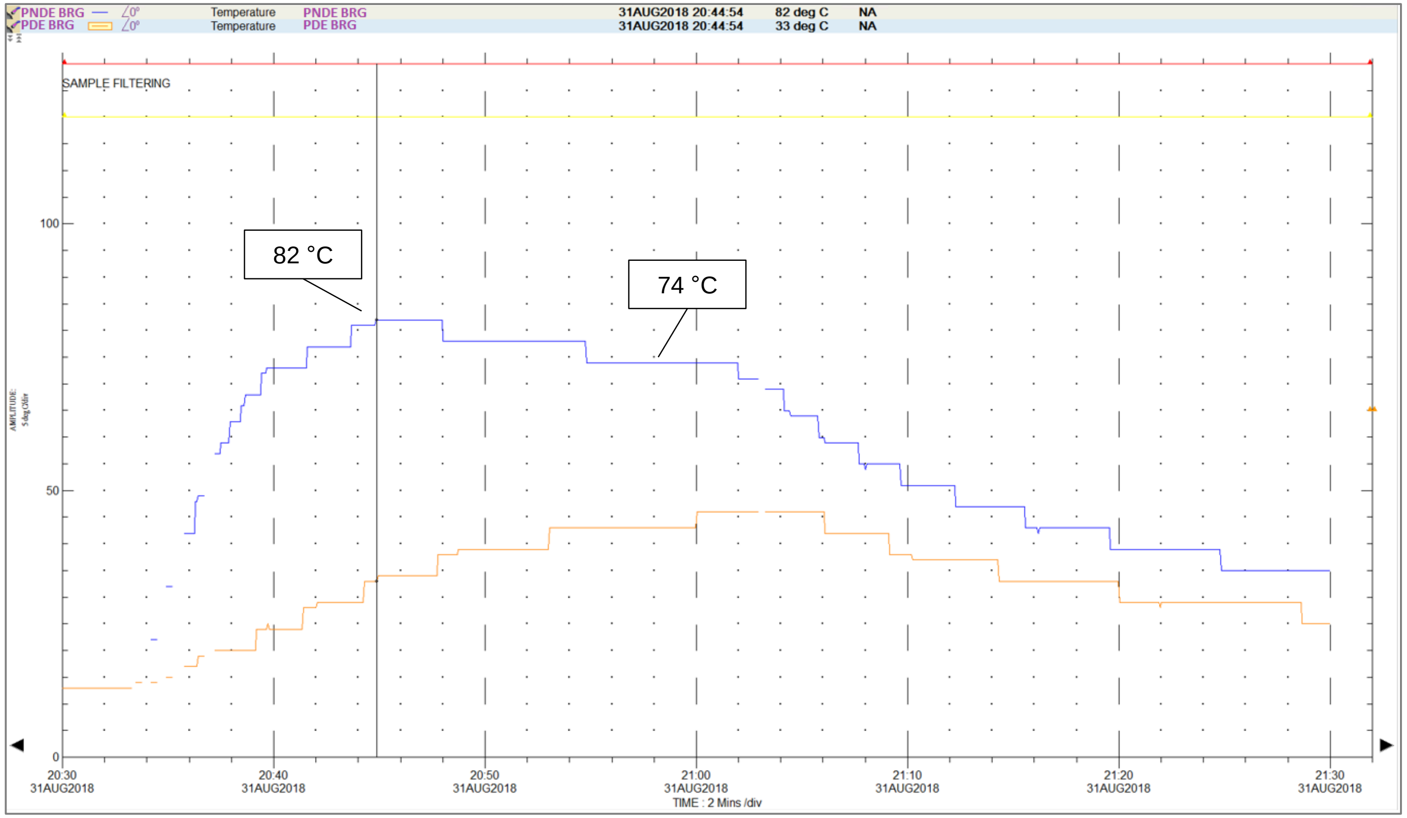

Figure 5: Pump NDE & DE, Bearing Temperature Trends, Test Run 1.

