Bently Nevada
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Value of Cylinder Pressure Measurement for Reciprocating Compressor

S-Oil produces lube base oil, petro-chemical products, and operates crude oil refining facilities of 669,000 barrels a day in the Onsan Industrial Complex of Ulsan, Korea, which is the world's largest paraxylene (PX) production facility, and bunker-c cracking center of worldwide standard.

Machine Description

The Aromatic process plant's Hydrogen rich gas compressors are four throw, three-stage, double-acting horizontal API618 reciprocating compressors with 40,122 Nm3/h output.

In 2021, a Bently Nevada reciprocating compressor condition monitoring system, including on-line dynamic cylinder pressure, was implemented for this compressor to detect earlier indication of machine problems and provide better diagnostics capability. Figure 1 shows the transducer layout on one of these machines.

Table 1. Compressor Nameplate Information

Compressor Specification	
Suction Pressure	0.2060 KSCA
Discharge Pressure	3.0300 KSCA
Suction Temperature	43.0 °C
Discharge Temperature	109.0 °C
Total BHP	3,820.0 KW

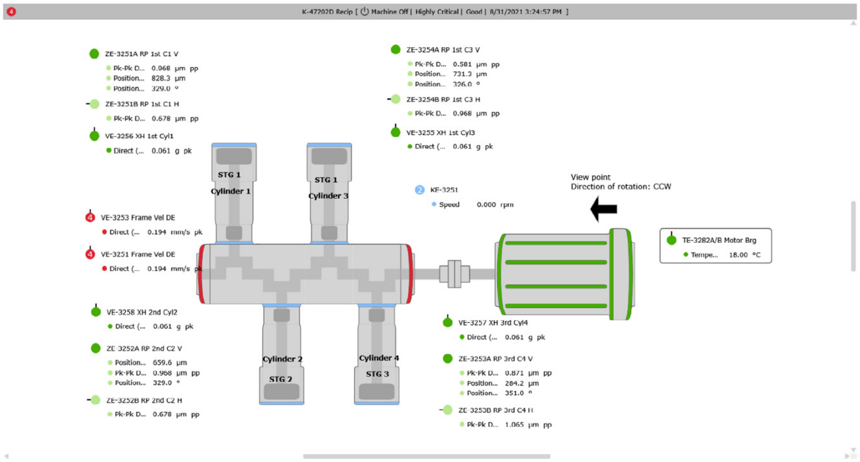


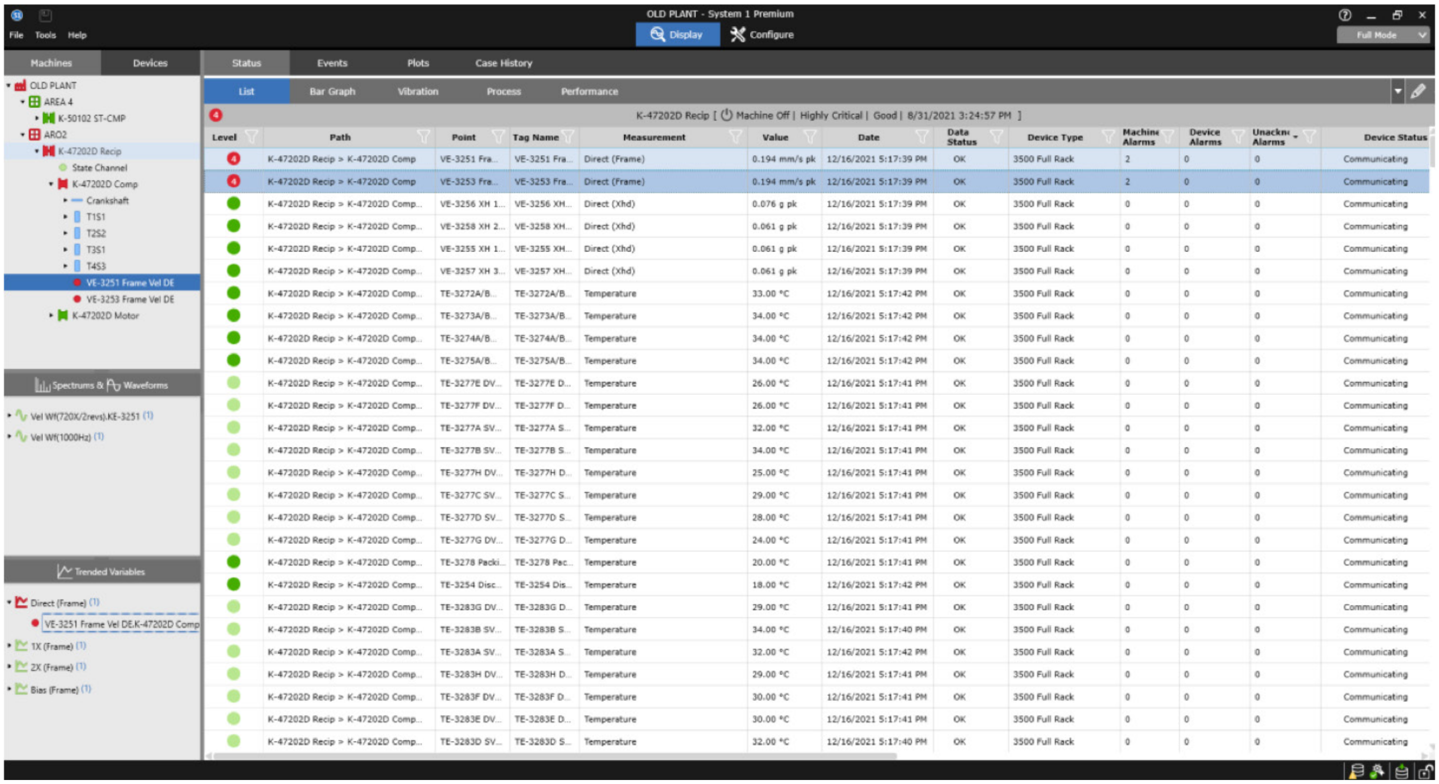
Figure 1. Machine Train Diagrams with Condition Monitoring Parameters