Monitoring & Control Solution – Results

- Several further runs were made, where wider process instability prevented success until Test Run 7.
- The valve positions were reset and initial start-up load peaked at 20.4 kN (*Figure 6*).
- The balance line pressure was increased from 20 barg to 32 barg via the PCVs, reducing axial load down to a stable 7.0 kN.

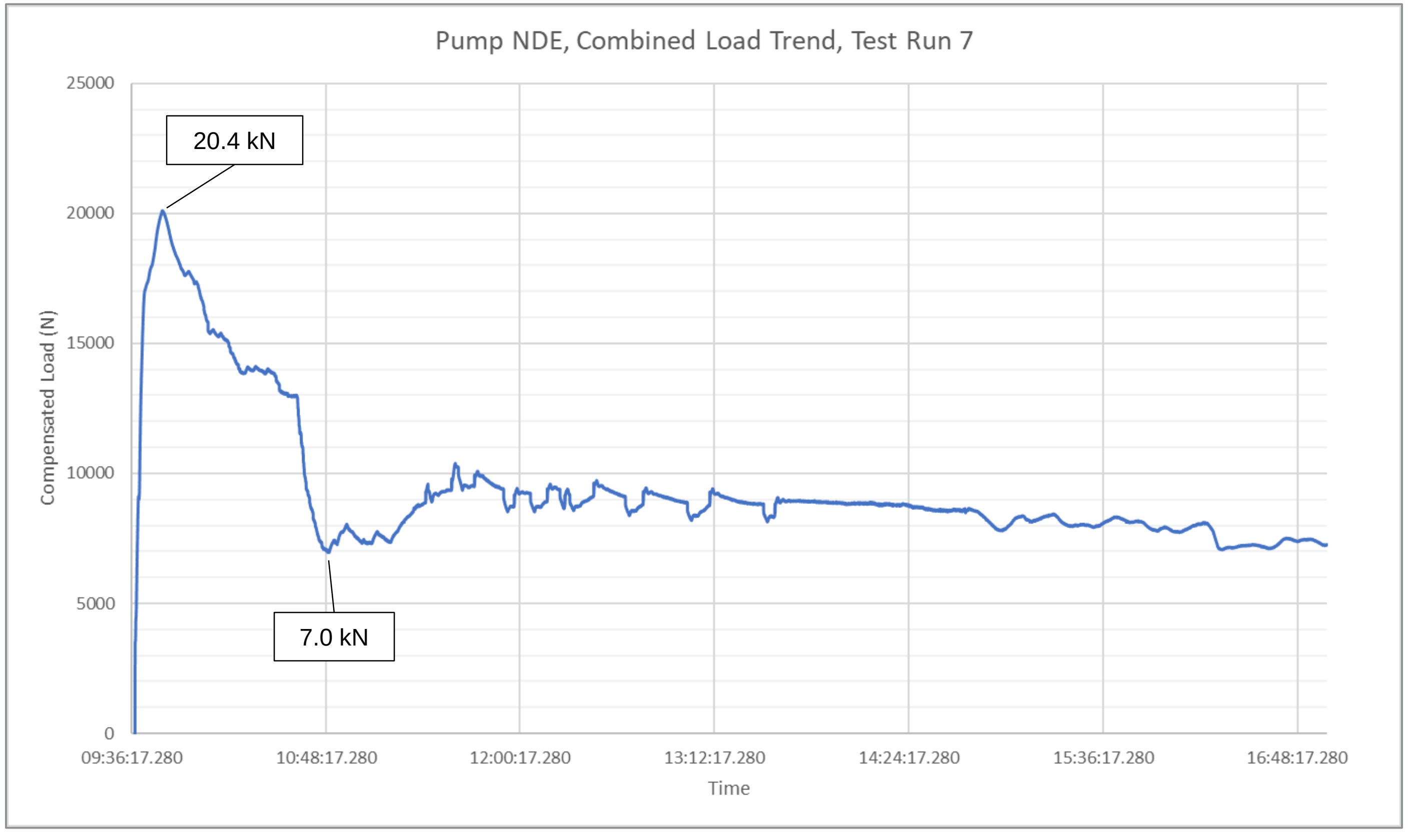

Figure 6: Pump NDE & DE, Bearing Temperature Trends, Test Run 1.

Monitoring & Control Solution – Results

- At this stage the pump was moved from full recycle of 12,000 barrels per day (bpd) to forward flow crude oil of 4,000 bpd – a total of 16,000 bpd.
- Closer examination of *Figure 6* indicates the step changes in load were measured alongside increases in forward flow.
- Due to limitations in available export process, the train was returned to Full Recycle (12,000 bpd).

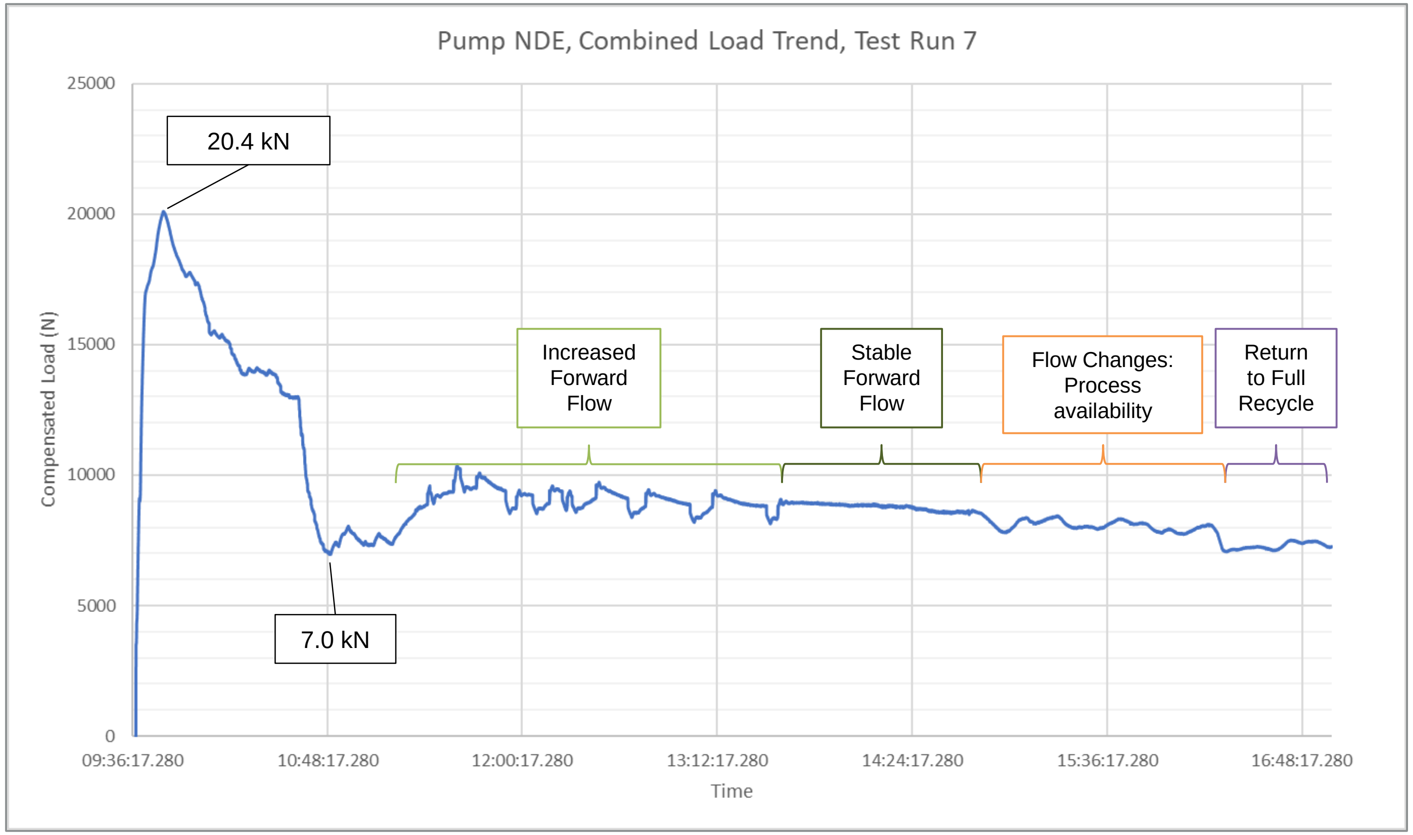

Figure 6: Pump NDE Axial Load (Combined) Trend, Test Run 7.

Monitoring & Control Solution – Results

- During Run 7, NDE bearing temperatures initially peaked at 67°C before reducing to a stable 41°C as the load reduced (*Figure 7*).
- Step changes in NDE temperature were seen to correlate, with slight lag, as a result of changes in forward flow.
- The DE remained stable at 48°C.