Condition Monitoring with Full Scope of Bently Nevada Best Practice

In addition to the monitoring parameters recommended by API and the machine manufacturer, S-Oil decided to plan for a machine protection and condition monitoring system to holistically observe key monitoring parameters for these new reciprocating compressors, at the machine design phase. Bently Nevada"s Reciprocating Compressor best practice document was used as reference for the front-end engineering design (FEED) specification.

As part of S-Oil's ongoing reciprocating compressor management program, various machine parameters are continuously monitored and trended with the on-line system. Parameters monitored by the system are cylinder pressure (Pressure vs Volume, Rod load, Rod reversal, Flow balance...), valve temperature, suction and discharge temperature, frame velocity, crosshead acceleration and piston rod position. 3500 machine protection system provides alarm for key monitoring parameters such as low rod load reversal, high vibration and changes in gap voltage. All key parameters are collected and displayed on System 1® Asset Condition Monitoring System. The Multi Event Wheel (MEW) signal is an important parameter measured by 3500 system and System 1 to calculate extremely accurate crank angle of each piston to support advanced diagnostics and machinery protection.

On December 16th, 2021, the 3500 rack detected a hardware alarm on the frame vibration. As Figure 2 shows, the compressor shut down because of this high vibration, initiating a follow-up investigation.



K-47202D Recip [Machine Off | Highly Critical | Good | 8/31/2021 3:24:57 PM]