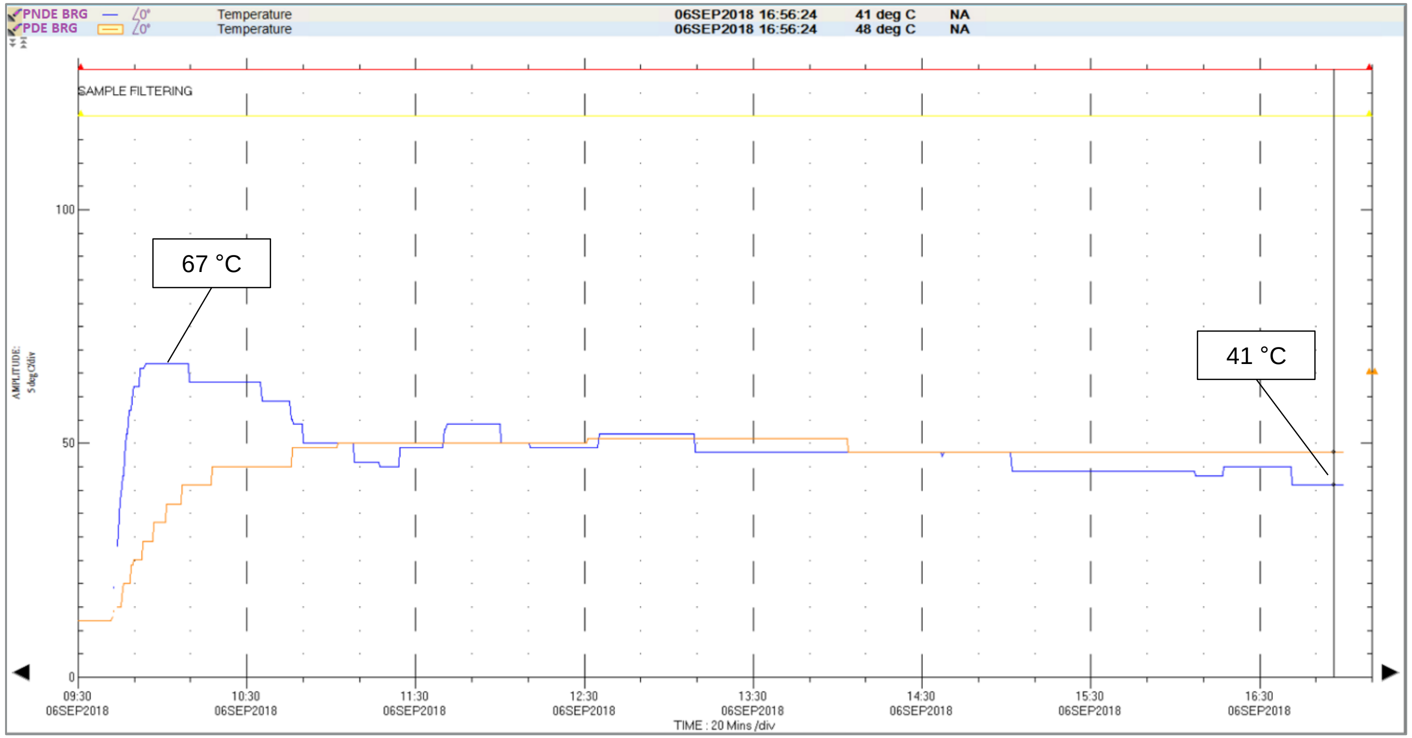

Figure 7: Pump NDE & DE, Bearing Temperature Trends, Test Run 7.

Initial Conclusions

- Successful steady state operation was achieved through balance line control and measurement of axial load.
- This allowed a 75% reduction in Pump NDE axial load to be realized.
- The temperature reaction to the decrease in loading was almost immediately apparent during the test runs.
- The monitoring & control solution was deployed on the second pump (Pump 2) successfully.
- Both Pump 1 & 2 were able to enter service and provide a throughput of 32,000 bpd (not including recycled) with successfully operation for 20 days.

Continued Operation – Bearing Failure

- However… over the next 20 days vibration increased on Pump 1.
- The increase was from the Ball Pass Frequency Inner Race (BPFI).
- The other components: Ball Pass Frequency Outer Race (BPFO), 2X and 1X remained constant (*Figure 8*).
- Indicative of the early stages of fatigue failure of the bearing – no doubt a result of the excessive load in early tests.

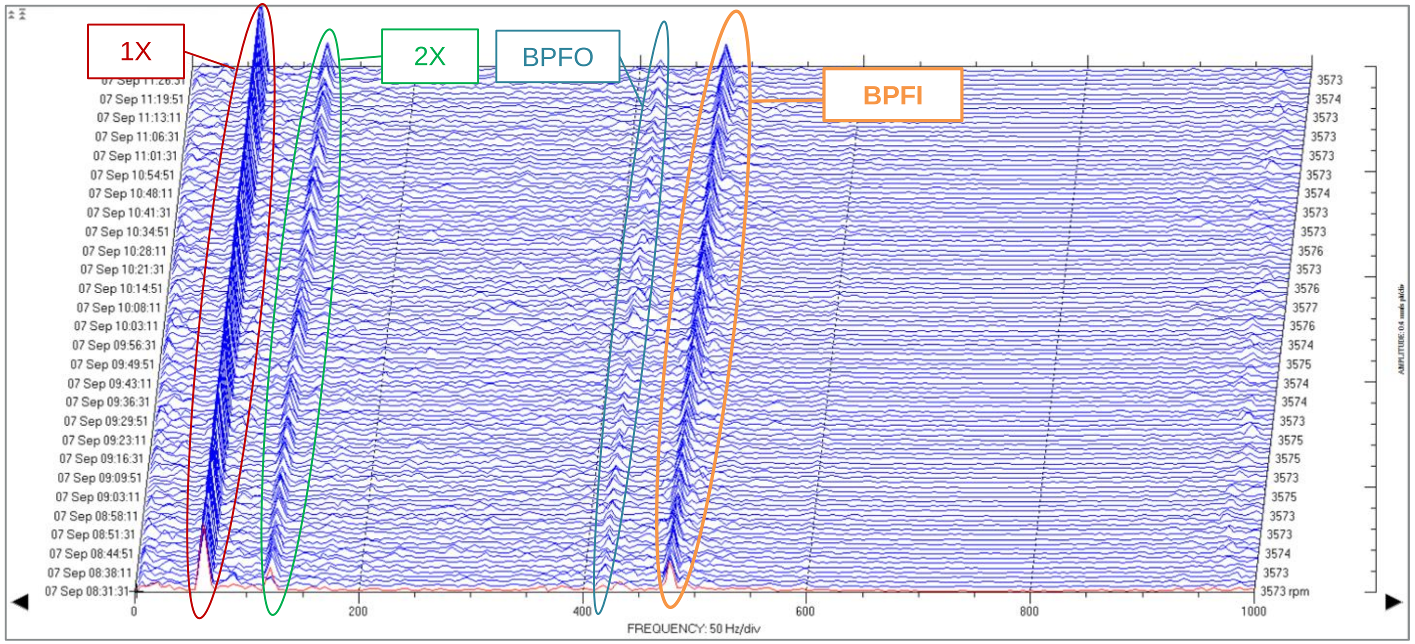

Figure 8: Pump 1 NDE, Asynchronous Half Spectrum Waterfall, Post Test Runs.

Continued Operation – Bearing Failure

- On Day 21, there was an unsuccessful attempt to move production from Pump 1 to Pump 2 – to allow Pump 1 to shutdown for maintenance.
- This resulted in an increase in load on Pump 1, with a trip initiated on high NDE bearing temperature.
- A peak in casing vibration lagged the temperature trip.
- Investigation found the NDE bearing had failed (*Figure 9*).

Figure 9: Pump NDE Bearing Inspection showing metal particulate.

Lessons Learnt

- This bearing failure highlighted the risks of this activity for long term production stability and safety.
- Despite the rapidly evolving situation, compromise to safety and MOC processes was not an option.
- The risks were re-evaluated and additional controls identified.
- Temperature set-points were reduced in the rack-based machinery protection system from 100 and 130°C for Alarm (High) and Danger (High-High) respectively to 65 and 85°C.
- Additional awareness was cascaded to the control room operators of the sensitivity of these pumps to process control changes.

Final Conclusions & Recommendations

- The case study demonstrates successful axial load real-time measurement and axial load control.
- However, it was clear that the pumps continued to be sensitive to transient process disruptions in fluid pressure and flow.
- Due care was required in controlling the process flow to avoid excessive axial loading in the pump.