Level	Path	Point	Tag Name	Measurement	Value	Date	Data Status	Device Type	Machine Alarms	Device Alarms	Unackn Alarms	Device Status
4	K-47202D Recip > K-47202D Comp	VE-3251 Fra...	VE-3251 Fra...	Direct (Frame)	0.194 mm/s pk	12/16/2021 5:17:39 PM	OK	3500 Full Rack	2	0	0	Communicating
4	K-47202D Recip > K-47202D Comp	VE-3253 Fra...	VE-3253 Fra...	Direct (Frame)	0.194 mm/s pk	12/16/2021 5:17:39 PM	OK	3500 Full Rack	2	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	VE-3256 XH 1...	VE-3256 XH...	Direct (Xhd)	0.076 g pk	12/16/2021 5:17:39 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	VE-3258 XH 2...	VE-3258 XH...	Direct (Xhd)	0.061 g pk	12/16/2021 5:17:39 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	VE-3255 XH 1...	VE-3255 XH...	Direct (Xhd)	0.061 g pk	12/16/2021 5:17:39 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	VE-3257 XH 3...	VE-3257 XH...	Direct (Xhd)	0.061 g pk	12/16/2021 5:17:39 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3272A/B...	TE-3272A/B...	Temperature	33.00 °C	12/16/2021 5:17:42 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3273A/B...	TE-3273A/B...	Temperature	34.00 °C	12/16/2021 5:17:42 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3274A/B...	TE-3274A/B...	Temperature	34.00 °C	12/16/2021 5:17:42 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3275A/B...	TE-3275A/B...	Temperature	34.00 °C	12/16/2021 5:17:42 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277E DV...	TE-3277E D...	Temperature	26.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277F DV...	TE-3277F D...	Temperature	26.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277A SV...	TE-3277A S...	Temperature	32.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277B SV...	TE-3277B S...	Temperature	34.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277H DV...	TE-3277H D...	Temperature	25.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277C SV...	TE-3277C S...	Temperature	29.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277D SV...	TE-3277D S...	Temperature	28.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3277G DV...	TE-3277G D...	Temperature	24.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
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●	K-47202D Recip > K-47202D Comp...	TE-3254 Disc...	TE-3254 Dis...	Temperature	18.00 °C	12/16/2021 5:17:42 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283G DV...	TE-3283G D...	Temperature	29.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283B SV...	TE-3283B S...	Temperature	34.00 °C	12/16/2021 5:17:40 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283A SV...	TE-3283A S...	Temperature	32.00 °C	12/16/2021 5:17:42 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283H DV...	TE-3283H D...	Temperature	29.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283F DV...	TE-3283F D...	Temperature	30.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283E DV...	TE-3283E D...	Temperature	30.00 °C	12/16/2021 5:17:41 PM	OK	3500 Full Rack	0	0	0	Communicating
●	K-47202D Recip > K-47202D Comp...	TE-3283D SV...	TE-3283D S...	Temperature	32.00 °C	12/16/2021 5:17:40 PM	OK	3500 Full Rack	0	0	0	Communicating

Figure 2. Alarm Event from Frame Vibration

Root cause analysis is Simple like this … if there is enough Data.

The following trend plot, Figure 3, indicates that the frame vibration had a step change back on December 2nd. However, this plot is not sufficient to determine a root cause of the vibration trip. Deeper diagnostic analysis is required.:

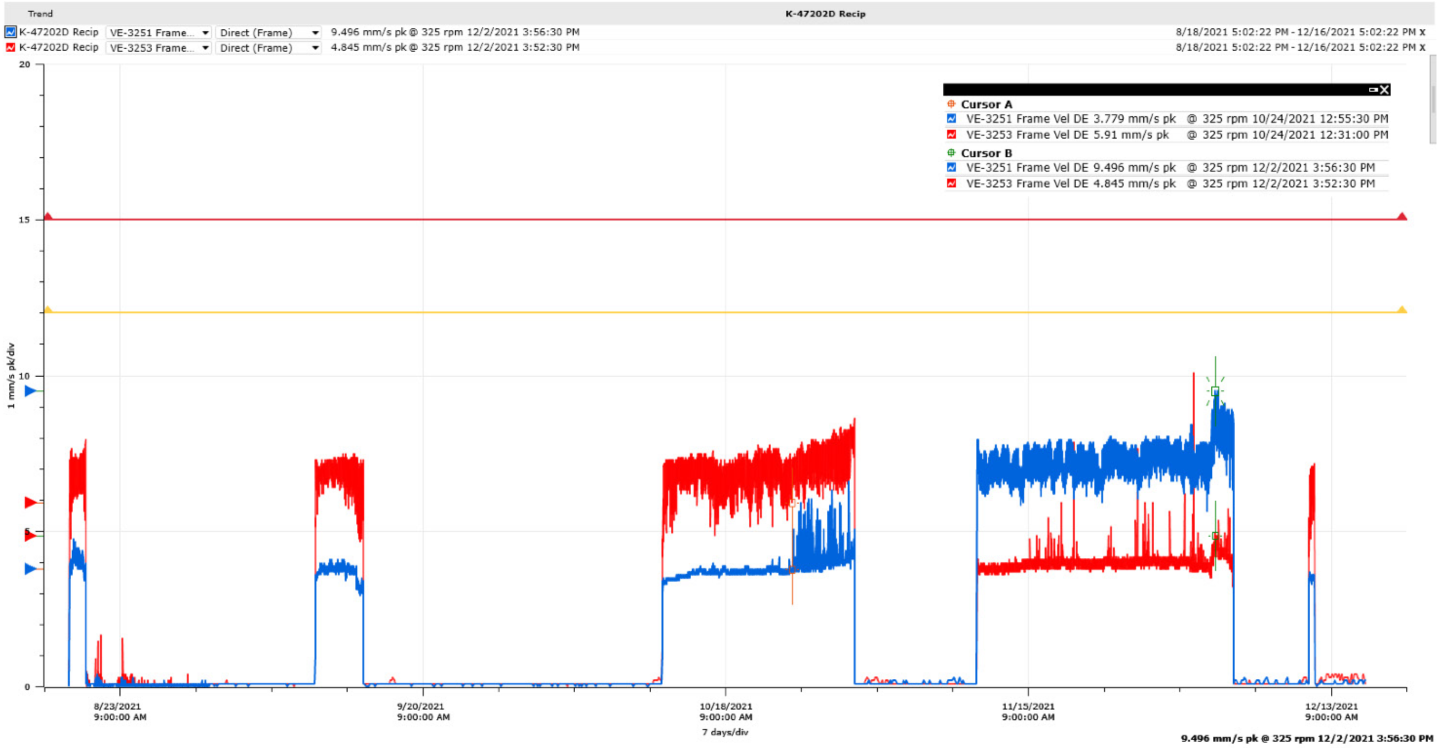


Figure 3. Frame Vibration Trend

The header temperature and pressure trends, as measured by DCS, were reviewed (Figure 4), but root cause of the machine trip could not be determined with this data. It was confirmed that both of CE (crank-end), HE (head-end) temperature and the pressure had both changed from around 2nd December as shown in the temperature trend plot below.

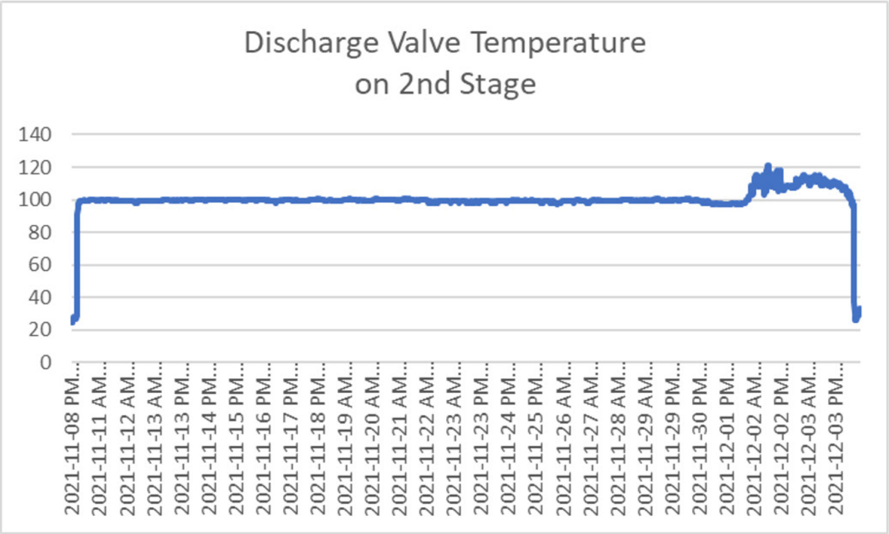


Figure 4. Valve Temperature Trend in DCS

Generally speaking, compressor frame vibration can increase due to a number of reasons, as mentioned below, often requiring full inspection of the reciprocating compressor to identify the root cause of the problem. The potential failure modes may include the following:

- Rotation related vibration transmitted to the compressor frame
- Imbalance due to an unusual pressure differential or inertial imbalance due to:
    - Valve Failures
    - Piston Ring Failures
- Looseness in the foundation assembly, degradation of grout
- High moments caused by excessive rod load. (also related to pressure component failure)
- Rider Band Wear
- Pressure Packing Leaks
- Crosshead & Pin Wear
- Liquid ingestion into the cylinder
- Main Bearing wear or failure
- Broken or loose piston rod