- A further reduction of the temperature Alarm and Danger Trip set-points was implemented, adding an additional level of bearing load protection.
- These two pumps continue in operation to date, successfully produce under stable process conditions averting the risk of failure for the customer.

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Acknowledgements

The Machinery Diagnostics Services (MDS) team would like to thank BP North Sea and the local Rotating Equipment team, as end user, for their efforts and support of this scope of work. In particular, recognizing co-authors Andrew Sharples, Clive Woolsey and Tim Vickers, for their endeavors in delivering the successful return to service and continued operation of the pumps.

The authors would also like to acknowledge the contributions of EUR ING Nicolas Peton PhD, Global Director of Machinery Diagnostic Services, and Peter Popaleny PhD, West Europe MDS Technical Leader, both of Bently Nevada for their support and guidance with execution of this scope.

Appendix A – Bearing Information

- The Pump NDE bearing was a matched single row tapered rolling element bearing at the NDE with the designation "31312J2/DF".

Table A.1: Bearing Dimensions (SKF 2020).

Dimensions		Abutment Dimensions	
d	60 mm	D_a maximum	74 mm
D	130 mm	D_a minimum	103 mm
T	67 mm	D_a maximum	119.5 mm
2B	62 mm	C_a maximum	5 mm
b	13 mm	r_a maximum	2.5 mm
K	10 mm	r_c maximum	1 mm
r_3, r_4	2.5 mm (minimum)		
r_5	1.0 mm (minimum)		

Table A.2: Bearing Calculation Parameters (SKF 2020).