Bently Nevada's System 1 ® is capable of measuring and monitoring the essential condition monitoring parameters for reciprocating compressors. In this case, System 1®'s P-θ (Pressure vs Crank Angle) plot for Throw 2 clearly indicated a more rapid pressure increase than the expected value curve, and a significant reduction in flow balance on the Head End chamber for the same Throw from around 2nd December. (Refer Figures 5, 6 and 7 below)

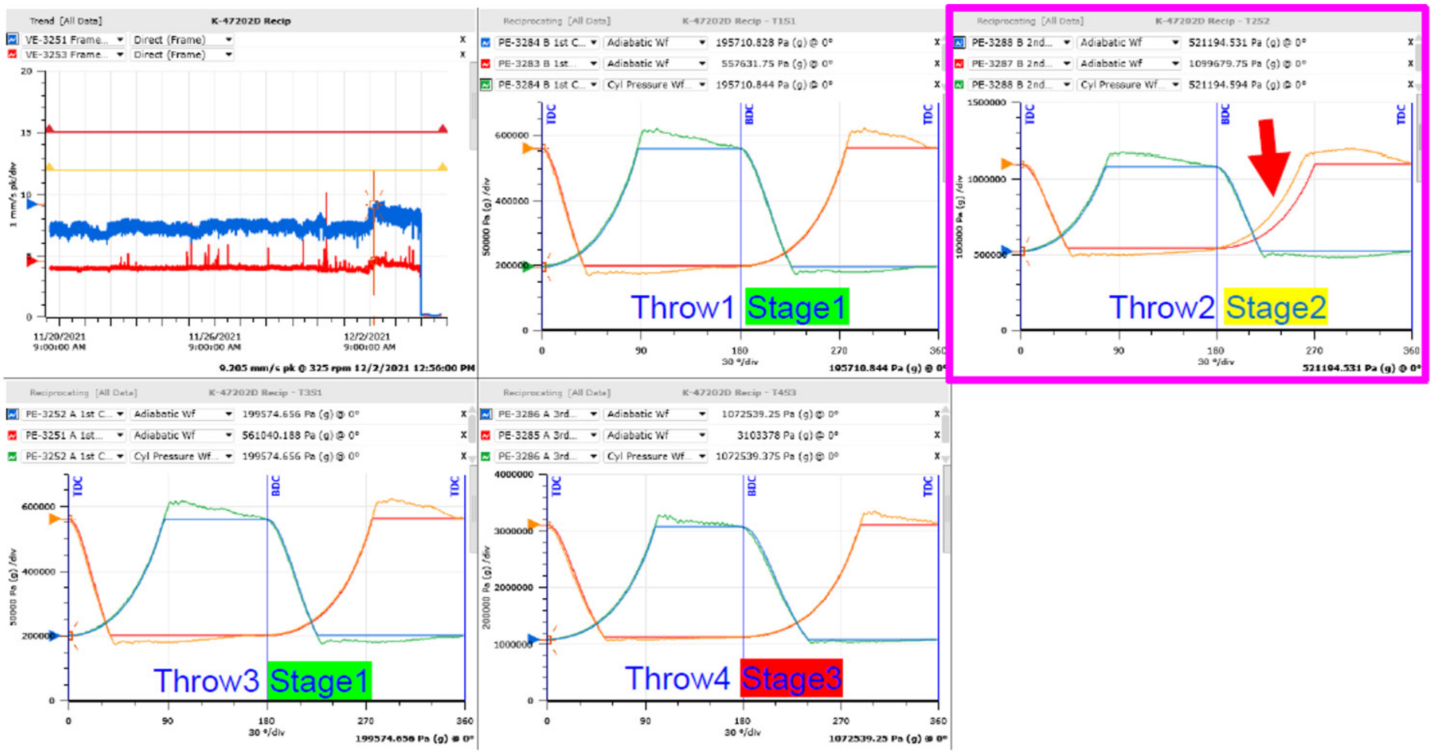


Figure 5. P-θ plot for Each Throw

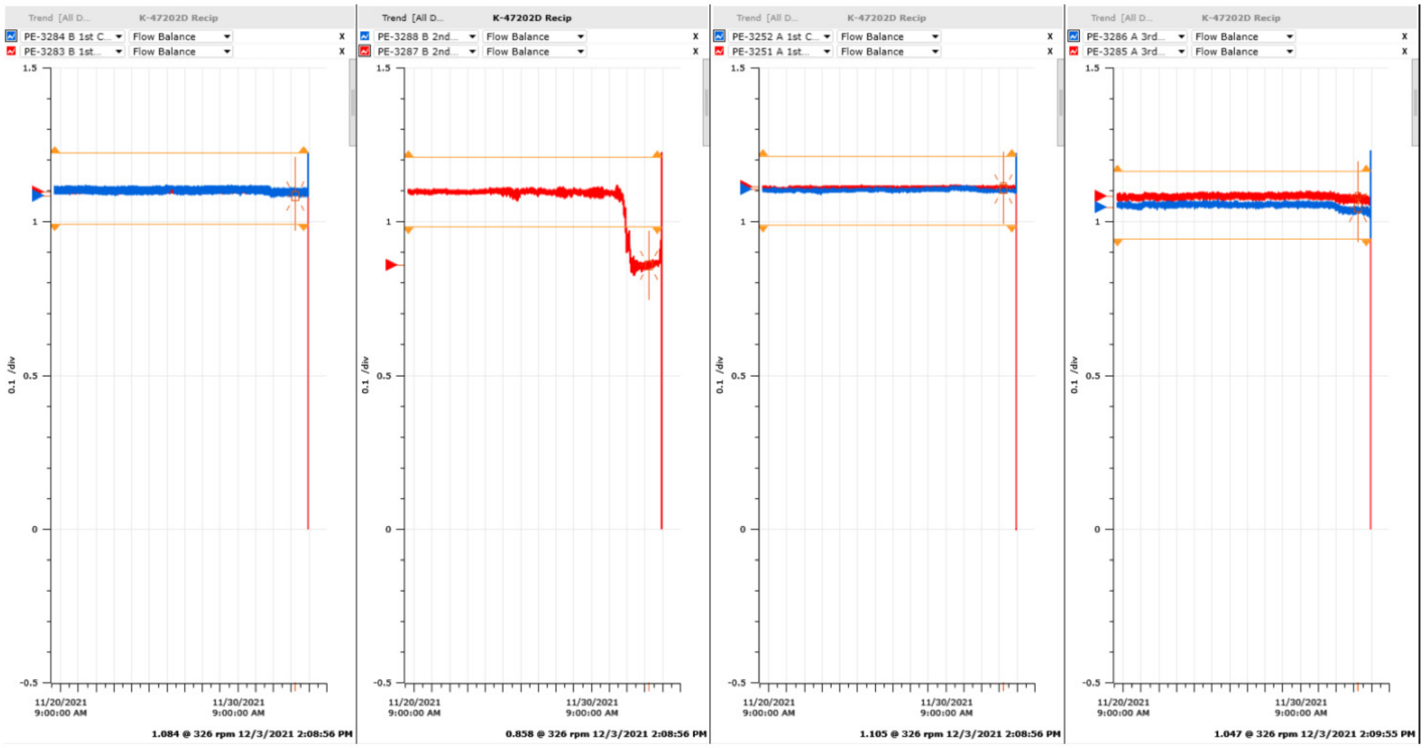


Figure 6. Flow Balance Trend for Each Throw

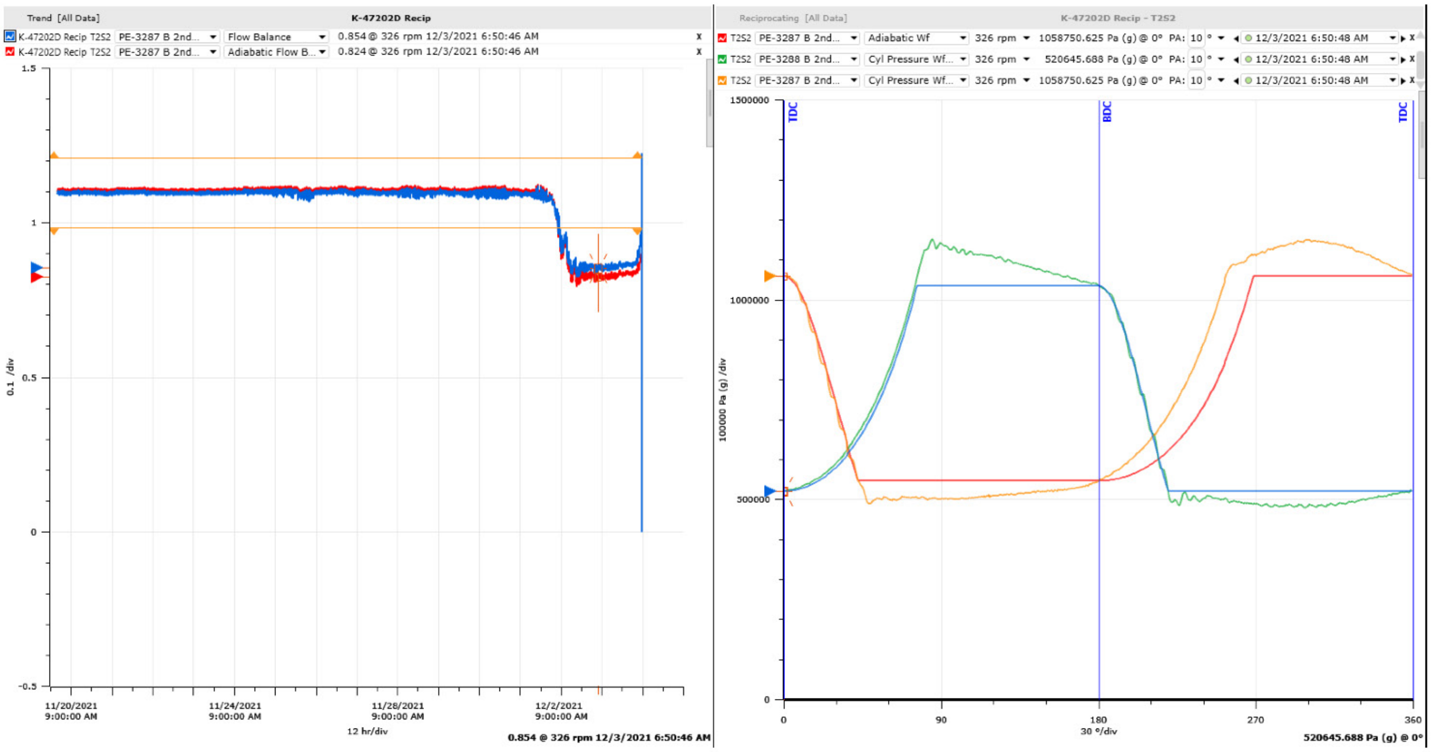
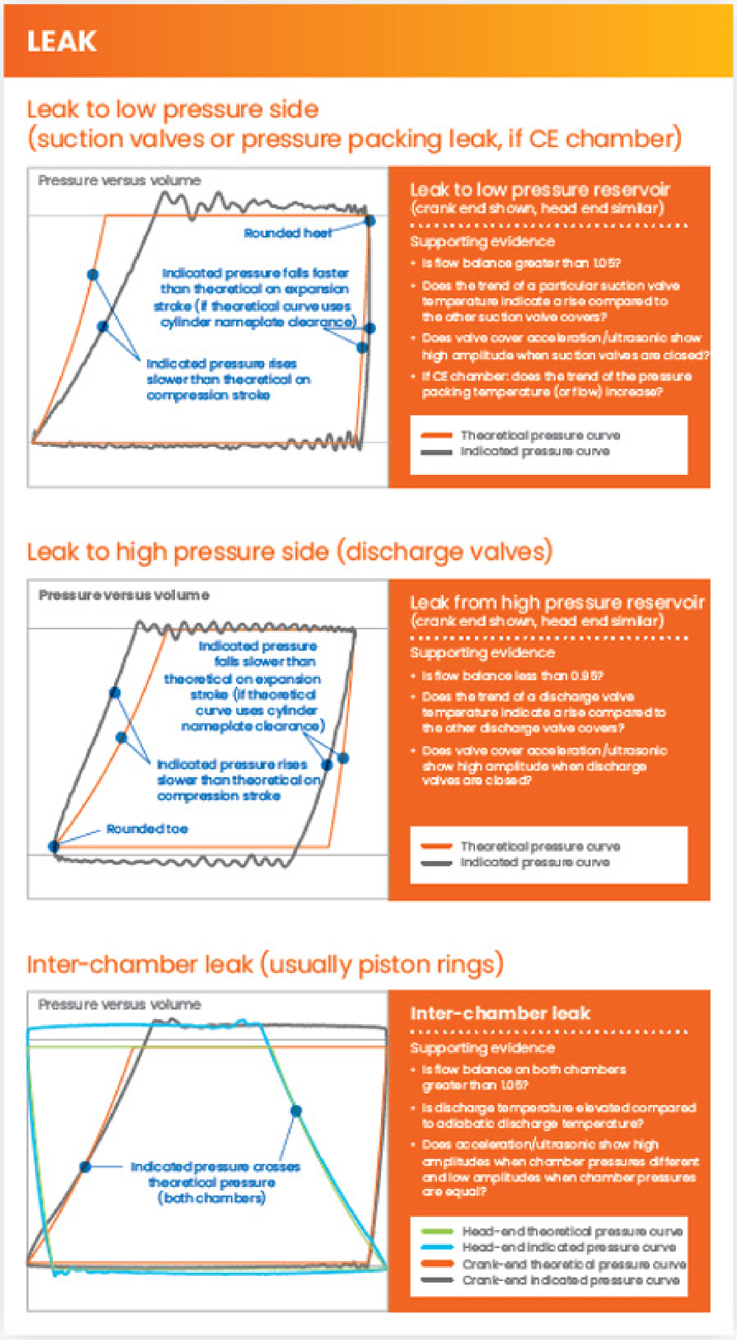