Calculation Data			
Basic dynamic load rating (C)	303 kN	Calculation factor (e)	0.83
Basic static load rating (C_0)	335 kN	Calculation factor (Y_1)	0.81
Fatigue load limit	40.5 kN	Calculation factor (Y_2)	1,2
Reference speed	3000 rpm	Calculation factor (Y_3)	0.8
Limiting speed	5300 rpm	Mass (bearing pair)	4.06 kg

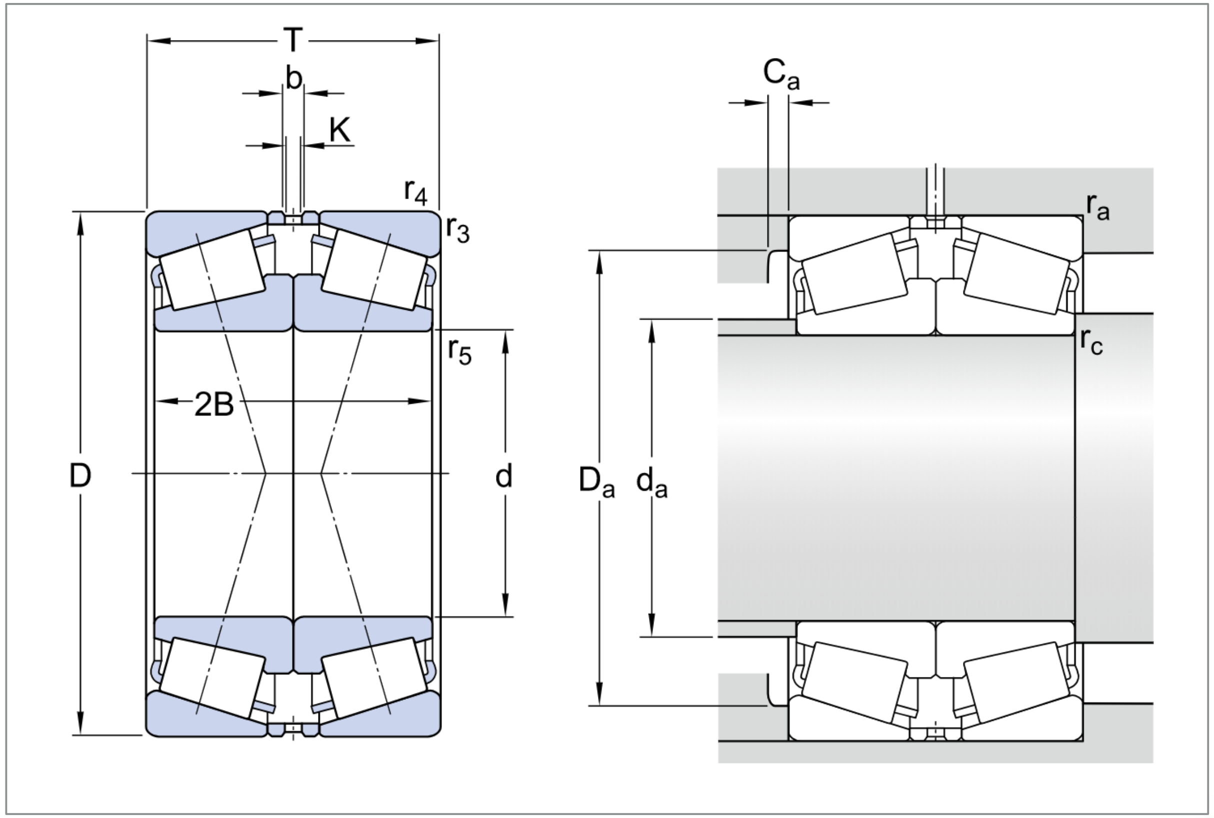

Figure A.1: Bearing General Arrangement Drawing (SKF 2020).

Appendix B – Kappa Calculations

- The following calculations (Table B.1 to B.6) were performed by the end-user.
- These determined the required operating parameters to achieve a Kappa ratio greater than 2 for the T46 oil – the ratio achieved at Factory Acceptance Test.
- Note the expected axial load of 10 kN in comparison to the re-calculated "field value" of 25 kN .
- The calculations conclude the operating temperature of the bearings needs to drop to below 70 °C to achieve this and thus a maximum permissible axial load of 10 kN is required.