Figure 7. Flow Balance and P-θ plot Change on 2nd Stage Throw

The P-θ plot is a valuable tool to diagnose valve problems by comparing the expected (theoretical adiabatic) vs actual current cylinder pressure curves as described below:



LEAK

Leak to low pressure side
(suction valves or pressure packing leak, if CE chamber)

Leak to low pressure reservoir
(crank end shown, head end similar)

Supporting evidence

- Is flow balance greater than 1.05?
- Does the trend of a particular suction valve temperature indicate a rise compared to the other suction valve covers?
- Does valve cover acceleration/ultrasonic show high amplitude when suction valves are closed?
- If CE chamber: does the trend of the pressure packing temperature (or flow) increase?

Leak to high pressure side (discharge valves)

Leak from high pressure reservoir
(crank end shown, head end similar)

Supporting evidence

- Is flow balance less than 0.95?
- Does the trend of a discharge valve temperature indicate a rise compared to the other discharge valve covers?
- Does valve cover acceleration/ultrasonic show high amplitude when discharge valves are closed?

Inter-chamber leak (usually piston rings)

Inter-chamber leak

Supporting evidence

- Is flow balance on both chambers greater than 1.05?
- Is discharge temperature elevated compared to adiabatic discharge temperature?
- Does acceleration/ultrasonic show high amplitudes when chamber pressures different and low amplitudes when chamber pressures are equal?

Figure 8: Flow balance is defined as Suction Capacity divided by Discharge Capacity.

$$Flow\ Balance = \frac{n_s}{n_d}$$

If the cylinder is in perfect condition, with no leakage past the valves, packing or rings, Flow Balance is exactly 1. If process gas leaks through the suction valve, flow balance shall be higher than 1. When the flow balance is lower than 1, the discharge valve is leaking.

Conclusion

After reviewing the various data captured by System 1®, S-Oil concluded that the root cause of high frame vibration was, in fact, an issue related to the Head End discharge valve on Throw 2.

In particular, the P-θ plot with expected (theoretical adiabatic) and actual cylinder pressure curves provided clear evidence of valve condition, together with flow balance and rod load trends plots.

An inspection was scheduled for the Throw 2 Head End discharge valve specifically, as opposed to the traditional approach of opening and inspecting all valves. Clear damage to the discharge valve ring plate was found as shown in pictures. (Refer to Figures 9 and 10 below)

Figure 9. HE Valve

Figure 10. Damage on Ring Plate

If frame vibration monitoring alone was installed, without additional parameters such as cylinder pressure, the frame vibration would still trigger an alarm, but the extensive time and effort to identify and rectify the correct root cause would result in significant delays to machine startup for production.

Prior to commissioning the System 1 diagnostics platform, the normal practice was to replace all valves when a problem was suspected. Clearly, having limited access to quality diagnostic data to indicate exactly which valve is faulty incurs higher costs for parts and maintenance labor. This quick and simple conclusion on root cause has been demonstrated to minimize the cost for inspection and repair on this critical reciprocating compressor, reducing downtime from 2~3 days to just 1 day for root cause analysis, inspection and repair.

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