Table B.1: Kappa Ratio Calculations for Factory Acceptance Test Condition (SKF 2020).

Condition at Factory Acceptance Test							
Parameters		Calculated Results					
Axial Load	10 kN	Oil flow rate [L/min]	0.025	0.050	0.100	0.150	0.200
Radial Load	0.75 kN						
Speed	3578 rpm	Bearing Temperature [°C]	72	74	74	71	69
Oil Inlet Temperature	60 °C						
Oil Type	T46	Kappa	1.8	1.7	1.7	1.8	2.0
Ambient Temperature	15 °C						

Table B.2: Kappa Ratio Calculations for Theoretical Condition 1 (SKF 2020).

Condition 1								
Parameters		Calculated Results						
Axial Load	25 kN	Oil flow rate [L/min]	0.025	0.050	0.100	0.150	0.200	0.800
Radial Load	0.75 kN							
Speed	3578 rpm	Bearing Temperature [°C]	145	138	127	118	112	85
Oil Inlet Temperature	60 °C							
Oil Type	T46	Kappa	0.4	0.4	0.5	0.6	0.7	1.3
Ambient Temperature	15 °C							

Appendix B – Kappa Calculations (continued)

Table B.3: Kappa Ratio Calculations for Theoretical Condition 2 (SKF 2020).

Condition 2								
Parameters		**Calculated Results**						
Axial Load	25 kN	Oil flow rate [L/min]	0.025	0.050	0.100	0.150	0.200	1.000
Radial Load	0.75 kN							
Speed	3578 rpm	Bearing Temperature [°C]	153	146	136	126	119	86
Oil Inlet Temperature	60 °C							
Oil Type	15W40: 106 cSt @ 40°C 14.4 cSt @ 100 °C	Kappa	0.7	0.8	0.9	1.1	1.2	2.7
Ambient Temperature	15 °C							

Table B.4: Kappa Ratio Calculations for Theoretical Condition 3 (SKF 2020).

Condition 3								
Parameters		**Calculated Results**						
Axial Load	15 kN	Oil flow rate [L/min]	0.025	0.050	0.100	0.150	0.200	0.700
Radial Load	0.75 kN							
Speed	3578 rpm	Bearing Temperature [°C]	121	119	115	109	104	85
Oil Inlet Temperature	60 °C							
Oil Type	15W40: 106 cSt @ 40°C 14.4 cSt @ 100 °C	Kappa	1.2	1.2	1.4	1.5	1.7	2.7
Ambient Temperature	15 °C							

Table B.5: Kappa Ratio Calculations for Theoretical Condition 4 (SKF 2020).

Condition 4								
Parameters		**Calculated Results**						
Axial Load	10 kN	Oil flow rate [L/min]	0.025	0.050	0.100	0.150	0.200	0.600
Radial Load	0.75 kN							
Speed	3578 rpm	Bearing Temperature [°C]	107	107	105	101	97	84
Oil Inlet Temperature	60 °C							
Oil Type	15W40: 106 cSt @ 40°C 14.4 cSt @ 100 °C	Kappa	1.6	1.6	1.7	1.8	2.0	2.8
Ambient Temperature	15 °C							

Table B.6: Kappa Ratio Calculations for Theoretical Condition 5 (SKF 2020).

Condition 5								
Parameters		**Calculated Results**						
Axial Load	10 kN	Oil flow rate [L/min]	0.025	0.050	0.100	0.150	0.200	0.300
Radial Load	0.75 kN							
Speed	3578 rpm	Bearing Temperature [°C]	95	95	94	91	88	84
Oil Inlet Temperature	60 °C							
Oil Type	T46	Kappa	1.0	1.0	1.0	1.1	1.2	1.3
Ambient Temperature	15 °C							